Volume 41 Number 4/2024

Edited by the Institute of Sport - National Research Institute,
located in Warsaw, Poland
eISSN 2083-1862

Indeks 353892
PL ISSN 0860-021x

Indexed in: Science Citation Index Expanded®
Web of Science Core Collection
PubMed®
SCOPUS
EBSCO SPORTDiscus™
Directory of Open Access Journals (DOAJ)
INDEX COPERNICUS

Biology of Sport

A QUARTERLY JOURNAL OF SPORT AND EXERCISE SCIENCES

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.134763
© Institute of Sport – National Research Institute

Analysis and prediction of unforced errors in men's and women's professional padel

AUTHORS: Rafael Conde-Ripoll[1], Diego Muñoz[2], Bernardino J. Sánchez-Alcaraz[3], Adrián Escudero-Tena[2]

[1] Universidad Europea de Madrid, Spain
[2] University of Extremadura, Spain
[3] University of Murcia, Spain

Corresponding author:
Rafael Conde-Ripoll
Universidad Europea de Madrid, Spain
E-mail: info.conderipoll@gmail.com

ORCID:
Rafael Conde-Ripoll
0000-0003-1272-5255

Diego Muñoz
0000-0003-4107-6864

Bernardino J. Sánchez-Alcaraz
0000-0001-7788-5175

Adrián Escudero-Tena
0000-0002-7196-5606

ABSTRACT: The aims were to I. assess the differences in unforced errors between men's and women's professional padel players, II. assess the differences in unforced errors between winners and losers of the set in professional padel players, III. analyse the evolution of unforced errors in professional padel. To do this, the unforced errors (which are provided by World Padel Tour (WPT)) were collected from 2,567 sets (1,476 men's sets and 1,091 women's sets) corresponding to matches from the final draw (round of 32, round of 16, quarterfinals, semi-finals and finals) of tournaments on the WPT men's and women's circuits during 2016 to 2022 seasons, which are available on the WPT YouTube channel and on the WPT TV website. The results with respect to the first aim indicate that the number of unforced errors was higher in women's padel than in men's, regardless of the set number, tournament round, season and court. With respect to the second aim, not committing unforced errors is a fundamental factor in professional padel to win the sets. Finally, regarding the third aim, the number of unforced errors decreased as the seasons progressed; therefore, to win, players should not only have to pass the ball without missing, but they might have to hit winners or generate forced errors of the opponent.

CITATION: Conde-Ripoll R, Muñoz D, Sánchez-Alcaraz BJ, Escudero-Tena A. Analysis and prediction of unforced errors in men's and women's professional padel. Biol Sport. 2024;41(4):3–9.

Received: 2023-07-02; Reviewed: 2023-11-20; Re-submitted: 2023-12-19; Accepted: 2023-12-21; Published: 2024-03-06.

Key words:
Racquet sports
Performance analysis
Shot efficacy
High performance
Gender

INTRODUCTION

Padel is a racket sport played in pairs on a 20×10 metre court, which is divided by a central net, with an exterior four-metre-high glass and netting enclosure at the back of the court and a lateral three-metre enclosure to the sides, against which the ball can be hit during play [1]. Padel is practised by players of different ages and competitive levels due to the simplicity of its rules and the fact that its physical and technical-tactical demands are adapted to the level of play [2–4]. This sport is currently played in more than 70 countries [1], which in recent years has led to a significant increase in the number of facilities, commercial agreements (sponsorships, employment contracts, etc.), sports licences, etc. [1]. In this context, the number of scientific studies on padel has increased in recent years [5, 6], with the most studied topic being analysis of performance.

In professional padel there are several tournament circuits (A1-Padel Tour, Premier Padel, World Padel Tour (WPT)), with the WPT being most important; it organises more than 20 events in different cities around the world each season. Thus, the players on this circuit have been the subject of several research studies that have identified the differences that exist in the parameters of play between men's and women's padel [7–10]. Studies have found that the duration of the points is longer in women's padel, as well as the number of shots per point [7, 8]. In terms of shot types, men hit more backhand volleys, flat or topspin smashes, and shots close to the net, while women hit more lobs, trays, and shots from the middle zone or the back of the court [8–12]. In addition, women make a higher percentage of errors (forced and unforced), while men make a higher percentage of winners [13, 14]. On the other hand, although men are more effective on the serve [15], women are more effective on break points [10, 16].

Similarly, studies have been conducted to identify the differences between match-winning and match-losing professional padel pairs [17, 18]. These studies indicate that match-winning pairs typically win long points (over 11 seconds), do not make unforced errors in the first four seconds of the point, and are very effective on break points. In addition, they perform more attacking actions in 85% of the points, spend more time in the net areas and hit more smashes. On the other hand, match-losing pairs tend to lose longer points, perform fewer attacking actions per point and per match, hit more groundstrokes with or without the wall during the match and hit more trays. Thus, a relationship has been found between winning points and playing in areas close to the net [19].

The last shot of the point has been widely analysed in men's and women's professional padel [10, 19–21] as well as in other racket

sports such as tennis or badminton [22–26]. These studies have concluded that the point can end with a winning shot, a forced error or an unforced error. A winning shot is that action where a player wins the point with a direct shot, while a forced error is that action where the player loses the point due to an error in a highly difficult shot, and with a poor position for its execution due to the opponent's prior shot [21]. And, finally, an unforced error is that action where the player loses the point due to bad play or an error in a situation that should be fully controlled by the player [19].

It is worth noting that the majority of points in professional padel and tennis matches end as a result of unforced errors [20, 27]. Moreover, making fewer unforced errors than the opponent is key for attaining success in padel [10, 19–21], tennis [28–30] and badminton [25, 31, 32]. Specifically, in padel, in relative terms, unforced errors usually occur with the double wall and, in absolute terms, with the forehand, backhand and volley [20].

Therefore, after carrying out an analysis of the scientific literature in professional padel and even in other racket sports, unforced errors seem to be a fundamental performance indicator. To the best of our knowledge, this is the first study which takes into account data from seven seasons. For this reason, the aims of the current study were: I. to assess the differences in unforced errors between men's and women's professional padel players, II. to assess the differences in unforced errors between winners and losers of the set in professional padel players, III. to analyse the evolution of unforced errors in professional padel.

MATERIALS AND METHODS

Samples

A total of 2,567 sets (1,476 men's sets and 1,091 women's sets) corresponding to matches from the final draw (round of 32, round of 16, quarterfinals, semi-finals and finals) of tournaments on the WPT men's and women's circuits were analysed. The data collection was carried out from the recording of the unforced errors provided by the WPT during the 2016 to 2022 seasons at the end of each set in the open access videos of WPT TV (https://www.worldpadeltourtv.com/) or on the official YouTube channel (https://www.youtube.com/@Worldpadeltour), following the ethical provisions of the Declaration of Helsinki [33].

Study variables

The performance indicator analysed was the unforced errors (as used in other investigations [17, 19, 20]). According to WPT, an unforced error occurs when a pair loses the point due to bad play in a situation without pressure from the opponents that should be fully controlled by the player of the team [19].

TABLE 1. Unforced errors as a function of the winning or losing pair of the set by gender (data expressed as mean and standard deviation)

Unforced errors according to:		Winners						Losers					
		Men		Women		p	d	Men		Women		p	d
		$\overline{X}$	SD	$\overline{X}$	SD			$\overline{X}$	SD	$\overline{X}$	SD		
Set	First	6.12	3.26	7.46	3.76	< **0.001**	0.369	7.78	3.31	9.44	3.88	< **0.001**	0.435
	Second	6.01	3.23	7.21	3.53	< **0.001**	0.341	7.97	3.39	8.98	3.61	< **0.001**	0.291
	Third	6.05	3.27	6.92	3.39	**0.004**	0.316	7.76	3.34	9.08	3.63	**0.001**	0.381
Round	Round of 32	5.36	2.83	6.32	3.18	**0.021**	0.310	7.36	3.52	7.99	3.16	**0.049**	0.265
	Round of 16	5.46	2.72	6.03	2.89	0.118	0.208	6.50	2.66	7.54	2.65	**0.016**	0.324
	Quarterfinals	6.04	3.25	7.43	3.63	< **0.001**	0.380	8.01	3.37	9.37	3.82	< **0.001**	0.345
	Semi-finals	6.51	3.44	7.54	3.73	< **0.001**	0.271	8.02	3.29	9.53	3.79	< **0.001**	0.404
	Finals	6.12	3.33	7.78	3.75	< **0.001**	0.482	8.18	3.45	9.84	3.92	< **0.001**	0.482
Season	2016	7.54	3.55	7.93	3.66	0.340	0.118	9.09	3.46	10.73	3.83	**0.001**	0.409
	2017	6.44	3.15	8.04	3.93	< **0.001**	0.440	8.79	3.20	10.11	4.19	**0.007**	0.322
	2018	7.31	3.72	8.53	4.11	**0.020**	0.300	10.17	3.78	10.54	3.59	0.238	0.151
	2019	7.13	3.45	9.19	4.08	< **0.001**	0.519	9.35	2.98	11.15	4.27	< **0.001**	0.482
	2020	5.93	3.04	6.83	3.38	**0.021**	0.278	7.07	3.33	8.51	3.65	**0.001**	0.389
	2021	4.85	2.81	6.13	3.11	< **0.001**	0.429	6.49	2.81	7.88	3.17	< **0.001**	0.440
	2022	5.25	2.76	6.51	3.03	< **0.001**	0.428	6.78	2.75	8.24	3.06	< **0.001**	0.501
Court	Outdoor	6.22	3.37	7.49	3.59	< **0.001**	0.376	8.22	3.57	9.56	3.51	< **0.001**	0.412
	Indoor	6.01	3.21	7.22	3.63	< **0.001**	0.341	7.73	3.26	9.08	3.80	< **0.001**	0.349

$\overline{X}$: mean; SD: standard deviation; p: p-value; d: effect size.

In addition, the following contextual variables were established: gender of the players (men and women), result of the set (winners or losers), tournament round (round of 32, round of 16, quarterfinals, semi-finals, and finals), set number (first, second and third sets) and court (outdoor and indoor).

With respect to the "result of the set" variable, several previous investigations have studied aspects of scoring in professional padel [34, 35]. These investigations use the set as a unit of measurement, instead of the match, since the data vary very significantly depending on whether two or three sets are played. According to the rules [1], a padel match is won by the pair that wins two sets before the opponent. Therefore, in the scenario of a three-set match, the results could lead to confusion as each pair would win and lose a set before playing a third and final set.

Process

The unforced errors analysed (which are provided by WPT) were collected from matches that are available on the WPT YouTube channel and the WPT TV website. The responsible analyst who recorded the unforced errors in WPT during the seasons indicated in the sample was a certified padel coach with more than 10 years of experience. However, an inter-observer reliability analysis was performed to ensure the veracity of the data collected. A doctor in sports sciences, author of numerous relevant scientific publications on padel and with more than 10 years of experience, using the LINCE video analysis software [36], analysed the unforced errors of a random sample of 380 sets to guarantee a relevant amount of data, between 10 and 20% of the total study sample [37]. The reliability of the analysis test was 0.93, considered almost perfect [38]. This doctor collected the contextual variables of the study, through an ad-hoc instrument. Furthermore, once the registration was completed, the doctor again collected a random sample of 380 sets in order to perform an intra-observer reliability analysis, with the average reliability of the analysis test being 0.98, considered almost perfect [38]. These reliability procedures have already been used in relevant padel studies [10, 17, 39, 40].

Statistical analysis

Unforced errors did not meet the normality criteria (Kolmogorov-Smirnov), so non-parametric statistical methods were used [41]. A descriptive analysis (means and standard deviations) of unforced errors organised according to the contextual variables was carried out. Subsequently, an inferential analysis was conducted, using the Mann-Whitney U test to identify differences between men's and women's professional padel and between the winners and losers of the set in professional padel according to the set number, the round, the season and outdoor or indoor tournament. Effect size was calculated, considering a small (0.20), medium (0.50), and large (0.80) effect size [42]. In addition, graphs were created through the Holt prediction model to determine the evolution of unforced errors in professional padel. Statistical analyses were performed using SPSS v.21 software (IBM Corp., Armonk, NY, USA) and statistical significance was set at $p < 0.05$.

RESULTS

Table 1 shows the differences found between men's and women's professional padel in unforced errors according to the set number, tournament round, season and court.

As shown in Table 1, professional women's padel players committed significantly more unforced errors than men ($p < 0.001$, $p = 0.001$, $p = 0.004$, $p = 0.007$, $p = 0.020$, $p = 0.021$, $p = 0.016$ or $p = 0.049$), regardless of the set number, tournament round, season or type of court, except for the winners in the round of 16 ($p = 0.118$) and in the 2016 season ($p = 0.340$), where although women committed more unforced errors than men, these differences were not significant. Furthermore, in the losers in the

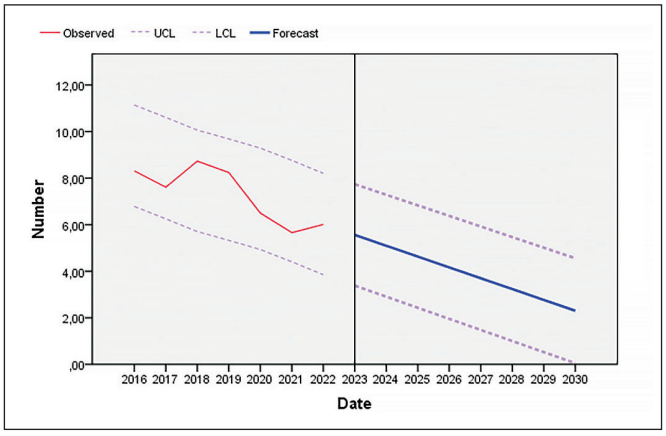


FIG. 1. Evolution of unforced errors in men's professional padel until the year 2030 (UCL: upper confidence limit; LCL: lower confidence limit).

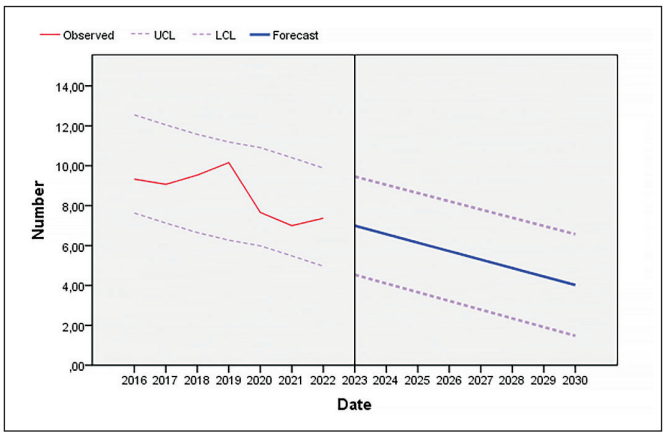


FIG. 2. Evolution of unforced errors in women's professional padel until the year 2030 (UCL: upper confidence limit; LCL: lower confidence limit).

TABLE 2. Descriptive and inferential analysis of unforced errors as a function of gender by winning/loser pair

Unforced errors according to:		Men						Women					
		Winners		Losers		p	d	Winners		Losers		p	d
		$\overline{X}$	SD	$\overline{X}$	SD			$\overline{X}$	SD	$\overline{X}$	SD		
Set	First	6.12	3.26	7.78	3.31	< **0.001**	0.532	7.46	3.76	9.44	3.88	< **0.001**	0.533
	Second	6.01	3.23	7.97	3.39	< **0.001**	0.612	7.21	3.53	8.98	3.61	< **0.001**	0.515
	Third	6.05	3.27	7.76	3.34	< **0.001**	0.569	6.92	3.39	9.08	3.63	< **0.001**	0.610
Round	Round of 32	5.36	2.83	7.36	3.52	< **0.001**	0.623	6.32	3.18	7.99	3.16	< **0.001**	0.546
	Round of 16	5.46	2.72	6.50	2.66	< **0.001**	0.455	6.03	2.89	7.54	2.65	< **0.001**	0.543
	Quarterfinals	6.04	3.25	8.01	3.37	< **0.001**	0.618	7.43	3.63	9.37	3.82	< **0.001**	0.530
	Semi-finals	6.51	3.44	8.02	3.29	< **0.001**	0.467	7.54	3.73	9.53	3.79	< **0.001**	0.556
	Finals	6.12	3.33	8.18	3.45	< **0.001**	0.661	7.78	3.75	9.84	3.92	< **0.001**	0.545
Season	2016	7.54	3.55	9.09	3.46	< **0.001**	0.484	7.93	3.66	10.73	3.83	< **0.001**	0.748
	2017	6.44	3.15	8.79	3.20	< **0.001**	0.777	8.04	3.93	10.11	4.19	< **0.001**	0.546
	2018	7.31	3.72	10.17	3.78	< **0.001**	0.765	8.53	4.11	10.54	3.59	< **0.001**	0.580
	2019	7.13	3.45	9.35	2.98	< **0.001**	0.677	9.19	4.08	11.15	4.27	< **0.001**	0.459
	2020	5.93	3.04	7.07	3.33	**0.002**	0.352	6.83	3.38	8.51	3.65	**0.001**	0.464
	2021	4.85	2.81	6.49	2.81	< **0.001**	0.607	6.13	3.11	7.88	3.17	< **0.001**	0.584
	2022	5.25	2.76	6.78	2.75	< **0.001**	0.587	6.51	3.03	8.24	3.06	< **0.001**	0.576
Court	Outdoor	6.22	3.37	8.22	3.57	< **0.001**	0.597	7.49	3.59	9.56	3.51	< **0.001**	0.630
	Indoor	6.01	3.21	7.73	3.26	< **0.001**	0.564	7.22	3.63	9.08	3.80	< **0.001**	0.511

$\overline{X}$: mean; SD: standard deviation; p: p-value; d: effect size.

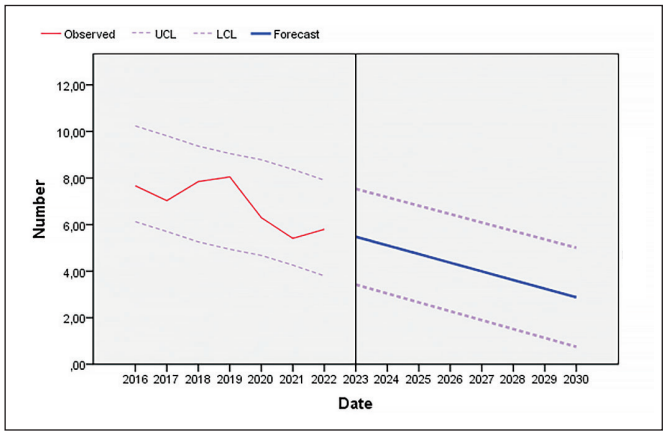


FIG. 3. Evolution of unforced errors committed by players who win sets in professional padel until the year 2030 (UCL: upper confidence limit; LCL: lower confidence limit).

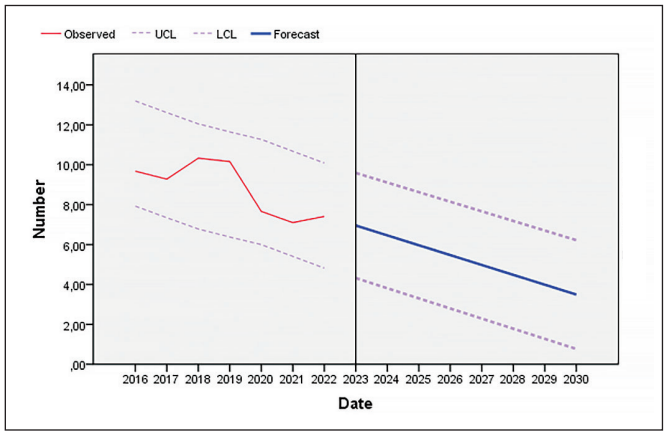


FIG. 4. Evolution of unforced errors committed by players who lose sets in professional padel until the year 2030 (UCL: upper confidence limit; LCL: lower confidence limit).

2018 season, men committed more unforced errors than women, although this difference was not significant ($p = 0.238$).

As Figures 1 and 2 show, the number of unforced errors decreased as the seasons progressed in both men's professional padel and women's professional padel.

Table 2 shows the differences found between winners and losers in men's and women's professional padel in unforced errors according to the number set, tournament round, season and court.

As shown in Table 2, the results show that the players who won the set committed significantly fewer unforced errors than the players who lost the set ($p < 0.001$ or $p = 0.002$), regardless of the set number, tournament round, season or court type.

As Figures 3 and 4 show, the number of unforced errors decreased as the seasons progressed, both in the pair of players who won the sets and in the pair that lost them.

DISCUSSION

The aims of the current study were to: I. assess the differences in unforced errors between men's and women's professional padel, II. assess the differences in unforced errors between winners and losers of the set in professional padel, III. analyse the evolution of unforced errors in professional padel.

The style of play in professional padel varies according to the gender of the athletes. The results of this study indicate that the number of unforced errors was higher in women's padel than in men's padel, regardless of the set number, tournament round, season, and court. Various studies that have analysed the most frequent technical-tactical action in professional men's and women's professional padel, as well as the differences between them, agree with the results of this study [13, 14]. Apart from showing that a higher number of errors (forced and unforced) are committed in women's compared to men's padel, it has also been found that men produce more winners than women. Women's professional padel is characterized by a more conservative style of play, where more continuity shots such as lobs and trays are performed [8, 9, 11, 12] and where to win, it is enough to pass the ball and not commit unforced errors. In contrast, in men's professional padel fewer unforced errors are committed and the athletes make more aggressive shots such as flat or topspin smashes [12, 14] to perform winning shots or to generate forced errors of the opponent. Nevertheless, these differences between playing styles in professional padel according to the gender of the athletes could be due to anthropometric and strength differences between elite men's and women's players [4, 43], since men are on average taller, and have a higher muscle percentage and higher values of vertical jump and grip strength than women players, which allows them to play a more aggressive game.

Not committing unforced errors is a fundamental factor in professional padel to win the sets. The results of this study show that the players who won committed fewer unforced errors than the players who lost the set, regardless of the game context analysed. Hence, to enhance their chances of success in matches, athletes should work closely with their coaches to develop strategies that minimize unforced errors during practice. For instance, coaches and players could watch competitive or practice matches, identify when unforced errors occur and find out ways to improve [44], and likewise, coaches could also propose exercises in which the unforced errors are monitored and penalized [45, 46]. Further investigation in this domain is required, given the scarcity of information regarding the influences of specific drills and training protocols in enhancing technical-tactical abilities [47].

As shown in Figures 1–4, players reduced the number of unforced errors between 2016 and 2022. This could be due to the professionalization of the sector which has led to enhancements in player skills. In addition, according to the data of the present investigation, the number of unforced errors will decrease as the seasons progress; therefore, to win, players must not only pass the ball, but must also hit winners or generate forced errors of the adversary. Various studies that have analysed the effectiveness of the last shot of the points in professional men's and women's padel in different game contexts [13, 17, 18, 48, 49] show that the players who win the matches commit fewer errors (forced and unforced) and more winners than the players who lose, which would reinforce one of the main objectives of this sport, which is to minimize the number of errors (forced and unforced). In addition, depending on the type of shot, the players who lose perform a higher percentage of backhand volleys [8, 18] and off-the-wall shots [8, 48]. Coaches and athletes should work in a cooperative way so that the latter develop a greater competitive performance by being more diverse and unpredictable in their actions thanks to appropriate challenging constraints [50]. Likewise, previous studies have indicated that winning pairs tend to win long points (more than 11 seconds) and do not usually commit unforced errors in the first four seconds of the point [19]. The same authors found that, at the net, losers committed unforced errors earlier in the rally than winners whereas there were no significant differences at the baseline. Similarly, Courel-Ibáñez and collaborators [51] found that winners made 40% fewer unforced errors at the net compared to losers. The study conducted by Escudero-Tena and collaborators [14] indicated that in men's padel more winning shots are made than in women's padel; thus men's padel is generally more aggressive, although this difference decreases as the importance of the point increases. On the other hand, in men's padel fewer errors (forced and unforced) are committed than in women's padel at non-key moments and at key moments, so women must train to achieve a more fluid game. However, men commit more errors (forced and unforced) than women in golden points, with women being more effective in these cases. Likewise, Sánchez-Alcaraz and collaborators [34] stated that the importance of the point for the match score causes players to change their game behaviour. Therefore, players must pay special attention to the different moments of the game, and create training routines in which specific situations are established, that is, train with a scoreboard simulation.

The results of this study are very novel, because as far as we know, it is the first study that analyses such an extensive data sample (seven seasons), allowing a predictive analysis of the development of the number of unforced errors in men' and women's professional padel. However, a limitation must be taken into account when interpreting the results, which is that the data recorded for the round of 32 and round of 16 pertain only to the 2022 season. In previous seasons, WPT did not provide these data in these or prior rounds (i.e., rounds from qualification). In addition, in future research, as unforced errors have been analysed, forced errors, winners, and shots that generate forced errors should be analysed.

CONCLUSIONS

The style of play in professional padel varies according to the gender of the athletes, because the number of unforced errors is higher in women's padel than in men's, regardless of the number of sets, the round of the tournament, the season and the court. Hence, since the

number of unforced errors in men's and women's professional padel will decrease as the seasons progress, the style of play in women's padel game should evolve so as to be more offensive.

In addition, not committing unforced errors is a fundamental factor in professional padel to win sets. Thus, players who win commit fewer unforced errors than those who lose, regardless of the context of the game. However, the number of unforced errors will decrease as the seasons progress. Therefore, in order to increase the chances of winning, players will not only have to pass the ball, but they will also have to hit winners and/or force errors on the opponent.

Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. International Padel Federation. Rules of the game in padel the International Padel Federation and list of countries associated with the International Padel Federation, https://www.padelfip. com/es/ (2023, accessed 7 May 2023).
2. Courel-Ibáñez J, Cordero JC, Muñoz D, et al. Fitness benefits of padel practice in middle-aged adult women. Sci Sport. 2018; 33(5):291–298.
3. García-Benítez S, Courel-Ibáñez J, Pérez-Bilbao T, et al. Game responses during young padel match play: Age and sex comparisons. J Strength Cond Res. 2018; 32(4):1144–1149.
4. Pradas F, Sánchez-Pay A, Muñoz D, et al. Gender differences in physical fitness characteristics in professional padel players. Int J Environ Res Public Health. 2021; 18(11):5967.
5. Martin-Miguel I, Escudero-Tena A, Muñoz D et al. Performance analysis in padel: a systematic review. J Hum Kinet. 2023; 89:213–230.
6. Sánchez-Alcaraz BJ, Cánovas-Martínez J, Sánchez-Pay A, et al. Investigación en pádel. Revisión sistemática. [research on padel. A systematic review]. Padel Sci J. 2022; 1(1):71–105.
7. García-Benítez S, Pérez-Bilbao T, Echegaray M, et al. Influencia del género en la estructura temporal y las acciones de juego del pádel profesional. [influence of gender on the temporal structure and game actions of professional padel]. Cult Cienc y Deporte. 2016; 11:241–247.
8. Lupo C, Condello G, Courel-Ibáñez J, et al. Efecto del género y del resultado final del partido en competiciones profesionales de pádel. [effect of gender and match outcome on professional padel competition] Rev Int Cienc Deporte. 2018; 14(51):29–41.
9. Torres-Luque G, Ramírez A, Cabello-Manrique D, et al. Match analysis of elite players during paddle tennis competition. Int J Perform Anal Sport. 2015; 15(3):1135–1144.
10. Escudero-Tena A, Courel-Ibáñez J, García-Rubio J, et al. Sex differences in professional padel players: analysis across four seasons. Int J Perform Anal Sport. 2021; 21(5):651–662.
11. Escudero-Tena A, Fernández-Cortes J, García-Rubio J, et al. Use and efficacy of the lob to achieve the offensive position in women's professional padel. Analysis of the 2018 WTP finals. Int J Environ Res Public Health. 2020; 17(11):4061.
12. Sánchez-Alcaraz BJ, Perez-Puche DT, Pradas F, et al. Analysis of performance parameters of the smash in male and female professional padel. Int J of Environ Res Public Health. 2020; 17(19):7027.
13. Escudero-Tena A, Almonacid B, Martínez J, et al. Analysis of finishing actions in men's and women's professional padel. Int J Sports Sci Coach. 2022. https://doi.org /10. 1177/17479541221139970.
14. Escudero-Tena A, Muñoz D, Sánchez-Alcaraz BJ, et al. Analysis of errors and winners in men's and women's professional padel. Appl Sci. 2022; 12(16):8125.
15. Sánchez-Alcaraz BJ, Muñoz D, Pradas F, et al. Analysis of serve and serve-return strategies in elite male and female padel. Appl Sci. 2020; 10(19):6693.
16. Escudero-Tena A, Mancha-Triguero D, Pozo-Ayerbe C, et al. Diferencias entre pádel profesional masculino y femenino en función del rendimiento según el set, la ronda y el tipo de torneo. [differences between meń s and womeń s professional padel based on performance according to the set, the round and the type of tournament]. Padel Sci J. 2022; 1(1):23–37.
17. Escudero-Tena A, Sánchez-Alcaraz J, García-Rubio J, et al. Analysis of game performance indicators during 2015–2019 world padel tour seasons and their influence on match outcome. Int J of Environ Res Public Health. 2021; 18(9):4904.
18. Sánchez-Alcaraz BJ, Courel-Ibáñez J, Muñoz D, et al. Análisis de las acciones de ataque en el pádel masculino profesional. [analysis of attack actions in meńs professional padel]. Apunt Educ Fís y Deportes. 2020; 142(4):29–34.
19. Courel-Ibáñez J, Sánchez-Alcaraz BJ, Cañas J, et al. Game performance and length of rally in professional padel players. J Hum Kinet. 2017; 55:161–169.
20. Mellado-Arbelo Ó, Baiget-Vidal E and Vivès-Usón M. Analysis of game actions in professional male padel. Cult Cienc y Deporte. 2019; 14(42):191–202.
21. Sánchez-Alcaraz BJ, Jiménez V, Muñoz D, et al. Diferencias en los parámetros de carga externa entre el pádel masculino y femenino profesional. [Differences in external load parameters between professional men´s and women´s padel]. J Sport Health Res. 2021; 13(3):445–454.
22. Attray H, Attray S. Cost of an unforced error in tennis: a statistical approach. Coach Sport Sci Rev. 2021; 29(84):12–14.
23. Meffert D, O'Shannessy C, Born P et al. Tennis at tiebreaks: addressing elite player's performance for tomorrow's coaching. Ger J Exerc Sport Res. 2019; 49(3):339–344.
24. Martínez-Gallego R, Guzmán JF, James N et al. The relationship between the incidence of winners/errors and the time spent in different areas of the court in elite tennis. J Hum Sport Exerc. 2013; 8(3proc):S601–S607.
25. Barreira J, Chiminazzo JGC. Who, how and when to perform winner points and unforced errors in badminton matches? An analysis of men's single matches in the 2016 Olympic Games. Int J Perform Anal Sport. 2020; 20(4):610–619.
26. Cabello-Manrique D, González-Badillo JJ. Analysis of the characteristics of competitive badminton. Br J Sports Med. 2003; 37(1):62–66.
27. Brody H. Unforced errors and error reduction in tennis. Br J Sports Med. 2006; 40(5):397–400.
28. Carboch J. Comparison of game characteristics of male and female tennis players at grand-slam tournaments in 2016. Trends Sport Sci. 2017; 4(24):151–155.
29. Djurovic N, Lozovina V, Pavicic L. Evaluation of tennis match data – new acquisition model. J Hum Kinet. 2009; 21(1):15–21.
30. Katic R, Milat S, Zagorac N et al. Impact of game elements on tennis match outcome in Wimbledon and Roland Garros 2009. Collegium Antropol. 2011; 35(2):341–346.
31. Laffaye G, Phomsoupha M, Dor F. Changes in the game characteristics of a badminton match: A longitudinal study through the olympic game finals analysis in men's singles. J Sports Sci Med. 2015; 14(3):584–590.
32. Yadav SK, Shukla TM. Analysis of unforced errors in relation to performance in singles in badminton. Int J Phys Educ. 2011; 4(1):117–119.

33. Sánchez-Alcaraz BJ, Siquier-Coll J, Toro-Román et al. Análisis de los parámetros relacionados con el marcador en el circuito World Padel Tour 2019: diferencias por género, ronda y tipo de torneo [Analysis of the parameters related to the score in the World Padel Tour 2019 circuit: differences by gender, round and type of tournament]. Retos. 2019; 39:200–204.
34. Sánchez-Alcaraz BJ, Courel-Ibáñez J, Díaz J et al. Efectos de la diferencia en el marcador e importancia del punto sobre la estructura temporal en pádel de primera categoría. [Effects of the difference in the score and importance of the point on the temporary structure in first category paddle tennis]. J Sport Health Res. 2019; 11(2):151–160.
35. World Medical Association. World medical association declaration of Helsinki. Ethical principles for medical research involving human subjects. Bull World Health Organ 2001; 79(4):373–374.
36. Gabin B, Camerino O, Anguera MT, et al. Lince: multiplatform sport analysis software. Procedia – Social Behav Sci. 2012; 46:4692–4694.
37. Igartua J. Métodos cuantitativos de investigación en comunicación. Barcelona: Bosch, https://core.ac.uk/download/pdf/ 230794660.pdf (2006, accessed 7 May 2023).
38. Landis J and Koch G. undefined. The measurement of observer agreement for categorical data. Biometrics. 1977; 33(1):159–174.
39. Escudero-Tena A, Galatti L, Sánchez-Alcaraz BJ, et al. Effect of the golden points and non-golden points on performance parameters in professional padel. Int J Sports Sci. 2023. https://doi.org/10.1177/17479541231161288.
40. Escudero-Tena A, Ibáñez SJ, Vaquer-Castillo A, et al. Analysis of the return in professional men's and women's padel. Int J Sports Sci Coach. 2023. https://doi.org/10.1177/174795 41231167752.
41. Field AP and Field AP. Discovering statistics using IBM SPSS statistics. London: Sage, 2018. https://app.kortext.com/borrow/269367.
42. Thalheimer W and Cook S. How to calculate effect sizes from published research: a simpified methodology. Work-Learning Research. 2002; 1:1–9.
43. Muñoz D, Toro-Román V, Courel-Ibáñez J, et al. La altura como factor de rendimiento en pádel profesional: diferencias entre géneros. [height as a performance factor in professional paddle tennis: differences between genders]. Acción Mot. 2022; 29(1):93–103.
44. García-González L, Moreno A, Gil A et al. Effects of decision training on decision making and performance in young tennis players: An applied research. J Appl Sport Psychol. 2014; 26(4):426–440.
45. Low WR, Freeman P, Butt J et al. The role and creation of pressure in training: Perspectives of athletes and sport psychologist. J Appl Sport Psychol. 2023; 35(4):710–730.
46. Stoker M, Lindsay P, Butt J et al. Elite coaches' experiences of creating pressure training environments. Int J Sport Psychol. 2016; 47(3):262–281.
47. Sánchez-Pay A, García-Castejón A, Courel-Ibáñez J et al. Influence of low-compression balls in padel initiation stage. RIMCAFD. 2020; 20(79):419–434.
48. Ramón-Llín J, Guzmán J, Martínez-Gallego R, et al. Stroke analysis in padel according to match outcome and game side on court. Int J Environ Res Public Health 2020; 17(21):7838.
49. Ramón-Llin J, Guzmán, JF, Llana S, et al. The effect of the return of serve on the server pair's movement parameters and rally outcome in padel using cluster analysis. Front Psychol. 2019; 10:1194.
50. Pol R, Balagué N, Ric A et al. Training or synergizing? Complex systems principles change the understanding of sport processes. Sports Med Open. 2020; 6(1):28.
51. Courel-Ibáñez J, Sánchez-Alcaraz BJ, Cañas J. Effectiveness at the net as a predictor of final match outcome in professional padel players. Int J Perform Anal Sport. 2015; 15(2):632–640.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.134760
© Institute of Sport – National Research Institute

Relationships between physical fitness and match running demands during a futsal congested-weeks training camp

AUTHORS: Francisco Tomás González-Fernández[1], Halil Ibrahim Ceylan[2], Rui Miguel Silva[3,4], Filipe Manuel Clemente[3,4,5], Pedro Bezerra[3,4], Yung-Sheng Chen[6,7,8]

[1] Department of Physical Education and Sports, Faculty of Sport Sciences. University of Granada, Granada 18071, Spain
[2] Physical Education and Sports Teaching Department, Kazim Karabekir Faculty of Education, Ataturk University, Erzurum, 25240, Turkey
[3] Escola Superior Desporto e Lazer, Instituto Politécnico de Viana do Castelo, Rua Escola Industrial e Comercial de Nun'Álvares, 4900-347 Viana do Castelo, Portugal
[4] Sport Physical Activity and Health Research & Innovation Center, Viana do Castelo, Portugal
[5] Gdansk University of Physical Education and Sport, 80-336 Gdańsk, Poland
[6] Department of Exercise and Health Sciences, University of Taipei, Taipei 111, Taiwan
[7] Exercise and Health Promotion Association, New Taipei City 241, Taiwan
[8] Tanyu Research Laboratory, Taipei 112, Taiwan

ABSTRACT: This study examines the relationships between body composition, anthropometry and physical fitness measures, and internal and external load (match physical and running demands) during a congested period of an overseas futsal training camp. Eleven under-20 national futsal players participated in a eleven-day training camp. During the matches, exercise heart rate (HR) and locomotion profiles were recorded via a Polar Team Pro system as the players' internal and external load. The friendly matches were scheduled on the training camp's 2nd, 4th, 6th, 8th, and 10th days. A repeated-measures analysis of variance (ANOVA) and Pearson's correlation coefficient were used for statistical analysis. The results revealed significant differences in sprint ($F = 2.74$, $p = 0.04$, $\eta^2 = 0.21$), accelerations ($F = 3.63$, $p = 0.04$, $\eta^2 = 0.27$), and decelerations ($F = 2.73$, $p = 0.04$, $\eta^2 = 0.21$) performance between the five matches ($p < 0.05$). Also, the overall body composition and physical fitness measures had large to very large correlations with match running demands during congested periods of futsal competition ($p < 0.05$). In conclusion, the baseline body composition and the overall physical fitness measures may be essential factors in match running demands during a congested futsal match period. Futsal players who perform better in the 30–15 Intermittent Fitness Test can sustain a greater volume of high-intensity accelerations during a congested period.

CITATION: González-Fernández T, Ceylan HI, Silva RM. Relationships between physical fitness and match running demands during a futsal congested-weeks training camp. Biol Sport. 2024;41(4):11–30.

Received: 2023-02-25; Reviewed: 2023-07-30; Re-submitted: 2023-11-22; Accepted: 2024-01-17; Published: 2024-03-06.

Corresponding author:
Yung-Sheng Chen
Department of Exercise and Health Sciences
University of Taipei
No.101, Sec. 2, Jhongcheng Rd.
Shihlin Dist. Taipei 11153
Taiwan
E-mail: yschen@utaipei.edu.tw

ORCID:
Francisco Tomás Francisco Tomás
0000-0002-1480-7521

Halil I. Ceylan
0000-0003-1133-5511

Rui M. Silva
0000-0003-3380-864X

Filipe M. Clemente
0000-0001-9813-2842

Pedro Bezerra
0000-0001-8219-5427

Yung-Sheng Chen
0000-0002-1013-3822

Key words:
Match load
Exercise intensity
Locomotion profile
Body composition
Indoor sports

INTRODUCTION

Futsal is a dynamic, intermittent, fast-paced team sport played indoors with five players on each side (5-a-side), imposing high physical, technical, and tactical demands [1–3]. The smaller dimensions of the playing field and the option of unlimited player substitutions in futsal cause players to exhibit high-level physical performances during a match, including high oxygen uptake (VO_2), short explosive movements (sprints), repeated plyometric requirements, accelerations, rapid changes in direction, and other high-intensity activities during transition phases [1, 4–8].

During a significant portion of a futsal game (more than 80%), players exceed 85 or 93% of their maximum heart rate (HR_{max}: ~193 ± 8.39 bpm) [1, 9–11], with a corresponding blood lactate concentration ranging from 4.2 to 21.8 mmol/L [9, 10]. Further, time-motion analysis showed that professional futsal players covered a mean distance of 4000 m (117.3 m per minute), with about 28.5% of this distance being medium-intensity activity, 13.7% (1232 m), high-intensity activity (speed ≥ 15 km · h^{-1}, 571 m), and 8.9% sprinting (speed ≥ 25 km · h^{-1}, 349 m) during the games [1]. Another study noted that elite futsal players covered an average of 121 metres per minute, and sprints and high-intensity runs made up 5% and 12% of the total playing time, respectively [10]. Moreover, a futsal player performs sprints or repetitive high-intensity activities that heavily strain the aerobic and anaerobic pathways every 79 seconds for more than 80% of the time spent on the field [1, 6, 10].

Regarding physical fitness, maximal VO_2 ($\dot{V}O_{2max}$) or aerobic capacity is considered a distinguishing factor in sustaining the physical demands and match performance, depending on the level of competition, as stated above [12]. Enhanced aerobic capacity helps with faster recovery between efforts and even after fatigue, delays the onset of fatigue in the second half of the match, improves lactate removal and phosphocreatine regeneration, increases the potential to cover longer distances in high-intensity runs and sprints, and contributes to being more involved in the game [7, 13, 14].

Body composition and anthropometric variables (height, body mass, lean body mass, and fat mass) play a fundamental role in maintaining high-level physical demands and match the above activity profile. Body fat percentage can limit an athlete's ability to perform explosive movements in team sports [15]. Typically, elite male futsal players display low body fat around 10–11% [16, 17], 12% [18], and 15% [19]. Previous studies have found that high-fat mass had a negative effect on match performance, especially on sprint distance [20, 21], high-speed running distance [22], change of direction or agility [20, 21], and aerobic capacity [23, 24] in soccer players. Moreover, recent studies indicated a positive correlation between the anthropometric parameters with a higher percentage of muscle mass and $\dot{V}O_{2max}$ [20, 21], and strength production characteristics of athletes [25].

Similar to soccer, international futsal tournaments and playoffs for major futsal leagues worldwide are played during congested schedules, with very little time for players to rest and recover between matches. Indeed, exposure to two or three matches a week can increase the burden and stress on players, leading to residual fatigue and an increased risk of injury [26–28]. Furthermore, various performance outputs and muscle functions can be affected due to the elevation of markers associated with inflammation and muscle damage [29, 30]. Previous studies have found that congested schedules decreased muscle contractile function or muscle stiffness [30, 31] and hamstring strength performance [32] due to cumulative fatigue and lack of muscle recovery. Thus, there is a need to understand better how players participating in multiple matches within a week cope with the external demands placed upon them [33].

The matches played during congested weeks significantly impact external load parameters in professional soccer players [29, 33, 34]. However, there is a need for more research on the effects of playing matches during a congested period in futsal, and the uncertainty regarding its impact remains. Despite the limited number of studies that have examined the match demands of professional male [1, 7, 10, 28, 35, 36] and female futsal players [37], these studies could contribute not only to a better understanding of the workload and intensity requirements of players during the game but also to the improvement of their performance, and to minimize the risk of non-functional overreaching, overtraining, and injury [38]. For instance, a study showed that the match intensity of Oceania futsal players, evaluated through their HR, recovery kinetics, and health status, remained unchanged during a 4-day FIFA futsal tournament. However, later in the study, it was observed that despite a slight increase in players' subjective perception of effort between matches, there was a decrease in sprint activity [11].

It was previously suggested that futsal players with high training load and aerobic and anaerobic capacity and power tend to perform at high intensities during a 4-day FIFA futsal tournament and take longer to recover from these intense efforts (intensity and recovery kinetics via HR measurements) [11]. In a study conducted on professional soccer players, a strong positive correlation was observed between the maximum aerobic speed (MAS) achieved during the final stage of the 30–15 Intermittent Fitness Test (IFT) and external load measures such as total distance, high-intensity running, accelerations, and decelerations [39]. In a recent study, professional soccer players with lower fat content and higher aerobic capacity covered longer distances in sprints and high-speed running (HSR) during official matches [22]. Lastly, the available evidence from a previous study suggested that the 30-m sprint test might be predicted by the session rate of perceived exertion (RPE), average and HR_{max}, total distance covered per minute, maximal speed, and average speed in young national futsal players [18].

Considering the studies mentioned above, there is a need for more research examining the link between body composition, aerobic capacity, and external load metrics during futsal matches played in congested weeks. Therefore, closely monitoring external load during matches in very short and congested fixtures can provide valuable information to coaches and sports scientists to optimize players' recovery and performance and design appropriate training programmes.

This study has two objectives: (1) to analyse differences in match physical and running demands among matches (from match 1 (M1) to match 5 (M5)); and (2) to examine the relationships between body composition, anthropometry, and physical fitness measures, and match physical and running demands during a congested week of an overseas futsal training camp. We assumed there would be variations in external load parameters during five matches played in a congested period (11 days). Additionally, physical fitness and body composition would positively affect the external load parameters during the congested period.

MATERIALS AND METHODS

Experimental Approach to the Problem

This is an observational study during an eleven-day futsal training camp in Luso, Portugal, two weeks before the Asian under-20 Futsal Championship final. The training camp consisted of 5 friendly match days played with the regional futsal clubs, two tactical training days (3rd day, 82 min and 5th day, 72 min), 1 technical and tactical training day (7th day, 80 min), and 1 resting day (9th day of the camp). The friendly matches were scheduled on the training camp's 2nd (Atlético Luso U-20, 4:2. win), 4th (ACR Vale de Cambra U-20, 13:5. win), 6th (CS São João U-20, 1:2. lost), 8th (União de Chelo U-20, 1:2. lost), and 10th (Burinhosa U-20, 6:1. win) day. The exercise HR and locomotion profile were recorded during the matches as the

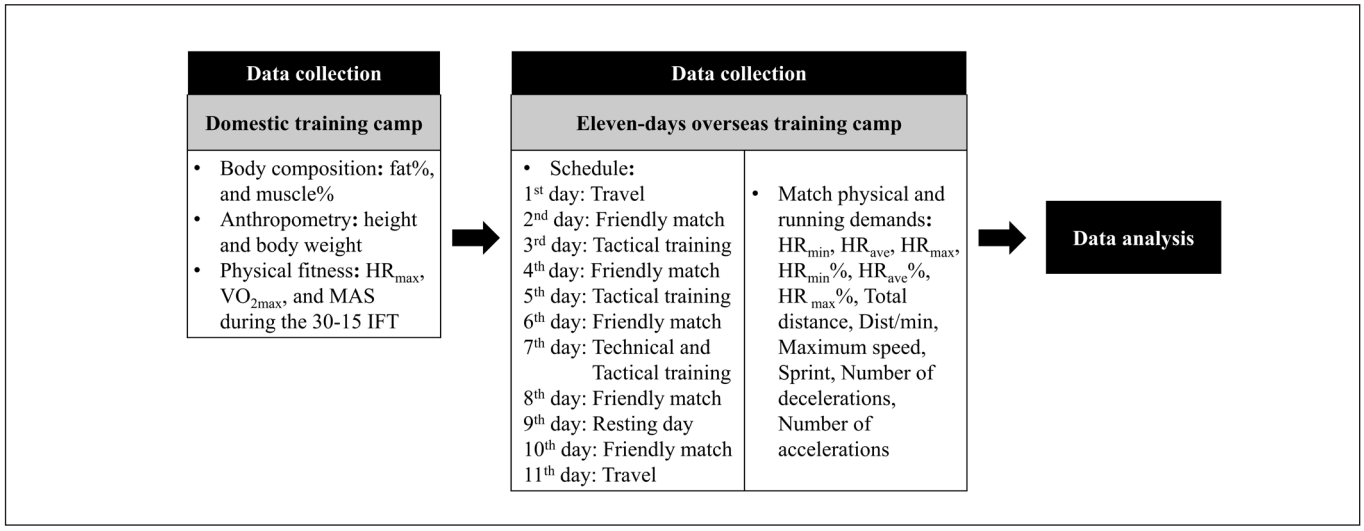


FIG. 1. Flowchart of experimental design of the study.

TABLE 1. Anthropometrical measures and physical fitness of the participants.

	Mean ± SD	Min	Max
Age (yrs)	18.6 ± 0.7	18.0	20.0
Height (cm)	170.8 ± 7.6	157.0	181.0
Body weight (kg)	64.1 ± 8.4	51.0	75.9
Fat (%)	12.7 ± 3.0	9.3	20.5
Muscle (%)	43.2 ± 2.4	37.9	46.3
HR_{max} (bpm)	196.2 ± 8.8	173.0	203.0
$\dot{V}O_{2max}$ (ml/kg/min)	51.80 ± 3.8	45.8	56.6
30–15 IFT (km/h)	19.3 ± 1.6	17.0	21.0

Note: SD: Standard deviation; Min: Minimum; Max: Maximum; yrs: Years; cm: Centimeters; K: Kilograms; HR_{max}; Heart rate maximum; $\dot{V}O_{2max}$: Maximal oxygen uptake. 30–15 Intermittent Fitness Test: 30–15 IFT.

players' internal and external loads, respectively. Data extracted from three goalkeepers were excluded from the statistical analysis. Figure 1 presents the flowchart of the experimental design of the study.

Participants

Eleven outfield players in the Chinese Taipei under-20 national futsal team voluntarily participated in this study (See Table 1). The inclusion criteria were based on: (i) being present at all sessions; (ii) not being injured in the two weeks preceding the training camp. (iii) not being injured or ill during the two weeks of observation; (iv) players who were absent for more than two training sessions were excluded from the sample. The players signed informed consent forms and were familiar with the testing protocol. The study was approved by the institutional board of the Human Ethics Committee at the University of Taipei (UT-IRB-2018-068) and abided by the Declaration of Helsinki and its later amendments in 2013.

Procedure

Before international travel, the players' height, body weight, and body composition were determined using a stadiometer (Seca 213, SECA, Germany), an electrical weight scale (Xyfwt382, TECO, Taiwan), and a skinfold caliper (Lange Skinfold Caliper, BETA Technology, USA), respectively. A team sports trainer used four skinfold thicknesses to determine the percentage of body fat and muscle. The formula for calculating body composition was reported in our previous study [40]. Subsequently, the players performed the 30–15 IFT for physical fitness measures (HR_{max}, $\dot{V}O_{2max}$, and MAS) in an indoor sports hall. A 10-min dynamic warm-up exercise was performed prior to the test.

A portable telemetric HR monitor system (Polar team Pro, Polar Electro, Kempele, Finland) was used to determine the HR_{max} during the 30–15 IFT. Our recent publication also reported the testing procedures to determine the players' physical fitness [18].

On match days, the Polar Team Pro HR monitor system was used to record the exercise HR (HR_{min}, HR_{ave}, HR_{max}, HR_{min}%, HR_{ave}%, and HR_{max}%). Before the match, all players were issued a Polar Team Pro sensor and HR strap for the entire futsal match. The players familiarized themselves with securing the sensor at the chest level. Furthermore, the locomotor demands were monitored using a Polar telemetric global positioning system (GPS) (Polar team Pro GPS, Polar Electro, Kempele, Finland) with a sampling frequency of 10 Hz. The Polar GPS was accurate and reliable in collecting measures of total distance (TD) and distances covered at different speed thresholds [41]. The following measures were extracted for each match: 1) TD; 2) dist/min (average distance covered per minute, Dist); 3) maximum speed (peak speed registered in the session, MS); 4) average speed (km/h^{-1}, AS); 5) sprint (number of sprints > 25 km/h, S); 6) number of decelerations (-50.00 – -3.00 m/s^2, ND1); 7) number of decelerations (-2.99 – -2.00 m/s^2, ND2); 8) number of deceleration (-1.99 – -1.00 m/s^2, ND3); 9) number of decelerations (-0.99 – -0.50 m/s^2, ND4); 10) number of accelerations (0.50–0.99 m/s^2, NA1); 11) number of accelerations (1.00–1.99 m/s^2, NA2); 12) number of accelerations (2.00–2.99 m/s^2, NA3); 13) number of accelerations (3.00–50.00 m/s^2, NA4).

All sensors were synced to a Polar Team Pro dock after the matches. All data were uploaded to a secure cloud server and then exported to a laptop for data analysis. Data were excluded from statistical analysis when the detection of the HR response and locomotion record was lost (due to physical contact or vigour of physical activity).

Statistical Analyses

The statistical analysis was conducted using Statistica software (version 13.1; StatSoft, Inc., Tulsa, OK, USA) and the tool Real Statistica Using Excel. The significance level was set at $p < 0.001$. Tests for normal distribution and homogeneity (Kolmogorov-Smirnov and Levene's, respectively) were conducted on all metrics, and the data were found to have a normal distribution. Descriptive statistics were calculated for each anthropometric measure (age, height, body weight, fat%, and muscle%), physical fitness values during the 30–15 IFT (HR_{max}, $\dot{V}O_{2max}$, and MAS), and match physical and running demands (N, D, HR_{min}, HR_{ave}, HR_{max}, HR_{min}%, HR_{ave}%, HR_{max}%, TD, Dist, MS, AS, S, ND1, ND2, ND3, ND4, NA1, NA2, NA3, and NA4) during the congested schedule of five futsal matches (matches 1–5: M1–M5). A within-subjects comparison was performed for the statistical approach. A repeated-measures analysis of variance (ANOVA) was used to analyse the differences in match physical and running demands during the congested schedule from M1 to M5. The effect size was determined with partial eta squared for Fs. Pearson's correlation coefficient (r) was then used to examine the relationship between anthropometric measures and physical fitness values and match physical and running demands during the congested schedule of futsal matches. To interpret the magnitude of these correlations, the following criteria were used: $r \leq 0.1$, trivial; $0.1 < r \leq 0.3$, small; $0.3 < r \leq 0.5$, moderate; $0.5 < r \leq 0.7$, large; $0.7 < r \leq 0.9$, very large; and $r > 0.9$, almost perfect [42]. Repeated measures correlation (rmcorr) was performed to examine the overall relationship or common intra-individual association between measures to adjust for inter-individual variability statistically. The 95% confidence interval (CI) was calculated for each rmcorr. The statistical analysis was conducted using Python software (version; 3.11.4) for rmcorr.

RESULTS

Descriptive statistics were calculated for each variable to match physical and running demands (Table 2).

For comparative analyses, a repeated-measures ANOVA with mean match physical and running demands data during the congested schedule from M1 to M5 did not reveal significant main effects of match on N, D, HR_{min}, HR_{ave}, HR_{max}, HR_{min}%, HR_{ave}%, HR_{max}%, TD, Dist, MS, AS, S, ND1, ND2, ND4, NA1, NA3, and NA4 ($p > .05$). Crucially, the analysis revealed a significant main effect on S ($F = 2.74$, $p = 0.04$, $\eta^2 = 0.21$), ND3 ($F = 2.73$, $p = 0.04$, $\eta^2 = 0.21$), and NA2 ($F = 3.63$, $p = 0.04$, $\eta^2 = 0.27$).

A correlation analysis between age and match running demands during the congested schedule of futsal matches revealed in M1 a very large negative correlation with TD, Dist, and AS ($r = -.88$, $p = .004$, $r = -.89$, $p = .003$, $r = -.81$, $p = .01$, respectively). In M2, the analysis showed a very large negative correlation with Dist, MS, AS, S, and ND1 ($r = -.75$, $p = .03$, $r = -.78$, $p = .02$, $r = -.75$, $p = .03$, $r = -.79$, $p = .02$, $r = -.72$, $p = .04$, respectively). In M3, the analysis revealed a very large negative correlation with MS ($r = -.80$, $p = .02$) and S ($r = -.75$. $p = .03$) and in M4, the analysis revealed a very large negative correlation with Dist, MS, AS, S, and ND1 ($r = -.78$, $p = .02$, $r = -.82$, $p = .01$, $r = -.79$, $p = .02$, $r = -.89$, $p = .003$, $r = -.89$, $p = .003$, respectively) (Figure 2).

A new correlation analysis was performed between height and match physical and running demands during the congested schedule of futsal matches and only showed in M4 a very large negative correlation with HR_{min} ($r = -.74$, $p = .035$) (Figure 3).

Another correlation analysis was performed between body weight and match physical and running demands during the congested schedule of futsal matches. It revealed in M3 a very large negative correlation with TD ($r = -.71$, $p = .05$) and in M4 another very large negative correlation with HR_{min} ($r = -.74$. $p = .04$) (Figure 4).

A further correlation analysis was performed between fat% and match physical and running demands during the congested schedule of futsal matches. In M1, correlation analysis showed a very large negative correlation with ND4 ($r = -.77$, $p = .03$). In M3, the dataset revealed another very large negative correlation with N ($r = -.77$. $p = .02$), and in M4, the analysis showed a very large negative correlation with HR_{min} ($r = -.71$. $p = .05$) (Figure 5).

TABLE 2. Match physical and running demands profiles during congestive schedule.

	Match 1			Match 2			Match 3			Match 4			Match 5		
	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max
Substitution (n)	5.3 ± 0.9	4.0	7.0	4.5 ± 1.0	2.0	6.0	5.7 ± 1.6	3.0	8.0	5.6 ± 2.1	2.0	8.0	5.6 ± 1.4	4.0	4.0
Duration (min)	273.0 ± 27.1	216.7	311.8	269.4 ± 47.5	216.0	389.6	246.5 ± 53.6	172.3	333.6	269.9 ± 38.5	193.0	321.6	235.3 ± 53.5	103.0	294.4
$HR_{min.}$ (bpm)	123.5 ± 10.5	106.0	136.0	123.9 ± 14.7	97.0	142.0	123.3 ± 13.7	101.0	148.3	121.4 ± 14.8	96.7	140.3	127.8 ± 10.1	106.5	141.0
HR_{ave} (bpm)	174.3 ± 7.3	161.0	183.3	174.0 ± 7.1	160.8	181.2	173.0 ± 6.9	160.3	181.6	173.8 ± 9.3	158.0	186.0	172.9 ± 7.2	157.5	187.5
HR_{max} (bpm)	190.4 ± 6.7	176.4	200.2	190.5 ± 6.0	176.0	199.2	190.2 ± 5.4	180.8	200.2	190.9 ± 8.1	175.0	200.6	187.2 ± 6.6	171.5	199.3
HR_{min}%	63.5 ± 5.9	52.2	71.8	63.7 ± 8.0	47.8	76.0	63.5 ± 7.8	49.5	79.5	62.5 ± 8.2	47.7	75.0	65.5 ± 4.7	59.0	75.0
HR_{ave}%	89.6 ± 4.7	81.6	97.3	89.5 ± 4.5	79.6	95.8	88.9 ± 4.8	78.8	95.5	89.4 ± 5.6	77.7	96.2	88.9 ± 3.7	85.3	97.3
HR_{max}%	97.9 ± 3.6	91.8	103.3	97.9 ± 3.5	93.0	103.5	97.8 ± 4.5	91.8	104.6	98.2 ± 4.7	88.7	103.2	96.3 ± 4.0	92.0	103.8
TD (m)	499.1 ± 84.7	348.7	616.2	480.3 ± 112.9	357.5	759.4	453.0 ± 108.6	297.8	581.4	489.6 ± 98.1	354.8	634.0	425.2 ± 129.7	205.0	672.8
Dist (m/min)	108.8 ± 11.8	89.4	127.0	107.1 ± 10.1	91.5	123.8	110.4 ± 11.4	91.2	132.8	109.3 ± 14.3	89.0	138.2	108.2 ± 14.7	91.0	141.3
MS (m/s)	24.9 ± 1.7	22.0	27.2	24.8 ± 2.1	19.3	27.8	24.3 ± 1.7	21.7	26.6	25.2 ± 1.8	20.3	27.3	24.3 ± 2.6	18.2	28.0
AS (m/s)	6.6 ± 0.7	5.4	7.6	6.5 ± 0.6	5.5	7.4	6.6 ± 0.7	5.5	8.0	6.6 ± 0.9	5.4	8.30	6.5 ± 0.9	5.5	8.5
S (m/min)	1.3 ± 0.6	0.3	2.5	1.3 ± 0.8	0.0	2.8	1.4 ± 0.9	0.2	2.8	2.0 ± 1.0	0.0	3.6	1.5 ± 1.6	0.0	5.5
ND1 (n)	4.4 ± 1.7	2.2	8.3	4.2 ± 1.4	2.3	6.8	3.6 ± 1.6	2.0	6.2	4.6 ± 1.6	1.8	7.0	3.8 ± 2.1	2.0	9.5
ND2 (n)	11.4 ± 1.9	8.3	13.8	11.4 ± 2.7	7.6	16.4	11.2 ± 3.3	7.5	18.8	11.5 ± 2.7	7.0	17.3	10.2 ± 2.3	7.0	13.8
ND3 (n)	34.1 ± 4.9	26.8	41.8	33.0 ± 7	22.8	44.0	29.2 ± 6.7	22.8	43.0	32.5 ± 5.2	22.0	40.6	28.3 ± 7.1	15.0	42.6
ND4 (n)	22.0 ± 3.8	17.7	29.8	21.1 ± 6.3	13.8	37.4	19.1 ± 4.5	10.8	27.4	20.7 ± 5.1	13.0	29.8	17.9 ± 6.7	7.0	27.0
NA1 (n)	19.6 ± 3.7	13.0	25.4	19.1 ± 3.6	13.8	26.8	17.2 ± 5.1	11.0	24.6	18.2 ± 3.8	12.0	23.8	16.1 ± 3.8	9.0	23.2
NA2 (n)	31.1 ± 3.7	24.6	36.2	30.5 ± 5.2	25.0	39.8	27.3 ± 4.7	20.0	34.8	29.9 ± 4.5	19.0	33.8	25.6 ± 7.3	14.0	36.6
NA3 (n)	16.1 ± 2.56	11.0	20.0	15.7 ± 3.6	11.3	21.4	14.3 ± 4.2	9.2	23.0	16.5 ± 2.8	11.8	20.8	13.9 ± 3.5	9.0	21.5
NA4 (n)	0.1 ± 0.1	0.0	0.3	0.3 ± 0.3	0.0	1.0	0.2 ± 0.2	0.0	0.6	0.2 ± 0.3	0.0	1.0	0.2 ± 0.4	0.0	1.3

Note: SD: Standard deviation; Min: Minimal; Max: Maximal; N: Number of substitution; D: Duration; HR_{min}: Heart rate minimum; HR_{ave}: Heart rate average; HR_{max}: Heart rate maximum; HR_{min}%: Percentage of heart rate minimum; HR_{ave}%: Percentage of heart rate average; HR_{max}%: Percentage of heart rate maximum; TD: Total distance; Dist: Distance; MS: Maximum speed; AS: Average speed; S: Sprint; ND1: Number of decelerations (-50.00 – -3.00 m/s^2); ND2: Number of decelerations (-2.99 – -2.00 m/s^2); ND3: Number of decelerations (-1.99 – -1.00 m/s^2); ND4: Number of decelerations (-0.99 – -0.50 m/s^2); NA1: Number of accelerations (0.50–0.99 m/s^2); NA2: Number of accelerations (1.00–1.99 m/s^2); NA3: Number of accelerations (2.00–2.99 m/s^2) and NA4: Number of accelerations (3.00–50.00 m/s^2)

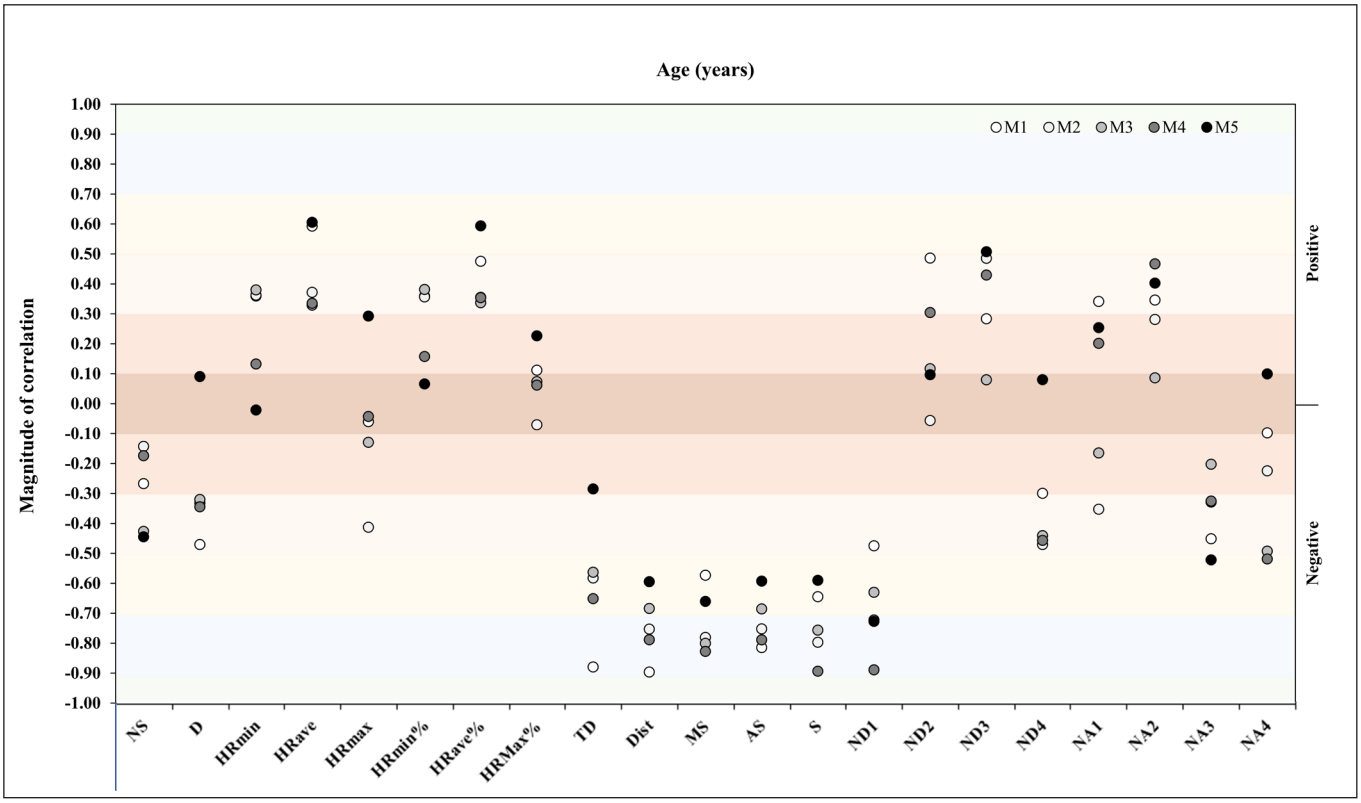


FIG. 2. Correlation analysis between age and match physical and running demands.

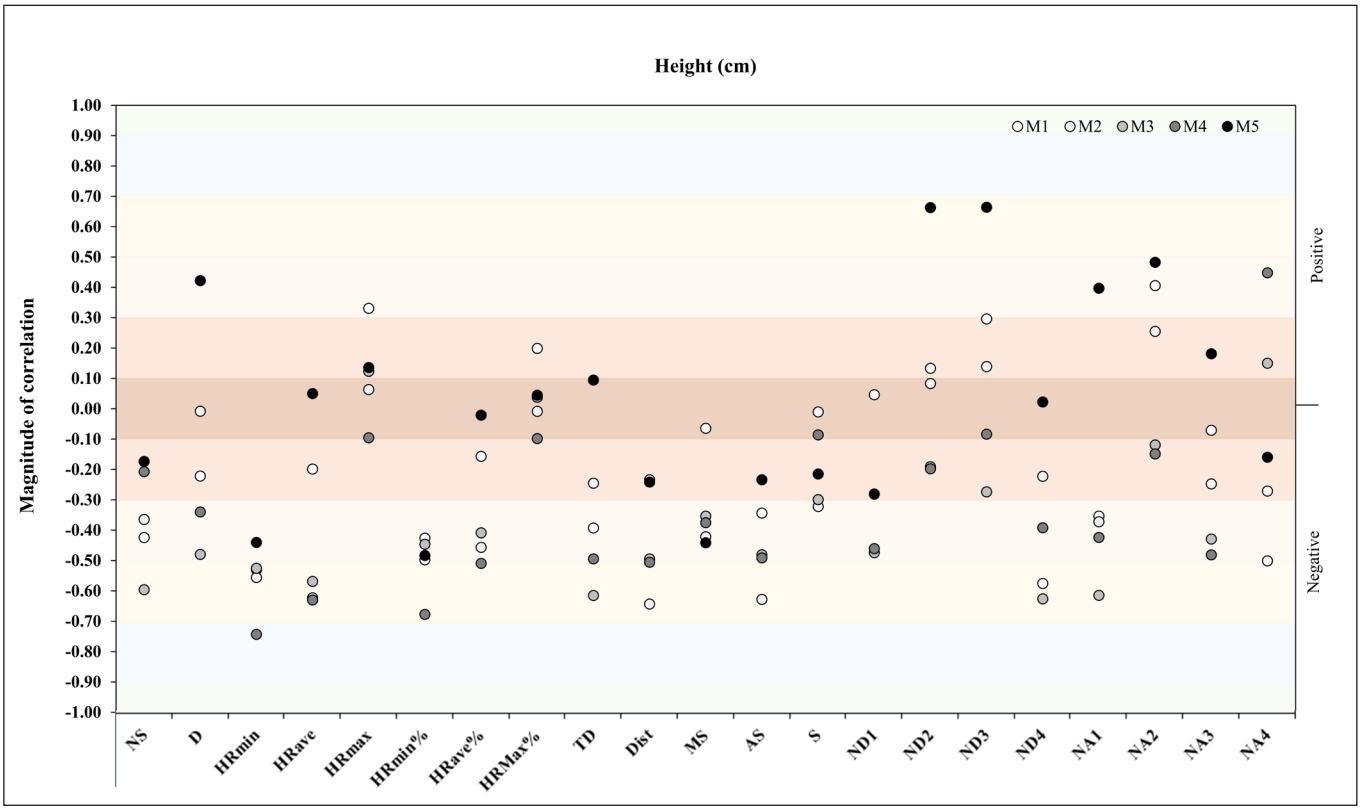


FIG. 3. Correlation analysis between height and match physical and running demands.

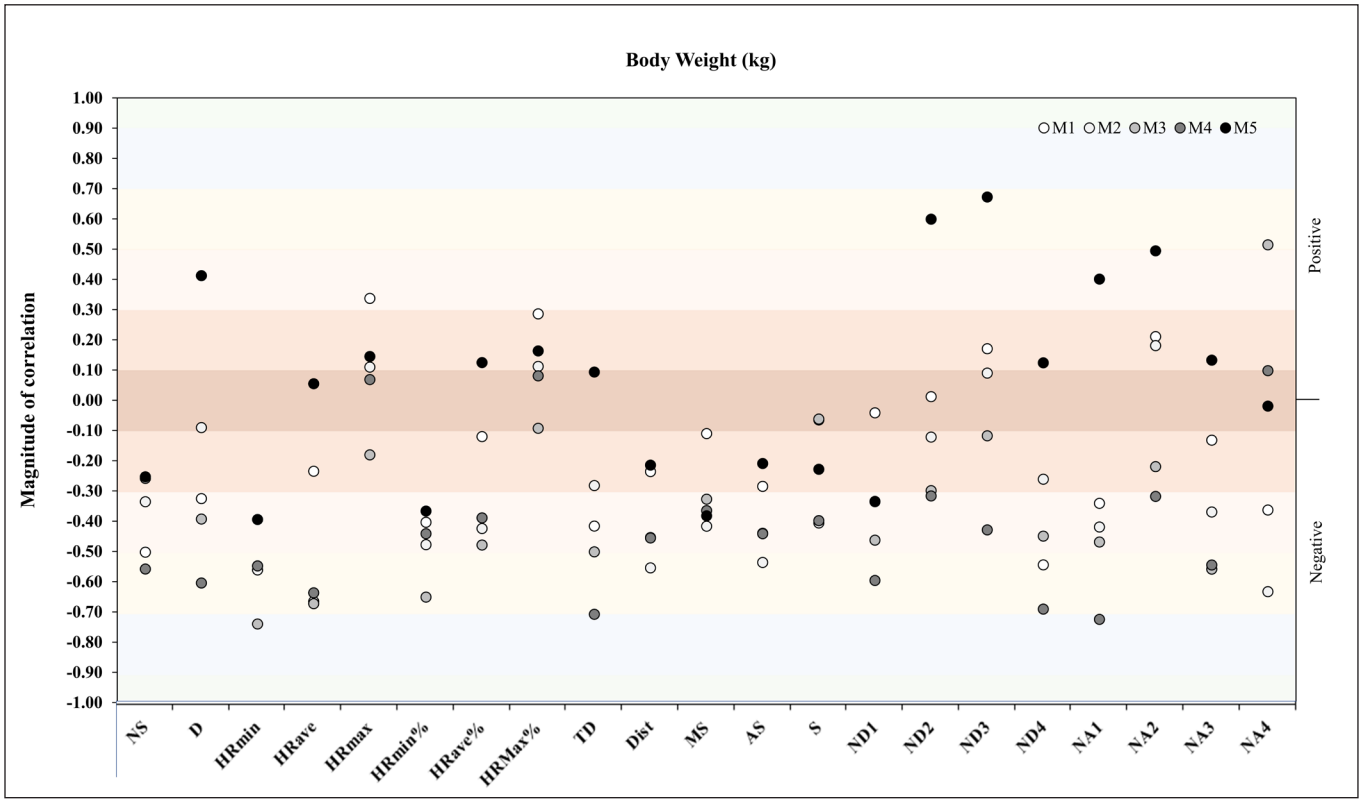


FIG. 4. Correlation analysis between body weight and match physical and running demands.

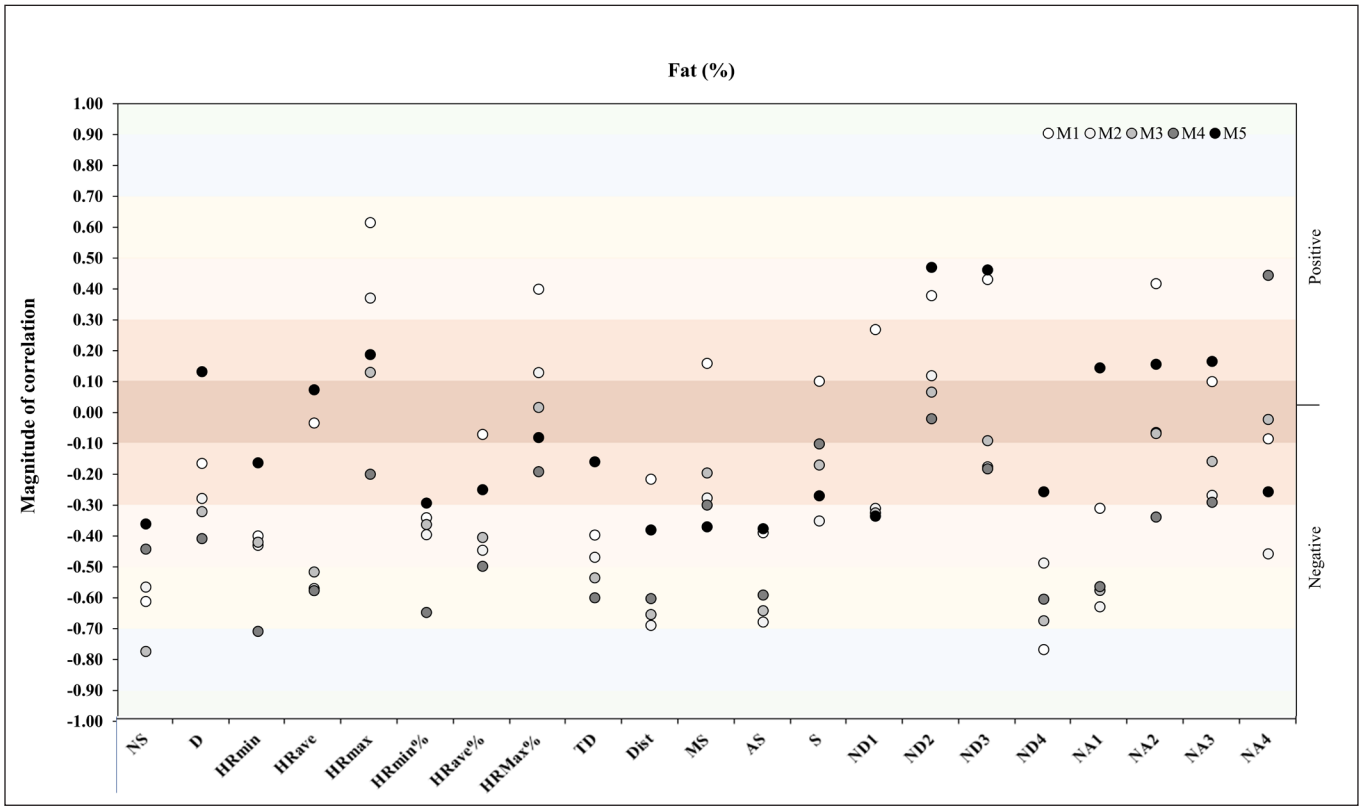


FIG. 5. Correlation analysis between fat% and match physical and running demands.

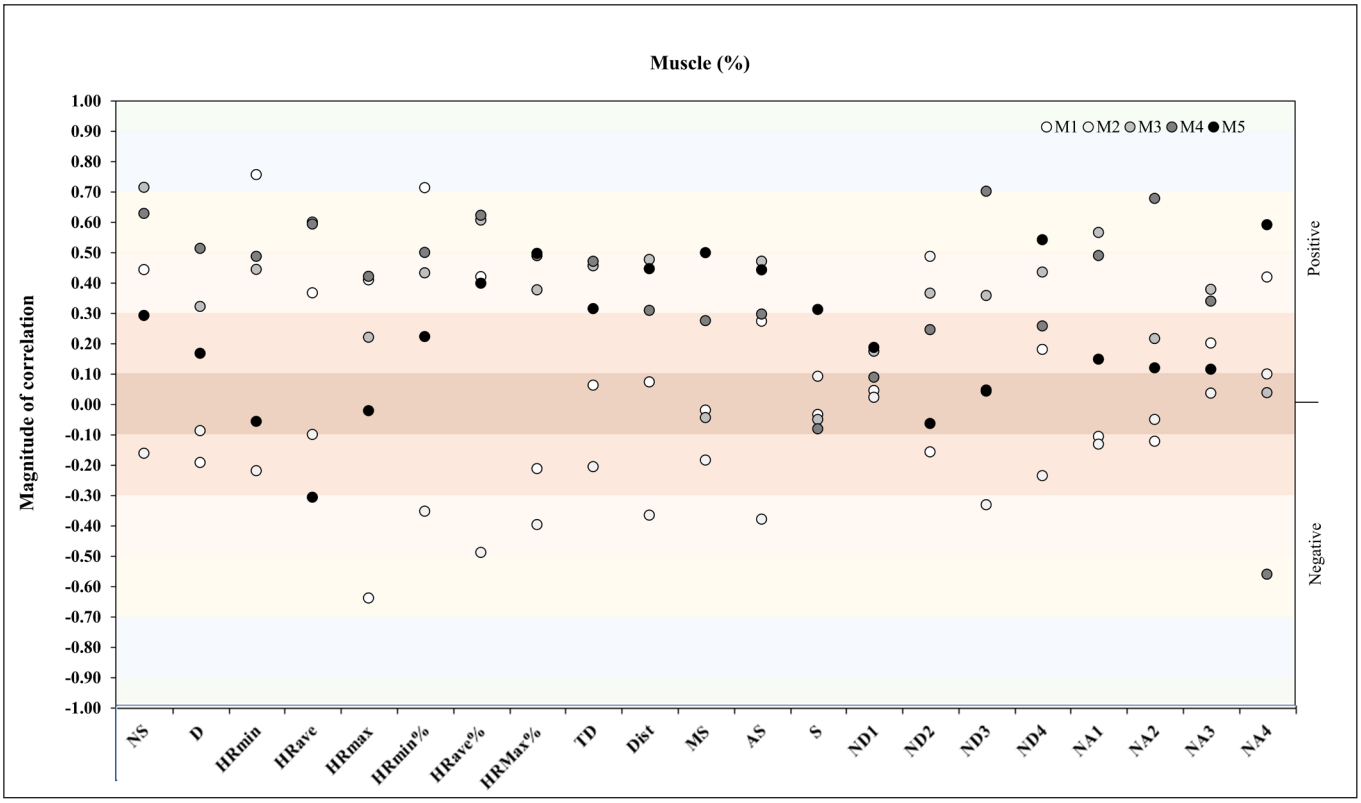


FIG. 6. Correlation analysis between muscle% and match physical and running demands.

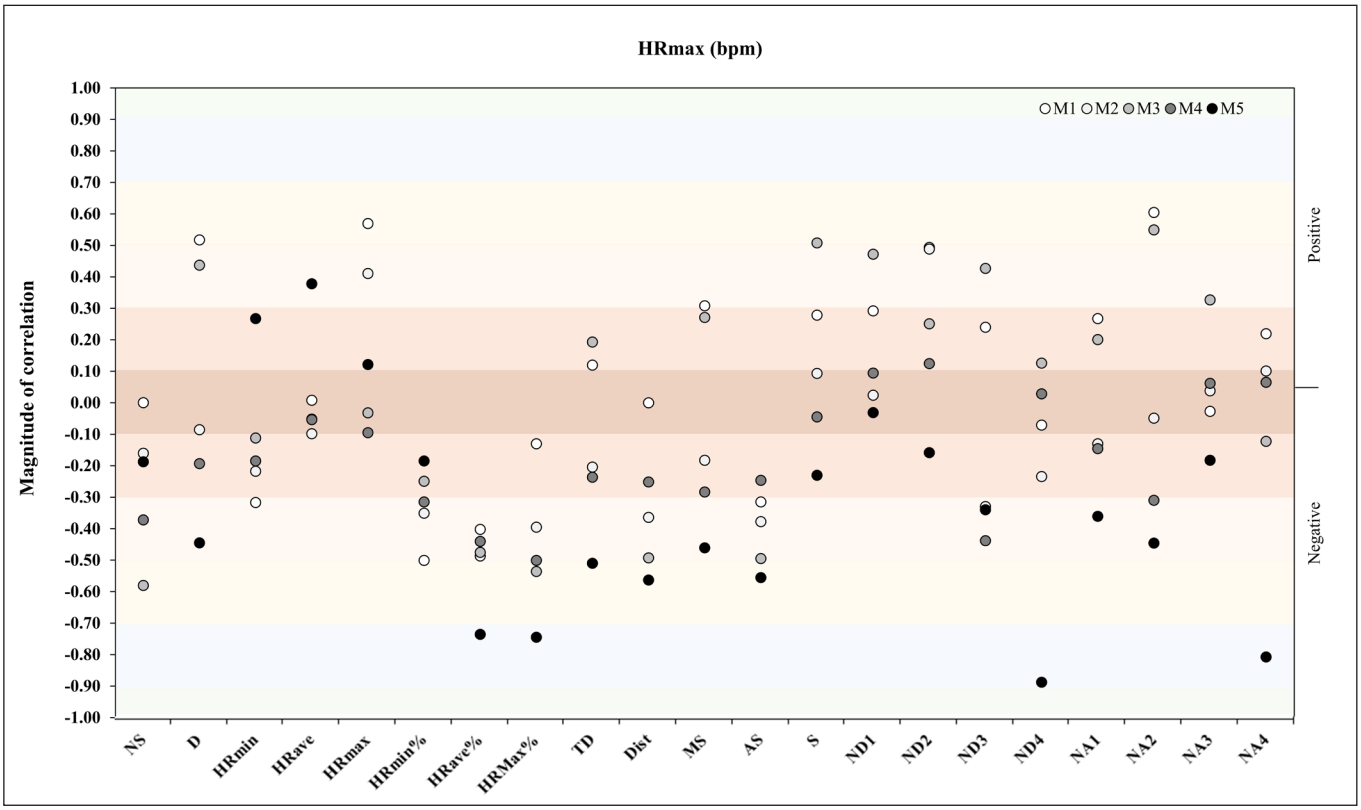


FIG. 7. Correlation analysis between HR_{max} and match physical and running demands.

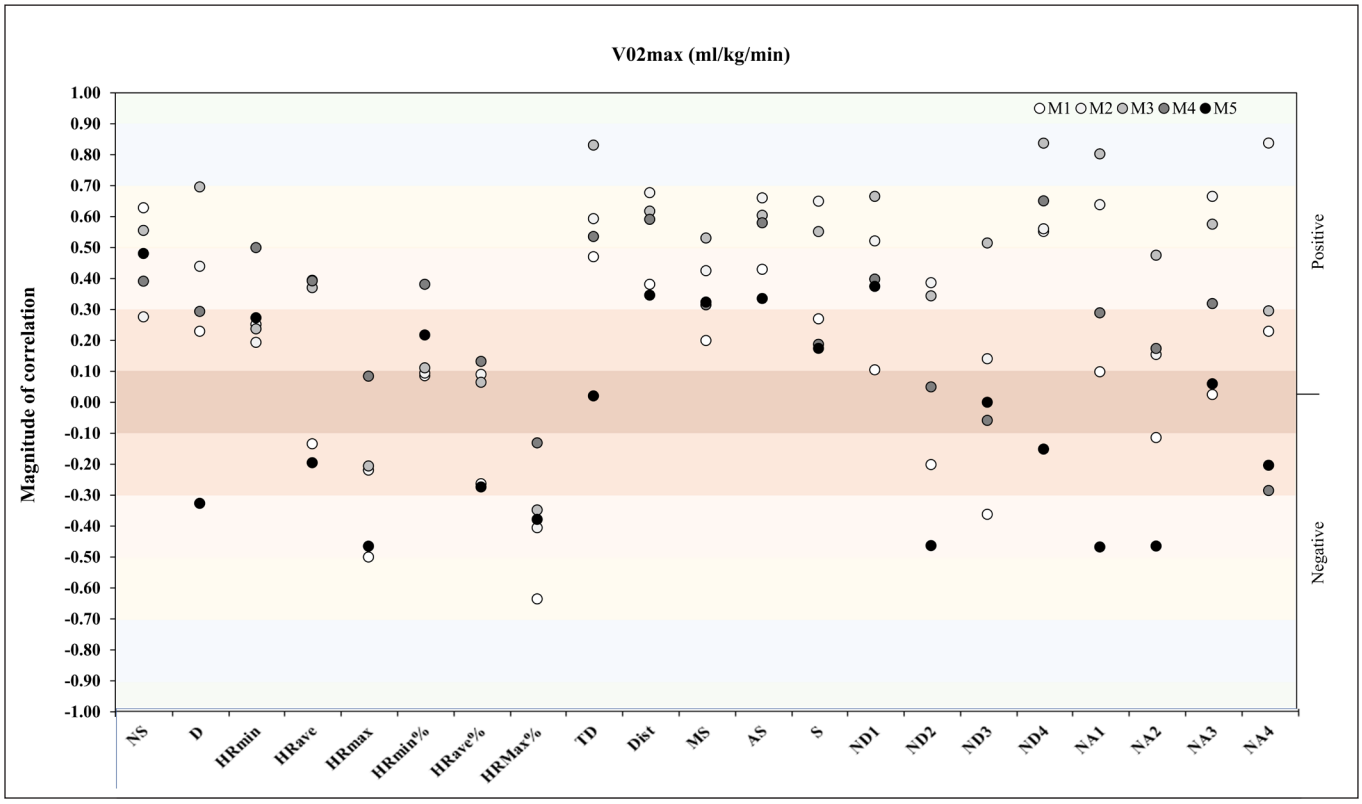


FIG. 8. Correlation analysis between $\dot{V}O_{2max}$ and match physical and running demands.

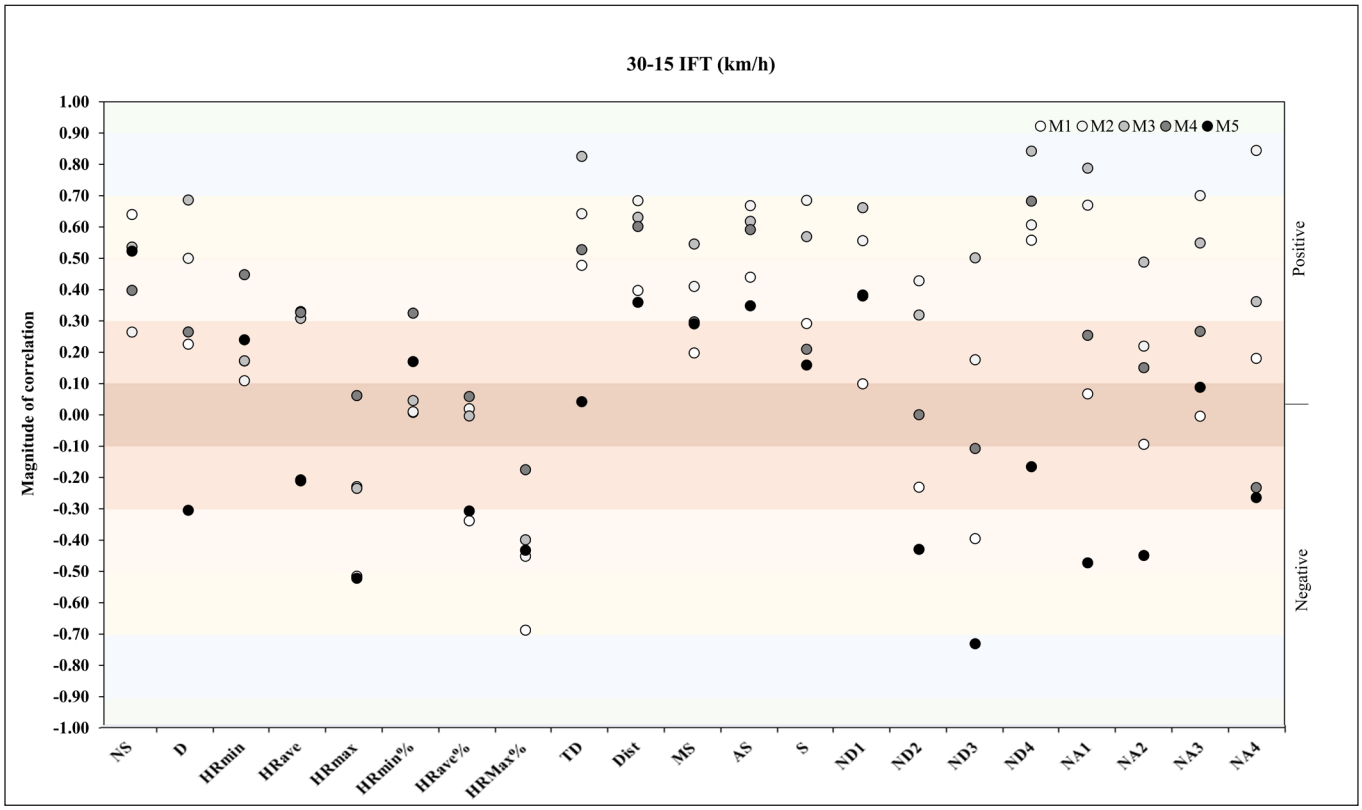


FIG. 9. Correlation analysis between maximal aerobic speed and match physical and running demands.

Another correlation analysis was performed between muscle% and match physical and running demands during the congested schedule of futsal matches. It revealed in M1 a very large positive correlation with HR_{min} (r = .76, p = .03) and HR_{min}% (r = .71, p = .05), and in M3 a very large positive correlation with HR_{min} (r = .72, p = .03) (Figure 6).

Regarding HR_{max}, in match 5, we found a very large negative correlation with ND4 (r = -.89, p = .01) and NA4 (r = -.81, p = .03) (Figure 7). In reference to $\dot{V}O_{2max}$, the analysis showed a very large positive correlation with NA4 (r = -.84, p = .01) and a very large positive correlation with TD, ND4, and NA1 (r = -.83, p = .01, r = -.84, p = .01, r = -.80, p = .02) in M2 and M3, respectively (Figure 8).

Lastly, for the relationship between MAS and match physical and running demands, the analysis revealed a very large positive correlation with NA4 in M2 (r = -.84, p = .01). In M3, correlation analysis showed a very large positive correlation with TD, ND4, and NA1 (r = -.76, p = .03, r = -.71, p = .05, r = -.71, p = .05) (Figure 9).

A repeated measures correlation was performed to evaluate the intra-individual association between anthropometric measures and physical fitness values and match running demands during the congested schedule of futsal matches considering within-subjects association and using the degrees of freedom (DF). An rmcorr repeated measures correlation analysis between age and match running demands during the congested schedule of futsal matches revealed a very large positive correlation for Dist (*rmcorr:* 0.45, *DF*: 43, p = .001, *CI 95%:* [-0.66, -0.19] and power: 0.89), and a moderate positive correlation for NA1 and NA4 (*rmcorr:* – 0.30, *DF:* 43, p = 0.04, *CI 95%:* [-0.55, -0.02] and power: 0.55 and *rmcorr:* – 0.30, *DF:* 43, p: 0.04; *CI 95%:* [-0.55, 0.01] and power: 0.53, respectively) (Figure 10).

A new repeated measures correlation analysis was performed between height and match running demands during the congested schedule of futsal matches and only showed a moderate positive correlation for NA1 and NA4 (*rmcorr*: – 0.32, *DF:* 43, p: 0.03, *CI 95%:* [-0.56, -0.03] and power: 0.57, and *rmcorr*: -0.30, *DF:* 43, p: 0.04, *CI 95%:* [-0.55, -0.01] and power: 0.54, respectively) (Figure 11).

Another repeated measures correlation analysis was performed between body weight and match running demands during the congested schedule of futsal matches and revealed a moderate positive correlation for NA1 and NA4 (*rmcorr*: – 0.31; *DF:* 43, p: 0.03, *CI 95%:* [-0.56, -0.03] and power: 0.57, and *rmcorr*: – 0.30; *DF:* 43, p: 0.04, *CI 95%:* [-0.55, -0.01] and power: 0.53, respectively) (Figure 12).

Along the same line, a further repeated measures correlation analysis was performed between fat% and match running demands during the congested schedule of futsal matches. It showed a moderate positive correlation for D, AS, S, and NA4 (*rmcorr*: – 0.50, *DF:* 43, p: 0.001, *CI 95%:* [-0.69, 0.24] and power: 0.94; *rmcorr*: – 0.35, *DF:* 43, p: 0.01, *CI 95%:* [-0.59, -0.07] and power: 0.69; *rmcorr*: – 0.31, *DF:* 43, p: 0.04, *CI 95%:* [-0.55, -0.02] and power: 0.55 and *rmcorr*: – 0.29, *DF:* 43, p value: 0.05, *CI 95%:* [-0.54, -0.001] and power: 0.50, respectively) (Figure 13).

Another repeated measures correlation analysis was performed between muscle% and match running demands during the congested schedule of futsal matches. It revealed a moderate positive correlation for NA1 and NA4 (*rmcorr*: – 0.32, *DF:* 43, p: 0.03, *CI 95%:* [-0.57, -0.04] and power: 0.60, and *rmcorr*: -0.28, *DF:* 43, p: 0.05, *CI 95%:* [-0.54, 0.01] and power: 0.49, respectively) (Figure 14).

A new repeated measures correlation analysis was performed between HR_{max} and match running demands during the congested schedule of futsal matches and revealed a very large positive correlation for TD (*rmcorr*: – 0.43, *DF:* 43, p: 0.002, *CI 95%:* [-0.65, -0.16] and power: 0.86) and a moderate positive correlation for NA1 and NA4 (*rmcorr*: – 0.31, *DF:* 43, p: 0.03, *CI 95%:* [-0.56, -0.03] and power: 0.58, and *rmcorr*: – 0.28, *DF:* 43, p: 0.05, *CI 95%:* [-0.54, 0.01] and power: 0.48, respectively) (Figure 15).

Lastly, for the relationship between $\dot{V}O_{2max}$ and match running demands, the repeated measures correlation analysis revealed an almost perfect correlation for S (*rmcorr*: 0.46, *DF:* 43, p: 0.001, *CI 95%:* [0.20, 0.67] and power: 0.90) and a moderate positive correlation for ND4 and NA4 (*rmcorr*: – 0.30, *DF:* 43, p: 0.04, *CI 95%:* [-0.55, -0.01] and power: 0.53 and *rmcorr*: 0.31, *DF:* 43, p: 0.03, *CI 95%:* [0.03, 0.56] and power: 0.57, respectively) (Figure 16).

DISCUSSION

The present study aimed to analyse the match physical and running demands among matches and to examine the relationships between body composition, physical fitness measures, and match physical and running demands during a congested week of a futsal training camp. The main findings were that only the sprint, deceleration, and acceleration performance significantly differed among matches. Also, the overall body composition and physical fitness measures had large to very large correlations with match-running demands during congested periods of futsal competition.

Although there is no evidence regarding the differences between match physical and running demands of congested weeks in futsal, a recent systematic review reported that significant differences could be observed in the overall match running demands between match halves [43]. A decrease was observed from the first to the second half when considering the total volume of each external load measure. On the other hand, an increase was observed from the first to the second match half when considering the external load measures relativized per minute (e.g., according to each player's time of match participation) [44]. Thus, the analysis of the match running demands should be relativized per minute, which was not the case in the present study and is considered as a limitation. However, in the present study, such differences were not present between matches during

congested weeks, except for sprints. Our findings regarding the lack of differences among matches agree with a previous study that reported no significant differences for any external load measure [39]. However, that study [39] examined the differences between training sessions and not between matches, which may limit our inferences and extrapolation to the differences between matches.

Previous studies on different team sports have reported the influence that body composition has on physical fitness performance [45]. The literature focuses on body composition and anthropometric measures' impact on physical performance [45]. However, a few studies have tested the associations between anthropometric measures and match-running demands in team sports. From the available evidence regarding the dependencies of match-running demands on body composition, it was reported that the sprinting distances covered were largely and negatively associated with the percentage of change of fat and lean mass [20, 21]. However, our findings contrast with those previously reported [20, 21]. Indeed, we did not observe any significant correlation between the fat% and sprint performance across the five matches. As a greater fat mass negatively affects sprint performance, it would be expected for positive correlations to be observed between them. A possible explanation may be related to the fact that the players maintained a relatively stable frequency of sprint volume during the five matches, as previously reported [46].

Regarding the relationships between physical fitness measures and match-running demands, our findings can be easily attributed to the interference of randomness, and it is. However, one can make a deterministic inference with a degree of uncertainty regarding our findings. First, a higher HR_{max} is one of the factors influencing a decrease in acceleration activities only during the last match of a congested week. This finding may be attributed, among others factors, to acute (e.g., short-term) mental fatigue, which causes an increase in sympathetic activity and decreases parasympathetic nerve activity [47]. This is particularly interesting for coaches to consider when selecting players with high match participation in congested periods. An athlete with a lower HR_{max} is more susceptible to poor heart rate responses when exposed to high-intensity stimuli during a specific period [48]. As a complement to the above statement, a greater level of $\dot{V}O_{2max}$ is positively associated with greater acceleration activities and TD in M2 and M3.

Our findings suggest that a greater 30–15 IFT performance is associated with greater activity of high-intensity accelerations during M2. On the other hand, a greater performance on the 30–15 IFT is associated with decreased activity of low-intensity accelerations and TD during M3. A previous study [39] conducted on sixteen professional football players revealed large to very large correlations between the 30–15 IFT performance and TD (r = 0.69 to 0.87), high-intensity running (r = 0.66 to 0.75), and accelerations and decelerations (r = 0.56 to 0.68), which is somewhat consistent with our findings. However, that study was conducted on football players and not on futsal. Also, the study methodology had a very different approach to our study, as the authors examined such associations using small-sided games [39]. In the case of the futsal context, and to the best of the authors' knowledge, only one study tested the relationships mentioned above in futsal players [18]. That study showed that the 30 m sprint test could be explained by HR_{ave}, HR_{max}, dist/min, MS, and AS between 38 and 48%.

Moreover, a recent study investigated the interplay between weekly training load and performance outcomes in a professional male futsal team over two seasons [49]. The study analysed training load, recovery status, well-being, neuromuscular performance variability, and match performance. Notably, the study's path analysis model elucidated that this framework accounted for 31% of team performance, highlighting the intricate connections between training load, neuromuscular performance, and match outcomes. The findings underscore the importance of monitoring variables such as neuromuscular performance variability in comprehending player and team performance dynamics.

The present study presents some limitations that need to be addressed. One of the main limitations is related to the small sample used, which does not allow the generalization of the results. The fact that the physical fitness assessments were carried out only once (at the beginning of the training camp) limits the power of the correlations. The concise time frame of the observations and the fact that it was conducted during a training camp were also among the main limitations of the present study. Future studies should consider observing an entire futsal season to improve the power of the present findings.

CONCLUSIONS

During a futsal training camp of eleven days with five futsal matches, no significant differences in match running demand measures were found, excepted for sprint performance. The baseline body composition and the overall physical fitness measures may be essential factors in matching running demands during a congested futsal match period. Futsal players who perform better in the 30–15 IFT can sustain a greater volume of high-intensity accelerations during a congested period.

Competing interests

The authors declare that they have no competing interests.

Acknowledgments

The authors appreciate the study participants.

Funding

Filipe Manuel Clemente and this work are funded by the Fundação para a Ciência e Tecnologia/Ministério da Ciência, Tecnologia e Ensino Superior through national funds, and when applicable, co-funded by EU funds under the project UIDB/50008/2020.

REFERENCES

1. Barbero-Alvarez JC, Soto VM, Barbero-Alvarez V, Granda-Vera J. Match analysis and heart rate of futsal players during competition. J Sports Sci. 2008; 26:63–73. https://doi.org/10.1080/02640410701287289.
2. Oliveira R, Leicht A, Bishop D, Barbero-Álvarez J, Nakamura F. Seasonal Changes in Physical Performance and Heart Rate Variability in High Level Futsal Players. Int J Sports Med. 2012; 34:424–30. https://doi.org/10.1055/s-0032-1323720.
3. Nakamura FY, Costa JA, Travassos B, Ortuño D, Pino-Ortega J. Intraindividual Relationships Between Training Loads and Heart-Rate Variability in High-Level Female Futsal Players: A Longitudinal Study. Int J Sports Physiol Perform. 2023:1–7. https://doi.org/10.1123/ijspp.2021-0500.
4. Baena-Raya A, García-Ortega D, Sánchez-López S, Soriano-Maldonado A, Reyes P, Rodríguez-Pérez M. The Influence of Sprint Mechanical Properties on Change of Direction in Female Futsal Players. J Hum Kinet. 2021; 79:221–8. https://doi.org/10.2478/hukin-2021-0075.
5. Berdejo-del-Fresno, D., Moore, R., & Laupheimer MW. $\dot{V}O_{2max}$ changes in English futsal players after a 6-week period of specific small-sided games training. Am J Sport Sci Med. 2015; 3:28–34.
6. de Moura NR, Cury-Boaventura MF, Santos VC, Levada-Pires AC, Bortolon J, Fiamoncini J, et al. Inflammatory Response and Neutrophil Functions in Players After a Futsal Match. J Strength Cond Res. 2012; 26:2507–14. https://doi.org/10.1519/JSC.0b013e31823f29b5.
7. Dogramaci SN, Watsford ML, Murphy AJ. Time-Motion Analysis of International and National Level Futsal. J Strength Cond Res. 2011; 25:646–51. https://doi.org/10.1519/JSC.0b013e3181c6a02e.
8. Taylor JB, Wright AA, Dischiavi SL, Townsend MA, Marmon AR. Activity Demands During Multi-Directional Team Sports: A Systematic Review. Sport Med. 2017; 47:2533–51. https://doi.org/10.1007/s40279-017-0772-5.
9. Bekris E, Gioldasis A, Gissis I, Katis A, Mitrousis I, Mylonis E. Effects of a Futsal Game on Metabolic, Hormonal, and Muscle Damage Indicators of Male Futsal Players. J Strength Cond Res. 2022; 36:545–50. https://doi.org/10.1519/JSC.0000000000003466.
10. Castagna C, D'Ottavio S, Vera JG, Álvarez JCB. Match demands of professional Futsal: A case study. J Sci Med Sport. 2009; 12:490–4. https://doi.org/10.1016/j.jsams.2008.02.001.
11. Charlot K, Zongo P, Leicht AS, Hue O, Galy O. Intensity, recovery kinetics and well-being indices are not altered during an official FIFA futsal tournament in Oceanian players. J Sports Sci. 2016; 34:379–88. https://doi.org/10.1080/02640414.2015.1056822.
12. Álvarez JCB, D'Ottavio S, Vera JG, Castagna C. Aerobic fitness in futsal players of different competitive level. J Strength Cond Res. 2009; 23:2163–6. https://doi.org/10.1519/JSC.0b013e3181b7f8ad.
13. Helgerud J, Engen LC, Wisloff U, Hoff J. Aerobic endurance training improves soccer performance. Med Sci Sports Exerc. 2001; 33:1925–31.
14. Tomlin DL, Wenger HA. The Relationship Between Aerobic Fitness and Recovery from High Intensity Intermittent Exercise. Sport Med. 2001; 31:1–11. https://doi.org/10.2165/00007256-200131010-00001.
15. Spyrou K, Freitas TT, Marín-Cascales E, Herrero-Carrasco R, Alcaraz PE. External match load and the influence of contextual factors in elite futsal. Biol Sport. 2022; 39:349–54. https://doi.org/10.5114/BIOLSPORT.2022.105332.
16. de Moura NR, Borges LS, Santos VC, Joel GB, Bortolon JR, Hirabara SM, et al. Muscle Lesions and Inflammation in Futsal Players According to Their Tactical Positions. J Strength Cond Res. 2013; 27:2612–8. https://doi.org/10.1519/JSC.0b013e31827fd835.
17. Rodrigues VM, Ramos GP, Mendes TT, Cabido CE, Melo ES, Condessa LA, et al. Intensity of Official Futsal Matches. J Strength Cond Res. 2011; 25:2482–7. https://doi.org/10.1519/JSC.0b013e3181fb4574.
18. Silva AF, González-Fernández FT, Oliveira R, Clemente FM, Bezerra P, Hung C-H, et al. Selected vs. Non-Selected Under-20 National Futsal Players: Differences between Physical Performance and Training Intensity Experienced in Training Camps. Biology (Basel). 2022; 11:434. https://doi.org/10.3390/biology11030434.
19. Garrido-Chamorro R., Sirvent-Belando JE, González-Lorenzo M, Blasco-Lafarga C, Roche E. Skinfold sum: reference values for top athletes. Int J Morphol. 2012; 30:803–9.
20. Castillo M, Martínez-Sanz JM, Penichet-Tomás A, Sellés S, González--Rodriguez E, Hurtado-Sánchez JA, et al. Relationship between Body Composition and Performance Profile Characteristics in Female Futsal Players. Appl Sci. 2022; 12:11492. https://doi.org/10.3390/app122211492.
21. Clemente F, Nikolaidis PT, Rosemann T, Knechtle B. Dose-response relationship between external load variables, body composition, and fitness variables in professional soccer players. Front Physiol. 2019; 10:1–9. https://doi.org/10.3389/fphys.2019.00443.
22. Radzimiński Ł, Szwarc A, Padrón-Cabo A, Jastrzębski Z. Correlations between body composition, aerobic capacity, speed and distance covered among professional soccer players during official matches. J Sports Med Phys Fitness. 2020; 60:257–262. https://doi.org/10.23736/S0022-4707.19.09979-1.
23. Dragijsky M, Maly T, Zahalka F, Kunzmann E, Hank M. Seasonal Variation of Agility, Speed and Endurance Performance in Young Elite Soccer Players. Sports. 2017; 5:12. https://doi.org/10.3390/sports5010012.
24. Silva, A. F., González-Fernández, F. T., Ceylan, H. I., Silva, R., Younesi, S., Chen, Y. S., Badicu, G., Wolanski, P., Murawska-Ciałowicz, E., & Clemente FM. Relationships between Fitness Status and Blood Biomarkers in Professional Soccer Players. J Heal Eng. 2022:5135817. https://doi.org/10.1155/2022/5135817.
25. Vieira LHP, de Souza Serenza F, de Andrade VL, de Paula Oliveira L, Mariano FP, Santana JE, et al. Kicking Performance and Muscular Strength Parameters with Dominant and Nondominant Lower Limbs in Brazilian Elite Professional Futsal Players. J Appl Biomech. 2016; 32:578–85. https://doi.org/10.1123/jab.2016-0125.
26. Bengtsson H, Ekstrand J, Hägglund M. Muscle injury rates in professional football increase with fixture congestion: an 11-year follow-up of the UEFA Champions League injury study. Br J Sports Med. 2013; 47:743–7. https://doi.org/10.1136/bjsports-2013-092383.
27. Page RM, Field A, Langley B, Harper LD, Julian R. The Effects of Fixture Congestion on Injury in Professional Male Soccer: A Systematic Review. Sport Med. 2023; 53:667–85. https://doi.org/10.1007/s40279-022-01799-5.
28. Ribeiro JN, Monteiro D, Gonçalves B, Brito J, Sampaio J, Travassos B. Variation in Physical Performance of Futsal Players During Congested Fixtures. Int J Sports Physiol Perform. 2022; 17:367–73. https://doi.org/10.1123/ijspp.2020-0922.
29. Garcia GR, Gonçalves LGC, Clemente FM, Nakamura FY, Nobari H, Bedo BLS, et al. Effects of congested fixture and matches' participation on internal and external workload indices in professional soccer players. Sci Rep. 2022; 12:1864. https://doi.org/10.1038/s41598-022-05792-w.
30. Rojas-Valverde D, Gutiérrez-Vargas R, Rodríguez-Montero A, Pereira LA, Loturco I, Martín-Rodríguez S. Reduced muscle contractile function in elite young soccer players after a short-congested fixture period. Proc Inst Mech Eng Part P J Sport Eng Technol. 2019; 233:249–57. https://doi.org/10.1177/1754337118817957.

31. Lundberg TR, Weckström K. Fixture congestion modulates post-match recovery kinetics in professional soccer players. Res Sport Med 2017; 25:408–20. https://doi.org/10.1080/15438627.2017.1365296.
32. Wollin M, Thorborg K, Pizzari T. Monitoring the effect of football match congestion on hamstring strength and lower limb flexibility: Potential for secondary injury prevention? Phys Ther Sport. 2018; 29:14–8. https://doi.org/10.1016/j.ptsp.2017.09.001.
33. Silva, R., Ceylan, H.İ., Badicu, G., Nobari, H., Carvalho et al. S.A., Sant'Ana, T., Mendes, B., Chen, Y.S., Clemente FM. Match-to-match variations in external load measures during congested weeks in professional male soccer players. J Men's Heal. 2021; 17:207–217. https://doi.org/10.31083/jomh.2021.063.
34. Gualtieri A, Rampinini E, Sassi R, Beato M. Workload Monitoring in Top-level Soccer Players During Congested Fixture Periods. Int J Sports Med. 2020; 41:677–81. https://doi.org/10.1055/a-1171-1865.
35. Clemente FM, Silva AF, Sarmento H, Ramirez-Campillo R, Chiu Y-W, Lu Y-X, et al. Psychobiological Changes during National Futsal Team Training Camps and Their Relationship with Training Load. Int J Environ Res Public Health. 2020; 17:1843. https://doi.org/10.3390/ijerph17061843.
36. Makaje N, Ruangthai R, Arkarapanthu A, Yoopat P. Physiological demands and activity profiles during futsal match play according to competitive level. J Sports Med Phys Fitness. 2012; 52:366–74.
37. Beato M, Coratella G, Schena F, Hulton AT. Evaluation of the external and internal workload in female futsal players. Biol Sport. 2017; 3:227–31. https://doi.org/10.5114/biolsport.2017.65998.
38. Impellizzeri FM, Marcora SM, Coutts AJ. Internal and external training load: 15 years on. Int J Sports Physiol Perform. 2019; 14:270–3. https://doi.org/10.1123/ijspp.2018-0935.
39. Younesi S, Rabbani A, Clemente FM, Silva R, Sarmento H, Figueiredo AJ. Relationships Between Aerobic Performance, Hemoglobin Levels, and Training Load During Small-Sided Games: A Study in Professional Soccer Players. Front Physiol. 2021; 12. https://doi.org/10.3389/fphys.2021.649870.
40. Silva AF, Tom F, Oliveira R, Clemente FM, Bezerra P, Hung C, et al. Differences between Physical Performance and Training Intensity Experienced in Training Camps. Biology (Basel). 2022; 11:1–15.
41. Akyildiz Z, Yildiz M, Clemente FM. The reliability and accuracy of Polar Team Pro GPS units. Proc Inst Mec Eng, P: J Sport Eng Technol. 2022; 236(2):83–89. doi: 10.1177/1754337120976660.
42. Hopkins W, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41:3–12. https://doi.org/10.1249/MSS.0b013e31818cb278.
43. Spyrou K, Freitas TT, Marín-Cascales E, Alcaraz PE. Physical and Physiological Match-Play Demands and Player Characteristics in Futsal: A Systematic Review. Front Psychol. 2020; 11. https://doi.org/10.3389/fpsyg.2020.569897.
44. Ribeiro JN, Gonçalves B, Coutinho D, Brito J, Sampaio J, Travassos B. Activity Profile and Physical Performance of Match Play in Elite Futsal Players. Front Psychol. 2020; 11. https://doi.org/10.3389/fpsyg.2020.01709.
45. Jones CM, Griffiths PC, Mellalieu SD. Training Load and Fatigue Marker Associations with Injury and Illness: A Systematic Review of Longitudinal Studies. Sports Med. 2017; 47(5):943–974. doi:10.1007/s40279-016-0619-5.
46. Younesi S, Rabbani A, Clemente FM, Silva R, Sarmento H, Figueiredo AJ. Dose-Response Relationships between Training Load Measures and Physical Fitness in Professional Soccer Players. Int J Environ Res Public Health. 2021; 18:4321. https://doi.org/10.3390/ijerph18084321.
47. Tanaka M, Tajima S, Mizuno K, Ishii A, Konishi Y, Miike T, et al. Frontier studies on fatigue, autonomic nerve dysfunction, and sleep-rhythm disorder. J Physiol Sci. 2015; 65:483–98. https://doi.org/10.1007/s12576-015-0399-y.
48. Atakan MM, Li Y, Koşar ŞN, Turnagöl HH, Yan X. Evidence-based effects of high-intensity interval training on exercise capacity and health: A review with historical perspective. Int J Environ Res Public Health. 2021; 18. https://doi.org/10.3390/ijerph18137201.
49. Ribeiro JN, Monteiro D, Sampaio J, Couceiro M, Travassos B. How weekly monitoring variables influence players' and teams' match performance in elite futsal players. Biol Sport. 2023; 40:77–83. https://doi.org/10.5114/biolsport.2023.112091.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.



FIG. 10. Repeated measures correlation analysis between age and match running demands during the congested schedule of futsal matches. Rmcorr for values (and corresponding *p*-values).



FIG. 11. Repeated measures correlation analysis between height and match running demands during the congested schedule of futsal matches. Rmcorr for values (and corresponding *p*-values).

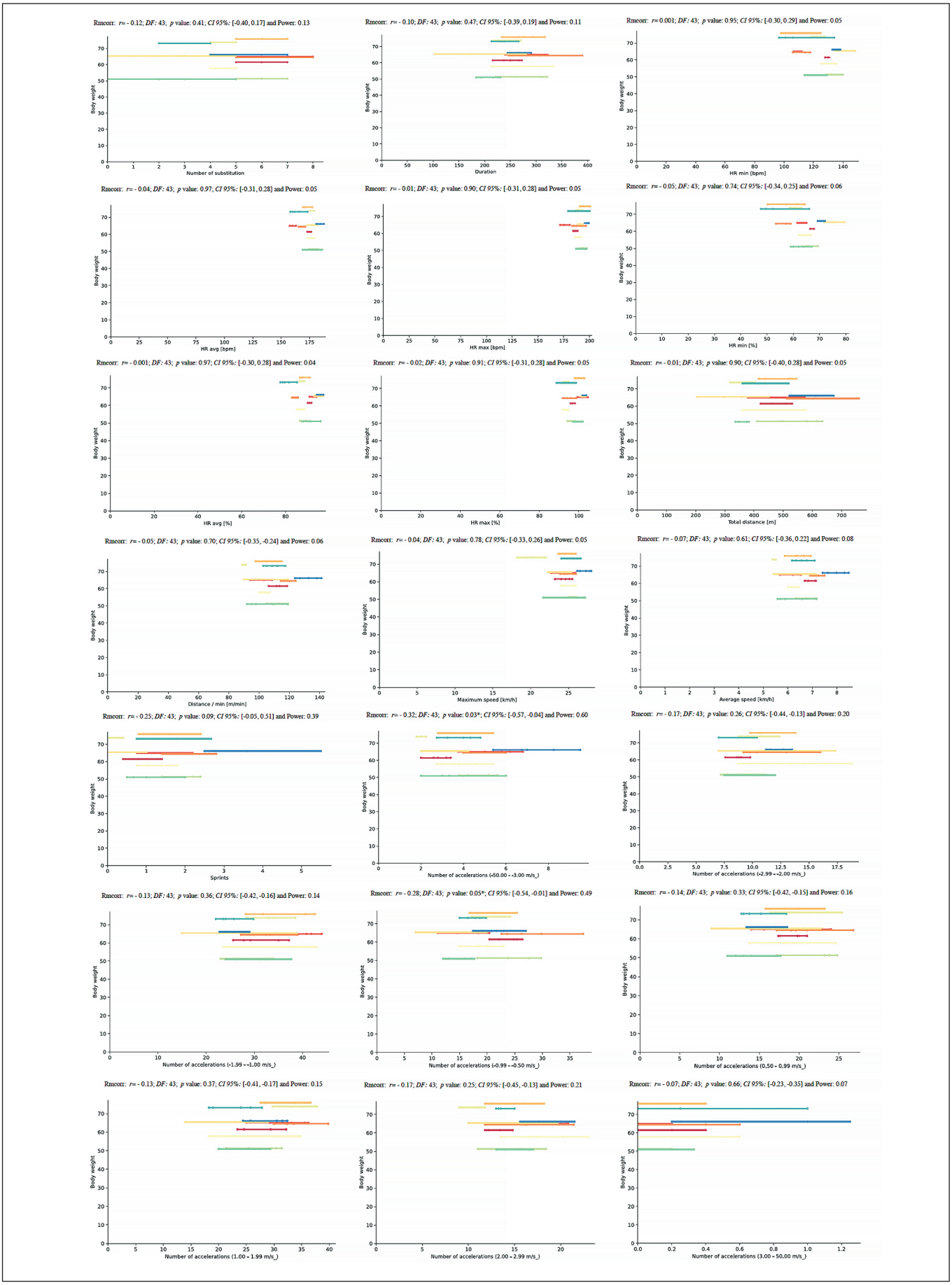


FIG. 12. Repeated measures correlation analysis between body weight and match running demands during the congested schedule of futsal matches. Rmcorr for values (and corresponding *p*-values).



FIG. 13. Repeated measures correlation analysis between fat% and match running demands during the congested schedule of futsal matches. Rmcorr for values (and corresponding *p*-values).

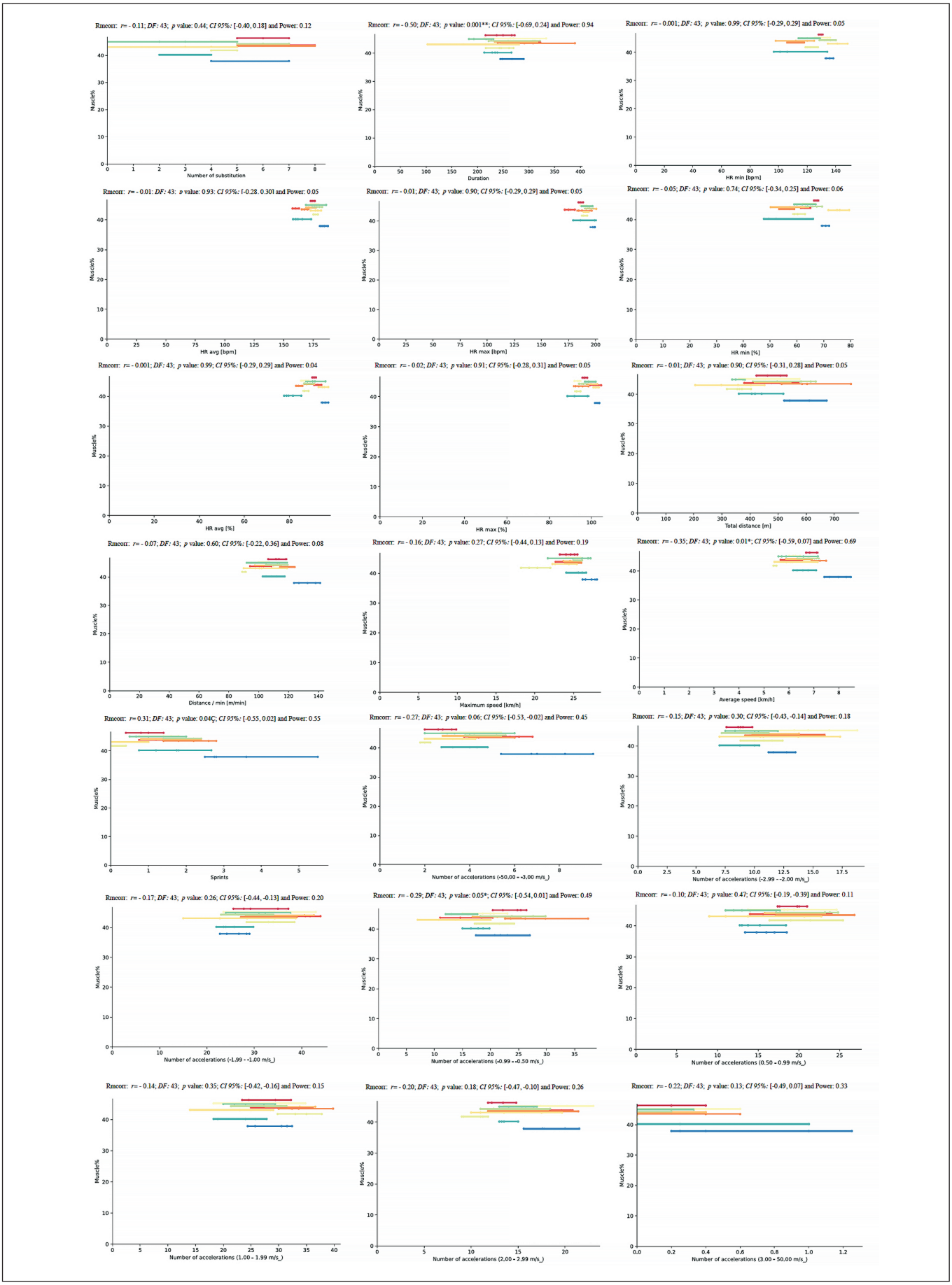


FIG. 14. Repeated measures correlation analysis between muscle% and match running demands during the congested schedule of futsal matches. Rmcorr for values (and corresponding *p*-values).

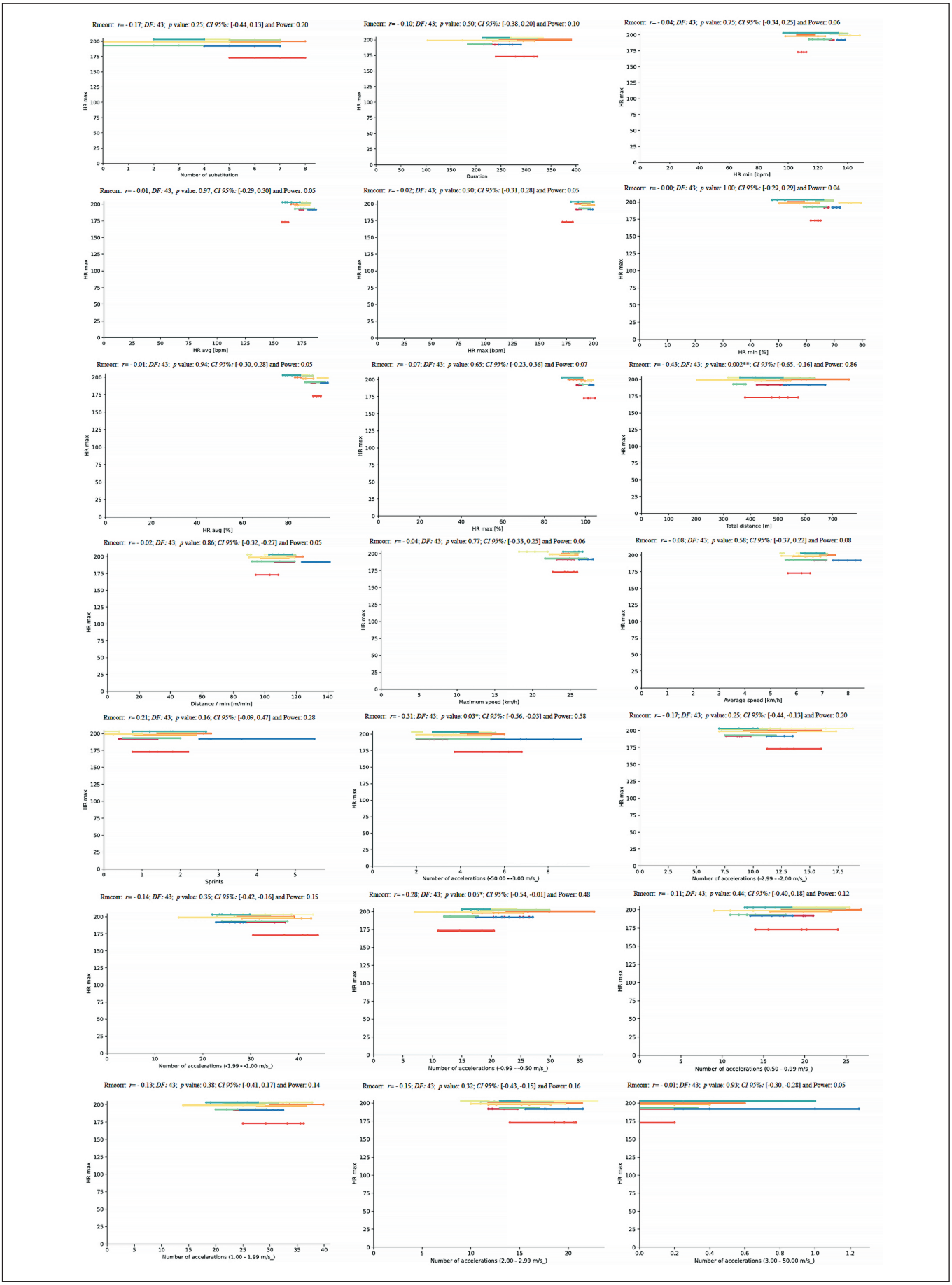


FIG. 15. Repeated measures correlation analysis between HR_{max} and match running demands during the congested schedule of futsal matches. Rmcorr for values (and corresponding *p*-values).

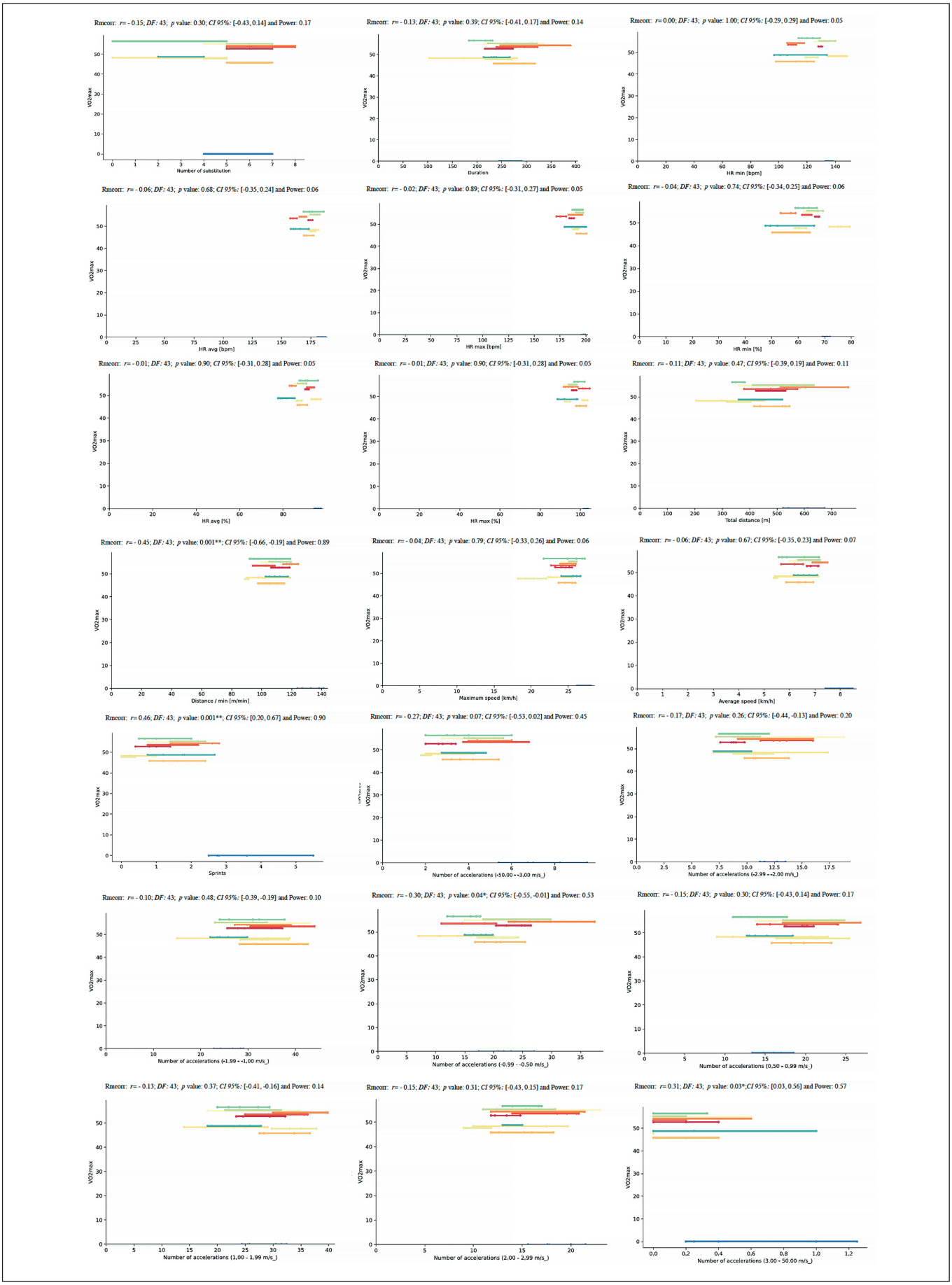


FIG. 16. Repeated measures correlation analysis between $\dot{V}O_{2max}$ and match running demands during the congested schedule of futsal matches. Rmcorr for values (and corresponding *p*-values).

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.134761
© Institute of Sport – National Research Institute

Effects of linear and change of direction high-intensity interval training on physical performance of elite female soccer players

AUTHORS: Mima Stanković[1], Nebojša Trajković[1], Draženka Mačak[2], Dušan Đorđević[1], Anja Lazić[1], Zoran Milanović[1,3,4]

[1] Faculty of Sport and Physical Education, University of Niš, Niš, Serbia
[2] Faculty of Sport and Physical Education, University of Novi Sad, Novi Sad, Serbia
[3] Science and Research Centre of Koper, Koper, Slovenia
[4] Faculty of Sports Studies, Incubator of Kinanthropological Research, Masaryk University, Brno, Czech Republic

ABSTRACT: The aim of this study was to determine the effects of linear and change of direction high-intensity interval training (HIIT) on physical performance in elite female soccer players. Thirty elite female soccer players (age: 19.6 ± 4.6 years; height: 166.5 ± 4.8 cm; body weight: 60.5 ± 8.3 kg; BMI: 21.9 ± 2.9 kg/m^2) were randomly allocated to HIIT linear ($HIIT_{LIN}$) and HIIT change of direction ($HIIT_{COD}$) training groups. The $HIIT_{LIN}$ group performed linear running for 15, 20 or 25 s by keeping constant pace during the entire distance. In contrast, the $HIIT_{COD}$ group performed three changes of direction (COD) with a 180° turn during each interval run at 15, 20 or 25 s. Physical performance was assessed using sprinting, agility, vertical jumps, repeated sprint ability (RSA) and 30–15 Intermittent Fitness Test (30–15 IFT). In both groups, all physical performance measurements improved ($p \leq 0.05$), except RSAbest in $HIIT_{LIN}$ ($p = 0.45$). Both interventions significantly improved speed over 10 m, 20 m, 30 m, Pro-agility, Zig-zag, RSAavg, fatigue index, maximal oxygen uptake, and velocity at 30–15 IFT, while moderate improvements were observed in countermovement jump (CMJ), CMJ with arm swing and squat jump. However, $HIIT_{COD}$ did not achieve superior improvements in any of the aforementioned measurements compared to $HIIT_{LIN}$. Based on the obtained results, we concluded that different types of HIIT training have a positive effect on physical performance in elite female soccer players.

CITATION: Stanković M, Trajković N, Mačak D et al. Effects of linear and change of direction high-intensity interval training on physical performance of elite female soccer players. Biol Sport. 2024;41(4):31–39.

Received: 2023-07-27; Reviewed: 2023-10-17; Re-submitted: 2023-10-24; Accepted: 2024-01-02; Published: 2024-03-06.

Corresponding author:
Zoran Milanović
University of Niš
Faculty of Sport and Physical Education, Niš, Serbia
Phone: 00381 63 7 399 366
E-mail: zoooro_85@yahoo.com

ORCID:
Mima Stanković
0000-0003-3328-0830

Nebojsa Trajkovic
0000-0001-6276-3052

Draženka Mačak
0000-0001-6846-896X

Dušan Đorđević
0000-0001-9618-0832

Anja Lazić
0000-0002-7742-3605

Zoran Milanović
0000-0002-3224-0506

Key words:
HIIT
Endurance
Interval
Women
Running
Power
Football

INTRODUCTION

Elite female soccer players cover around 9–11 km [1] of total distance during the game and spend 1.2–2.7 km performing high-intensity activities [2]. Furthermore, female soccer is characterized by frequent high-intensity activities throughout the game, which requires a high level of players' functional and motor skills. More precisely, speed, strength, agility, and endurance are crucial to perform a variety of elements such as jumping, accelerations, decelerations and changes of direction (COD) activities [3]. In order to repeat these actions and keep overall performance at the highest level, female soccer players must develop a very high level of aerobic and anaerobic capacity. However, little is known about the most effective strategy to simultaneously improve both aforementioned parameters in female soccer players because studies about female soccer players accounted for only 20% of all soccer research, while only 15% of them were dedicated to training and performance in elite female soccer players [4].

To date, some studies have confirmed that high-intensity interval training (HIIT) is one of the most effective methods for developing and improving aerobic and anaerobic capacity in team sports athletes [5]. In addition, HIIT training is potentially recognized as the most time-efficient method to achieve adaptive exercise goals [6]. Therefore, HIIT is considered to be the optimal type of training to improve both aerobic and anaerobic capacity and appears to be an effective method of fitness training for female soccer players [7]. However, the effects of HIIT on physical performance in female soccer players have received little research attention with only a few studies evaluating the effects of heart rate vs. speed-based HIIT, mixed methods HIIT and short-term HIIT in amateur [8], college [9] and youth [10] female soccer players, respectively. Specifically, in a recent study [8] both heart rate-based and speed-based HIIT induced meaningful improvements in aerobic and anaerobic capacity in amateur female soccer players. In addition, Rowan et al. [9] observed that short-term HIIT had positive effects on $\dot{V}O_{2max}$ (3.4–4.7%) in female college soccer players, while Wright et al. [10] reported very likely moderate and trivial improvements of Yo-Yo IR and the 20 m sprint test, respectively (effect size (ES) = 0.38–1.39), after six weeks in regional-level soccer players. Moreover, Wright et al. [10] also observed slightly improved agility (2.4%) and repeated sprint

(1.7–6.5%) performance in young female soccer players (age 13.4 ± 1.5 years). However, the effects of HIIT on physical performance in elite female soccer players remain unproven due to the scarcity of research attention.

All the aforementioned HIIT interventions were based on linear running despite practitioners' tendency to apply a more specific type of HIIT training which is similar to the specific game conditions [11]. More precisely, practitioners prefer HIIT training with a change of direction ($HIIT_{COD}$), which is more specific, in terms of movement patterns, to the female soccer match. In this vein, an approach to overcome this limitation in applied HIIT methods may be drawn from the combination of COD speed and HIIT research. More precisely, Ashton & Twist [12] found that the combination of HIIT and COD training leads to improved aerobic and anaerobic capacity in male soccer players. In addition, Teixeira et al. [13] concluded that HIIT with three directional changes per running bout achieved superior improvements in aerobic capacity, running economy, and repeated sprint ability (RSA) compared to one directional change in female futsal players. However, the effects of $HIIT_{COD}$ on physical performance in female soccer players are still unknown. In addition, there is no study comparing the effects of linear based HIIT ($HIIT_{LIN}$) and $HIIT_{COD}$ on physical performance in female soccer players. Therefore, the aim of this study was to determine the effects of linear and change of direction HIIT training ($HIIT_{COD}$ vs. $HIIT_{LIN}$) on physical performance in elite female soccer players. We hypothesized that both $HIIT_{LIN}$ and $HIIT_{COD}$ produce similar improvements in linear running performance while $HIIT_{COD}$ will be superior in COD movements.

MATERIALS AND METHODS

Participants

Thirty elite female soccer players (age: 19.6 ± 4.6 years; height: 166.5 ± 4.8 cm; body weight: 60.5 ± 8.3 kg; BMI 21.9 ± 2.9 kg/m^2) participated in this study. The participants were randomly allocated to $HIIT_{LIN}$ (N = 15; age: 19.2 ± 4.2 years; height: 165.5 ± 5.6 cm; body weight: 60.3 ± 8.2 kg; training experience: 6.3 ± 4.4 years) and $HIIT_{COD}$ (N = 15; age: 20.0 ± 5.0 years; height: 167.3 ± 4.3 cm; body weight: 63.6 ± 9.1 kg; training experience: 6.1 ± 4.7 years) after baseline measurements according to the procedure described by Suresh [14]. The inclusion criteria were as follows: individuals over the age of 15, who are competing at the highest level of soccer competition and who have trained with at least five training sessions per week. The exclusion criteria were: anyone with cardiovascular, respiratory, or other diseases, those undergoing rehabilitation, individuals who have had some kind of distortion in the last three months, as well as participants who had anterior cruciate ligament surgery in the previous year. All participants and their guardians were informed about the experimental design and testing procedures before providing written information and consent to participate. All study procedures were approved by the Human Research Ethics Committee at the University of Nis and followed the Helsinki Declaration guidelines (ref no. 04–1085/2). The club management and the participants were acquainted in detail with the experimental research.

Procedures

Measurements of the physical performance of all participants at the initial and the final measurements were conducted in a multidisciplinary diagnostic centre, as well as in the field with natural grass and lasted for two days. Measurements during both days were performed in the period 9–11 a.m. All tests were performed in the same order during initial and final measurements. The data were automatically stored in the computer by the direct method of input from the instrument measured in most cases, and only when there was no software solution would the results be manually entered on prepared lists for meters.

All participants performed a standard 20 min warm-up protocol consisting of jogging (6 min), stretching (5 min), progressive running (3 min), COD (3 min) and low-intensity plyometric jumps (3 min). Afterwards, participants performed vertical jumps (CMJ, CMJ with arm swing (CMJA), SJ) and RSA tests. On the second day after the same warm-up routine, participants performed additional physical performance tests as follows: 30 m sprint with time recorded at 10 m and 20 m, Pro-agility test, Zig-zag test, 9-6-3-6-3 sprint, 30–15 Intermittent Fitness Test (30–15 IFT). The same order of testing and procedure was performed by all participants at the initial and the final measurement.

Speed (running 0–30 m)

This study used 10 m, 20 m, and 30 m linear sprinting tests. The running speed was determined using three pairs of photocell infrared timing gates (Microgate, Polifemo Radio Light, Bolzano, Italy). Before testing, the players were familiarized with the procedures. Thirty cm behind the first pair of photocells was marked as the starting point. Participants were instructed to run as quickly as possible over the 30 m distance from a standing start. The timer was automatically activated as participants crossed the first gate at the starting line with split times at 10 m and 20 m. Acceleration was evaluated using the time to cover the first 10 m of the 30 m test. The participants performed three trials with at least 3 min rest between them [15]. The best performance of the three trials was used for further analysis.

Pro-agility test

The ability to change direction laterally to the right and left was measured by the Pro-agility test (5-10-5 m test). The running speed (5-10-5 m) was determined using photocell timing gates (Microgate, Polifemo Radio Light, Bolzano, Italy). The participants' starting position was in the middle of the 10 m separated cones and the timer was automatically activated as the participants crossed the first gate at the starting line. Each participant had to choose the side for the sprint (right or left) on the first attempt, while the opposite direction was used in the second attempt. The main task was to run laterally

(left/right) to the nearest cone (5 m), then run (left/right) to the next cone (10 m), and another one (left/right) which was the starting point (5 m). The time was automatically stopped when the participant re-crossed the starting line. The participants performed three trials with at least 3 min rest between them. The best performance of the three trials was used for further analysis. The test validity and reliability have been confirmed elsewhere [16].

Zig-zag test

The Zig-zag test measured running agility based on direction changes. The course consisted of four 5 m sections (20 m in total) with cones at a 100° and two pairs of photocells (Witty, Microgate, Bolzano, Italy) and required participants to slow down and accelerate around each cone as quickly as possible, from separated starting and finishing points. Before testing, the players were familiarized with the procedures. Starting from a standing position with the front foot 30 cm behind the first pair of timing gates, the players were instructed to complete the test as quickly as possible until they crossed the second pair of timing gates. The participants had a maximum of three attempts with an interval of 3 min of rest in between. The test validity and reliability have been confirmed elsewhere [17].

9-6-3-6-9 sprint (with 180° turns)

The players started after the signal and ran 9 m. Touching the line with one foot, they made a turn of 180° to the left or the right. The players then ran 3 m to the next line, made another 180° turn and ran 6 m forward. Then they made another 180° turn and ran 3 m forward, before making the last turn and the final 9 m run to the finish line. In addition, the main participants' aim was to perform the previously described test as fast as possible. The distance the players covered during this test was 21 m. The participants had a maximum of three attempts with an interval of 3 min of rest in between. The validity and reliability of the test have been confirmed elsewhere [18].

Vertical jumps (CMJ, CMJA, SJ)

Three types of vertical jumps were used to evaluate jump height (cm) – countermovement jump (CMJ), CMJ with arm swing (CMJA) and squat jump (SJ). Two photoelectric cells (Optojump, Microgate, Bolzano, Italy) were used to measure flight time between take-off and landing (cm). Before performing the tests, the participants were instructed to jump as high as they could. While performing the CMJ test, the participants had to put their hands on the hips and, on the previously set signal, flex the knees (approximately 90°) in order to jump upward without moving their hands from the hips. The CMJA test was performed the same way as the CMJ test, except the hands were free during all the phases of the maximum jump. The SJ test was performed with knees flexed at 90° and hands on the waist, as the maintained starting position (3 s), in order to jump upward without moving the hands from the hips. Additionally, for the jump to be correctly conducted, the participants had to avoid any knee or trunk countermovement. Each jump was completed after three trials with 1 min passive rest and 3 min passive rest between every test. For each test, the best result (cm) was taken into consideration. The validity and reliability of all previously described tests have been confirmed elsewhere [19].

Repeated sprint ability (RSA)

The repeated sprint ability (RSA) test consisted of six 40 m sprints separated by 20 s of passive recovery. Two pairs of infrared photocell timing gates (Microgate, Polifemo Radio Light, Bolzano, Italy) were set up at the start, and two in a straight line at a distance of 20 m from the starting line. The participants began the test 30 cm behind the starting line. When a participant was ready, they ran through the timing gates to a line marked on the track (20 m from the starting line). When the participants' foot reached the line at the 20 m mark, they turned as quickly as they could and ran back to the starting line. Then, the time was paused when the participant re-crossed the starting line. During testing, athletes were verbally instructed to take the starting position 30 cm behind the starting line 5 s before each sprint and a three second countdown was provided to start again. The procedure was repeated 6 times, with 20 s of active recovery between the runs. The results were added together and two results were recorded – the average time (RSAavg) and the total time (RSAtime) for the run section expressed in seconds with an accuracy of 1/100. Given that the RSA test caused fatigue in participants after a certain number of repetitions, the fatigue index in them was determined. The calculation of this parameter was done by dividing the difference between the best and the worst time with the best time and multiplying it by 100. The validity and reliability have been confirmed elsewhere [20]. In addition, the estimate of the fatigue index was calculated by the formula:

$$FI = 100 \times [(\text{best time (s)} - \text{worst time (s)}) / \text{best time (s)}]$$

where FI is the fatigue index, s is time on the RSA test expressed in seconds

30–15 Intermittent Fitness Test

The 30–15 IFT test was performed by placing cones 40 m apart from the beginning to the end and creating two three-metre zones in the middle of the testing area which helped guide the athletes to adjust and maintain their speed. Each player had their own line to run back and forth between 2 lines at a pace dictated by an auditory signal. The audio signal (beep) determined the running speed which started at 8 km/h for 30 s, with an increase of 0.5 km/h at each level (at 45 s). During the recovery period, the participants walked towards the nearest line, depending on where the previous run ended. During the 30–15 IFT, participants were verbally encouraged and instructed to cover as much distance as possible. The test ended when a participant was no longer able to maintain the imposed running speed or when she was unable to reach the 3 m zone around each line at the moment of the audio signal for 3 executive times.

From the 30–15 IFT results, the indirect estimate of the maximum oxygen consumption in relative and absolute values was obtained [21]. The validity and reliability of this test have been confirmed elsewhere [21].

Training protocol

The training programme was performed during the pre-season period with two HIIT sessions per week (Tuesday and Thursday) and lasted six weeks. Both experimental groups were supervised by at least one of the investigators during the intervention period. In addition, the participants also had five regular training sessions within the club consisting of technical and tactical drills. HIIT training sessions were separated by 48 h to allow sufficient recovery. All HIIT sessions during interventions were performed outdoors on the field with natural grass. Participants performed standardized warm-ups consisting of moderate-intensity jogging (5 min), static and dynamic stretching (5 min), passing and receiving drills (5 min) and acceleration running (2 min) prior to the HIIT session. Interval distances for each participant were individually adjusted according to each participant's final speed reached at the end of the 30–15 Intermittent Fitness Test (VIFT) [6], which was performed at baseline and repeated every third week in order to update the training speed.

Each session during the entire training programme involved work intervals of running effort at an intensity of 100% VIFT interspersed by an equivalent amount of passive recovery (0% VIFT). Training load was gradually increased from week 1 to week 6. While training intensity was performed at 100% VIFT, total training workload was calculated as arbitrary training units (ATU) [22]. The summary of the training plan and load for $HIIT_{LIN}$ and $HIIT_{COD}$ is presented in Table 1. Briefly, the $HIIT_{LIN}$ group performed linear running at 15, 20 or 25 s by keeping a constant pace during the entire distance. In contrast, the $HIIT_{COD}$ group performed three COD of 180° turn during each interval running at 15, 20 or 25 s. The individual interval distance for the $HIIT_{COD}$ group was reduced by 7% due to three turns of 180° which required additional energy. The aforementioned correction is based on the Laursen & Buchheit [6] recommendation that excess energy consumption should be compensated by reducing the distance by 2–3% for each COD compared to a straight line.

Participants started interval running from a standing position and followed audio signals to commence each subsequent run for the entire session. Upon completing each interval, participants immediately decelerated and were instructed to walk slowly to the next starting point and passively stand to await commencement of the next running interval. Every participant completed the running intervals in their own lane with fixed distances according to the calculated individualized VIFT. In addition to arbitrary training units, the rate of perceived exertion (RPE) scale was used to monitor training load of each HIIT session and provide greater insight into the training stresses [7].

$$\text{ATU} = [(\text{work intensity} + \text{rest intensity}) / 2] \times \text{number of repetitions} \times \text{number of series} \times \text{duration}$$

$$\text{Example of HIIT training load calculation for 1–2 weeks: } [(100 + 0) / 2] \times 8 \times 3 \times 15 = 18\,000 \text{ ATU}$$

Statistical analysis

G*power 3.1 power analysis software (Heinrich-Heine-University, Düsseldorf, Germany) determined the minimum total sample size (N-30) given the critical F = 4.60, effect size f = 0, P = 0.05, groups and time points = 2, and correlation among the measurements = 0.50. Data are expressed as mean [95% confidence interval] unless otherwise stated. The assumptions of normality and homogeneity of variances and covariances were verified using the Kolmogorov–Smirnov and Leven's and Box's tests, respectively.

A 2 × 2 mixed ANCOVA (group × time) model estimated the 6-week effects of $HIIT_{LIN}$ and $HIIT_{COD}$ training programmes on study outcomes after controlling for mean-centred age (mean = 19.60 years) and BMI (BMI = 21.88 kg/m^2) effects. We analysed the baseline differences between the groups in study outcomes using simple main effects of a group. A simple main effect of time evaluated the mean changes [95% CI] in each outcome from initial to final testing within the groups with Bonferroni adjusted p values and 95% CIs. A time by group interaction effect tested whether mean changes [95% CI] in each outcome after 6 weeks depended on whether players performed HIIT with or without change of direction. Mean changes [95%

TABLE 1. Detailed presentation of the experimental programme for both groups (LIN and COD) lasting 6 weeks

Week	Interval (s)	Intensity (%) (work/rest)	Repetition	Series	Total duration (min)	Training load (ATU)
1–2	15 × 15	100/0	8	3	≈18	18.000
3–4	20 × 20	100/0	8	3	≈22	24.000
5–6	25 × 25	100/0	8	3	≈26	30.000

Legend: HIIT – high-intensity interval training, VIFT – final speed reached at 30–15 intermittent fitness test, TL – training load, LIN – linear, COD – change of direction

CI] are based on estimated marginal means that are adjusted for mean-centred covariates appearing in the model. Cohen's d effect sizes (ES) were also calculated to determine the magnitude of the group differences in physical fitness. ES magnitude was interpreted as: trivial = < 0.20; small = 0.2–0.59; moderate = 0.60–1.19; large = 1.20–1.99; and very large = > 2.0. We used SPSS Statistics version 23.0 (IBM SPSS Statistics for Windows, Armonk, NY: IBM) and GraphPad Prism version 8.0 (GraphPad Software, San Diego, California USA) to analyse and plot the data obtained, respectively.

RESULTS

Baseline mean values of all study outcomes were similar across the groups ($p \leq 0.05$). There was no time × group interaction ($p \leq 0.05$) following 6 weeks of training (Table 2). In both groups mean performance of all tests significantly improved after 6 weeks ($p \leq 0.05$), except RSAbest in $HIIT_{LIN}$ ($p = 0.4$). We observed large improvements of $HIIT_{LIN}$ and $HIIT_{COD}$ mean performance of speed over 10 m ($HIIT_{LIN}$ vs. $HIIT_{COD}$: ES = 1.24 vs. 1.61), 20 m ($HIIT_{LIN}$ vs. $HIIT_{COD}$: ES = 1.21 vs. 0.95), and 30 m ($HIIT_{LIN}$ vs. $HIIT_{COD}$: ES = 1.55 vs.

TABLE 2. Physical performance parameters for $HIIT_{LIN}$ (N = 15) and $HIIT_{COD}$ (N = 15) groups before and after 6-week training intervention

Outcome	Group	Initial	Final	Mean changes [95% CI]	Δ (%)	ES	ANCOVA (group × time)	
							F	p
Speed 10 m (s)†	$HIIT_{LIN}$	2.06 ± 0.11	1.86 ± 0.20	-0.20 [-0.31, -0.08]**	-9.7%	1.24	0.42	0.84
	$HIIT_{COD}$	2.07 ± 0.13	1.89 ± 0.09	-0.18 [-0.30, -0.07]**	-8.7%	1.61		
Speed 20 m (s)†	$HIIT_{LIN}$	3.57 ± 0.13	3.38 ± 0.18	-0.19 [-0.33, -0.05]*	-5.3%	1.21	0.01	0.92
	$HIIT_{COD}$	3.54 ± 0.18	3.35 ± 0.22	-0.20 [-0.34, -0.06]**	-5.4%	0.95		
Speed 30 m (s)†	$HIIT_{LIN}$	5.05 ± 0.28	4.68 ± 0.19	-0.36 [-0.54, -0.19]***	-7.3%	1.55	0.02	0.94
	$HIIT_{COD}$	5.01 ± 0.29	4.68 ± 0.22	-0.34 [-0.52, -0.17]***	-6.6%	1.28		
Pro-agility (s)†	$HIIT_{LIN}$	5.49 ± 0.24	5.16 ± 0.18	-0.32 [-0.48, -0.15] ***	-6.0%	1.56	0.01	0.94
	$HIIT_{COD}$	5.40 ± 0.26	5.09 ± 0.15	-0.33 [-0.49, -0.16]***	-5.7%	1.46		
Zig-zag (s)†	$HIIT_{LIN}$	6.31 ± 0.25	5.89 ± 0.31	-0.42 [-0.58, 0.27]***	-6.7%	1.47	0.73	0.40
	$HIIT_{COD}$	6.24 ± 0.31	5.73 ± 0.33	-0.52 [-0.68, 0.36]***	-8.2%	1.59		
9-6-3-6-9 (s)†	$HIIT_{LIN}$	8.75 ± 0.45	8.26 ± 0.31	-0.47 [-0.71, -0.23]***	-5.6%	1.27	0.53	0.47
	$HIIT_{COD}$	8.78 ± 0.45	8.44 ± 0.28	-0.35 [-0.59, -0.11]**	-3.9%	0.91		
CMJ (cm)	$HIIT_{LIN}$	24.01 ± 3.60	26.2 ± 2.26	1.99 [0.94, 3.03]***	9.1%	-0.73	0.60	0.44
	$HIIT_{COD}$	22.62 ± 3.22	25.0 ± 2.62	2.55 [1.50, 3.59]***	10.5%	-0.81		
CMJA (cm)	$HIIT_{LIN}$	26.65 ± 4.08	29.28 ± 2.82	2.52 [1.35, 3.69]***	9.9%	-0.75	0.03	0.87
	$HIIT_{COD}$	25.42 ± 4.00	27.96 ± 2.88	2.66 [1.48, 3.83] ***	10.0%	-0.73		
SJ (cm)	$HIIT_{LIN}$	22.33 ± 3.13	24.11 ± 2.19	1.71 [0.37, 3.04]*	8.0%	-0.66	1.75	0.20
	$HIIT_{COD}$	20.83 ± 3.26	23.68 ± 3.01	2.93 [1.60, 4.27]***	13.7%	-0.90		
RSA(avg)	$HIIT_{LIN}$	8.84 ± 0.36	8.39 ± 0.43	1.71 [0.37, 3.04]*	-5.1%	1.13	0.05	0.83
	$HIIT_{COD}$	8.78 ± 0.47	8.37 ± 0.42	2.93 [1.60, 4.27]***	-4.7%	0.92		
RSA(best)	$HIIT_{LIN}$	8.26 ± 0.29	8.21 ± 0.34	-0.05 [-0.31, 0.22]	-0.6%	0.16	0.03	0.86
	$HIIT_{COD}$	8.26 ± 0.50	8.19 ± 0.33	-0.08 [-0.34, 0.18]	-0.8%	0.16		
FI(%)†	$HIIT_{LIN}$	12.18 ± 3.76	5.18 ± 1.88	-6.71 [-9.08, -4.33]***	-57.5%	2.35	0.003	0.96
	$HIIT_{COD}$	10.83 ± 4.41	4.50 ± 1.68	-6.62 [-8.99, -4.24]***	-58.4%	1.90		
$\dot{V}O_{2max}$ (mL/kg/min)	$HIIT_{LIN}$	42.23 ± 2.82	43.86 ± 2.89	1.60 [0.08, 3.11]*	3.9%	-0.57	2.41	0.13
	$HIIT_{COD}$	43.33 ± 1.60	46.52 ± 3.26	3.23 [1.71, 4.74]***	7.4%	-1.24		
VIFT	$HIIT_{LIN}$	16.11 ± 1.19	16.75 ± 1.19	0.64 [0.17, 1.12] **	4.0%	-0.47	3.56	0.07
	$HIIT_{COD}$	16.47 ± 0.54	17.75 ± 1.18	1.27 [0.79, 1.74] ***	7.8%	-1.39		

Δ (%) – percent change between initial and final measurement, ES – effect size, † – reverse scoring; CMJ – counter movement jump; CMJA – counter movement jump free arms; SJ – squat jump; RSA – repeated sprint ability; FI – fatigue index; VIFT – final speed reached at 30–15 intermittent fitness test; statistical power; * – significant difference between initial and final measurements ($p \leq 0.05$); ** – significant difference between initial and final measurements $p \leq 0.01$; *** – significant difference between initial and final measurements $p \leq 0.01$.

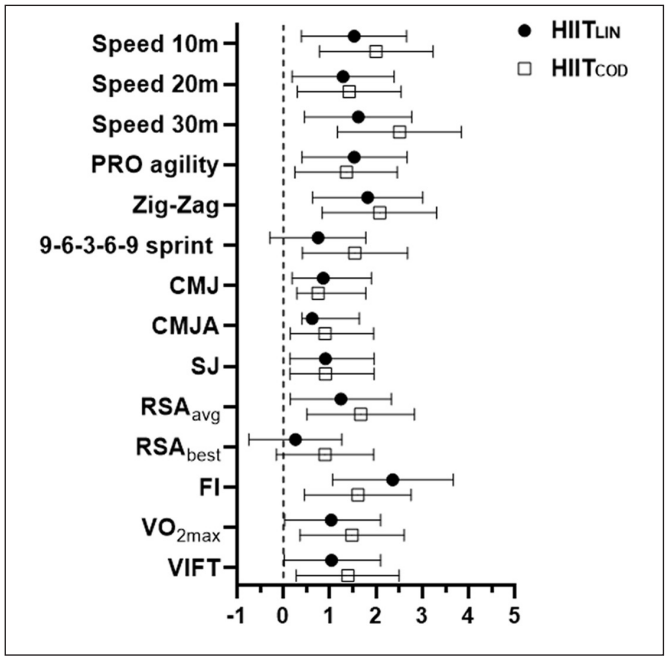


FIG. 1. Effect size (ES) for all included variables of physical performance.

1.28), Pro-agility ($HIIT_{LIN}$ vs. $HIIT_{COD}$: ES = 1.56 vs. 1.46), Zig-zag ($HIIT_{LIN}$ vs. $HIIT_{COD}$: ES = 1.47 vs. 1.59), RSAavg ($HIIT_{LIN}$ vs. $HIIT_{COD}$: ES = 1.13 vs. 0.92), FI ($HIIT_{LIN}$ vs. $HIIT_{COD}$: ES = 2.35 vs. 1.90), $\dot{V}O_{2max}$ ($HIIT_{LIN}$ vs. $HIIT_{COD}$: ES = -0.57 vs. -1.24), and VIFT ($HIIT_{LIN}$ vs. $HIIT_{COD}$: ES = -0.47 vs. -1.39), and medium improvements of $HIIT_{LIN}$ and $HIIT_{COD}$ mean performance CMJ, CMJA, and SJ (Figure 1). $HIIT_{COD}$ increased performance of Speed 30 m to a significantly larger extent than $HIIT_{LIN}$ ($p \leq 0.05$).

DISCUSSION

The aim of this study was to determine the effects of HIIT training with and without change of direction on physical performance in elite female soccer players. Both interventions, $HIIT_{LIN}$ and $HIIT_{COD}$, significantly improved speed over 10 m, 20 m, 30 m, Pro-agility, Zig-zag, RSAavg, FI, $\dot{V}O_{2max}$, and VIFT, while moderate improvements were observed in CMJ, CMJA and SJ. However, $HIIT_{COD}$ did not achieve superior improvements in any of the aforementioned measurements compared to $HIIT_{LIN}$ as we hypothesized.

Speed is an important determinant of successful performance in elite female soccer, especially during crucial match actions and off the ball running [23]. We observed similar improvements in acceleration (10 and 20 m) and maximal speed (30 m) in both groups, with increases in the $HIIT_{LIN}$ (5.3–9.7%) and $HIIT_{COD}$ (5.4–8.7%) groups. The differences in training adaptations were unclear between both groups. The magnitude of response was higher for all linear tests compared to the previous study [10] investigating the effects of mixed-methods HIIT intervention in young female soccer players. We observed large and medium average improvements in terms of speed, which is in accordance with Taylor et al. [19], who also observed effects after two weeks of HIIT and reported a large effect (3.6–9.6%) on the acceleration phase of sprinting in male soccer players. Furthermore, the mentioned study had a training programme similar to ours and also had the same linear and COD group. Based on the results, it is possible that the players in our study were less habituated to the training stimulus imposed by the HIIT approach than those in the above-mentioned earlier trials. In addition, based on participants' age (20 years in our study vs. 13 years), the heterogeneous results suggest that growth and maturation could be significant mediators when measuring physical fitness [24]. Our training programme was designed so that the training load was gradually increased, which was different from the above-mentioned studies. Moreover, the programme was not designed for a specific position. Having this in mind, Mäkiniemi et al. [25] reported position-specific differences in match demands, especially for the distance and number of acceleration and decelerations.

It is well documented that HIIT can improve COD in soccer [15, 19]. Our findings have shown that both training interventions ($HIIT_{LIN}$ and $HIIT_{COD}$) resulted in similar positive changes in players' ability to change direction. In addition, the magnitude of response in all three measured agility tests for $HIIT_{LIN}$ were from 5.6% to 6.7%, while for $HIIT_{COD}$ they were from 3.9% to 8.2%. The biggest changes were observed in the Zig-zag test in both groups ($HIIT_{LIN}$ 6.7%, $HIIT_{COD}$ 8.2%). The current results are slightly better than those obtained by Nayıroglu et al. [15], who reported a significant improvement (3.5%) in the 505 test. In addition, Wright et al. [10] observed moderate improvements in the T-test in two groups (before peak height velocity (PHV) 2.4%; after PHV 2.4%). Given the design of the experimental programme, we expected that the $HIIT_{COD}$ group would outperform $HIIT_{LIN}$, particularly in the change of direction tests. It should be taken into account that COD volume and their different turn angles during a training session were determinants for adaptations to occur [26]. The rapid improvement seen in the participants' performance could be explained by the different physiological changes, such as rapid adaptation, muscle fibre recruitment, and frequency and motor unit synchronization [27]. Hence, having in mind that our participants showed far more COD changes compared to the other mentioned studies, our results are understandable.

Improving soccer-specific strength, which is defined as a player's ability to employ muscle strength, power efficiency and consistent soccer-specific activities throughout the game, should be one of the most essential goals of training programmes [28]. After 6 weeks of HIIT, our programmes had improved the vertical jump in all three variables in both experimental groups. In addition, the magnitude of response in all three measured tests for $HIIT_{LIN}$ ranged from 8.0% to 9.9%, while for $HIIT_{COD}$ it ranged from 10.0% to 13.7%. In this regard, our findings are consistent with those of other soccer-related studies, which reported a significant improvement in CMJ (10.3%) and CMJA tests (10.2%) after eight weeks of HIIT training [15]. Following that, a study with a similar programme and experimental

groups to ours reported small improvements in CMJ in the linear (1.5%) and COD (1.8%) groups in men's soccer [19]. Although we also recorded notable changes in the SJ test in the $HIIT_{COD}$ group (13.7%), our study was also the first to report the effect of HIIT training in female soccer players. The higher number of changes of direction in our training programme could be the primary reason for the disparity of results. Likewise, participants' sample characteristics (middle-adolescent vs. young adults, professional vs. amateur) should also be taken into consideration. Additional upper-body muscles and eccentric muscular contractions [29] should not be excluded as a rationale for CMJA, as well as neuromuscular and metabolic factors [27], for SJ. Buchheit et al. [30] stated that as sprinting ability demands increase, the explosive strength also increases, which may be another possible explanation of our results. Increased muscular ability to create greater tension adds more contractile components and utilizes elastic energy, and may contribute to alterations in muscle function during jumping performances [31]. Likewise, based on the significant correlation between 10 m sprint and agility tests (180° and 100° angles) [32], we can assume that this is another possible explanation for our results, since our agility tests consisted of 10 m running distance, with 180° angles (Pro-agility test, 9-6-3-6-9 test) and 100° angles (Zig-zag). We can also assume that our results would have been even greater if we had conducted unilateral jump tests, but, unfortunately, we did not. In regard to the mentioned facts, there could be a slight connection, because the COD participants probably performed their agility turns on their preferred leg. Hence, we can speculate that this is a possible cause of our observed improvements in leg power.

Repeated sprint ability consists of a series of brief sprints separated by a short rest period [27], which is an important overall factor in soccer [19]. We observed improvements in both RSA(avg) ($HIIT_{LIN}$-5.1%; $HIIT_{COD}$ -4.7%) and RSA(best) ($HIIT_{LIN}$-0.6%; $HIIT_{COD}$-0.8%). There is a notable study disparity between the results from the study by Wright et al. [10] and the results from the current study. The mentioned study reported small decrements in RSA performance, with moderate individual differences. The RSA outcome was most likely similar to the related ability to develop maximum speed [33]. According to them, the magnitude of accelerations and the amount of time spent accelerating in each running bout are both important; therefore it appears reasonable to believe that these athletes performed more forceful accelerations and spent more time accelerating per running bout. Kaplan [34] did not find any significant differences in RSA, best time, average time and FI, while our study showed the opposite. One of the reasons is that they were evaluating these parameters based on the players' position, while we did not include that factor. Likewise, their sample consisted of amateur players, while ours consisted of elite players. Several studies [35, 36] have immediate practical implications in that, for both the development of fatigue-reduction methods and a better understanding of the physiological responses, repeated high-intensity exercises are to be followed. In addition, the programme was conducted in the preparation period, designed so that the training load was gradually increased; hence, the improved overall results were also logical. High-quality and accurate results enable the establishment of precise targets, tasks, and preparation cycles, as well as the implementation of appropriate means, loads, and methods for training [37].

Due to the fact that our HIIT programmes were used in preseason, the greatest improvements were expected for aerobic capacity. This was confirmed with large improvements in both groups in $\dot{V}O_{2max}$ ($HIIT_{LIN}$-3.9%; $HIIT_{COD}$-7.4%) and VIFT ($HIIT_{LIN}$-4.0%; $HIIT_{COD}$-7.8%) without significant differences between them. The results from the current study can be related to the results from the previous studies [8, 9, 15, 38]. According to Savolainen et al. [39], the total distance covered in a match could be increased by 1450 m as a result of the players' $\dot{V}O_{2max}$ improvement in an elite level by 10 ml/kg/min. In accordance with that, Rowan et al. [9] reported a significant increase in $\dot{V}O_{2max}$ (3.4–4.7%), while Arazi et al. [8] noted large improvements in the same variable after 6 weeks of an experimental programme (12.8%). Moreover, when VIFT was taken into account, we identified improvements in both groups. However, further discussion is limited due to the restricted number of studies in this area of investigation. Although the previous research has pointed out that HIIT alone can lead to the improvement of VIFT [40], we found that greater effects of improvement were observed in the COD group. This finding is congruent with the work of Nayıroglu et al. [15], who noted significant improvements (10.7%). In addition, Dolci et al. [38] reported significant differences after two weeks of HIIT in both groups (4.0% and 5.0%, respectively). A possible explanation for our results could be given by Taylor et al. [19], who suggested that incorporating COD activities into training leads to greater metabolic and neuromuscular stress, adaptation and better performance at the same time. In addition, Padulo et al. [41] stated that including specific COD movements/turns into a training programme may have better positive transfer to real game situations than linear running. Also, taking into account that VIFT is associated with changes in several variables, of which the most important are $\dot{V}O_{2max}$ and COD activities, it can be concluded that the improved VIFT values are also the result of the experimental treatment. More precisely, the same muscle groups are involved in a large number of sudden decelerations and accelerations during 30–15 IFT [30]. Furthermore, repeating the same patterns of these movements during HIIT training leads to positive changes and a positive transfer to the performance. Knowing the demands of elite women's soccer matches can be of great value not only to head coaches, but also to physical coaches, in order to plan tailor-made training [42].

We acknowledge that our study had some limitations. Firstly, our study is not generalizable beyond the study sample due to the wide range of age of the participants (16–26 years). Secondly, we failed to examine the effects of two different types of HIIT with the presence of the control group due to the lack of an adequate sample of the participants. Nevertheless, this is the first study aimed at comparing two different types of HIIT training (LIN-COD), especially in

the highest rank of the competition, and produced positive results. In future studies will be necessary to further investigate the role of different types of HIIT training in female soccer performance.

CONCLUSIONS

Based on the obtained results, we can conclude that different types of HIIT training, i.e., both LIN and COD, have a positive effect on physical performance in elite female soccer player. According to our research, the importance and effects of training that includes a change in direction of movement, which represents more specific movements similar to soccer, can be achieved. This study should be understood as a good practical framework, in order to level up the physical performance variables in the preparation period, as well as to achieve the maximum results. To conclude, these findings would be useful to coaches and sports scientists, who should include a specially created HIIT training programme for each player in particular and in the micro cycle as a powerful method of improving their performance.

Conflict of Interest

The authors declared no conflict of interest.

REFERENCES

1. Andersson HÅ, Randers MB, Heiner-Møller A, Krustrup P, Mohr M. Elite female soccer players perform more high-intensity running when playing in international games compared with domestic league games. J Strength Cond Res. 2010; 24(4):912–9.
2. Bendiksen M, Pettersen SA, Ingebrigtsen J, Randers MB, Brito J, Mohr M, et al. Application of the Copenhagen Soccer Test in high-level women players–locomotor activities, physiological response and sprint performance. Hum Mov Sci. 2013; 32(6):1430–42.
3. Manson SA, Brughelli M, Harris NK. Physiological characteristics of international female soccer players. J Strength Cond Res. 2014; 28(2):308–18.
4. Kirkendall DT, Krustrup P. Studying professional and recreational female footballers: A bibliometric exercise. Scand J Med Sci Sports. 2022; 32:12–26.
5. Sanchez-Sanchez J, Carretero M, Ramirez-Campillo R, Petisco C, Diego M, Gonzalo-Skok O, et al. Effects of high-intensity training with one versus three changes of direction on youth female basketball players'performance. Kinesiology. 2018; 50(1):117–25.
6. Laursen P, Buchheit M. Science and application of high-intensity interval training. Human kinetics; 2019.
7. Foster C, Farland C V, Guidotti F, Harbin M, Roberts B, Schuette J, et al. The effects of high intensity interval training vs steady state training on aerobic and anaerobic capacity. J Sports Sci Med. 2015; 14(4):747.
8. Arazi H, Keihaniyan A, EatemadyBoroujeni A, Oftade A, Takhsha S, Asadi A, et al. Effects of heart rate vs. speed-based high intensity interval training on aerobic and anaerobic capacity of female soccer players. Sports. 2017; 5(3):57.
9. Rowan AE, Kueffner TE, Stavrianeas S. Short duration high-intensity interval training improves aerobic conditioning of female college soccer players. Int J Exerc Sci. 2012; 5(3):6.
10. Wright MD, Hurst C, Taylor JM. Contrasting effects of a mixed-methods high-intensity interval training intervention in girl football players. J Sports Sci. 2016; 34(19):1808–15.
11. Aschendorf PF, Zinner C, Delextrat A, Engelmeyer E, Mester J. Effects of basketball-specific high-intensity interval training on aerobic performance and physical capacities in youth female basketball players. Phys Sportsmed. 2019; 47(1):65–70.
12. Ashton REM, Twist C. Number of directional changes alters the physiological, perceptual, and neuromuscular responses of netball players during intermittent shuttle running. J Strength Cond Res. 2015; 29(10):2731–7.
13. Teixeira AS, Arins FB, de Lucas RD, Carminatti LJ, Dittrich N, Nakamura FY, et al. Shuttle-run interval training with more directional changes induces superior gains in shuttle sprint performance in female professional futsal players. Hum Mov Spec Issues. 2018; 2018(5):40–51.
14. Suresh KP. An overview of randomization techniques: an unbiased assessment of outcome in clinical research. J Hum Reprod Sci. 2011; 4(1):8–11.
15. Nayıroğlu S, Yılmaz AK, Silva AF, Silva R, Nobari H, Clemente FM. Effects of small-sided games and running-based high-intensity interval training on body composition and physical fitness in under-19 female soccer players. BMC Sports Sci Med Rehabil. 2022; 14(1):1–10.
16. Mann JB, Ivey PA, Mayhew JL, Schumacher RM, Brechue WF. Relationship between agility tests and short sprints: Reliability and smallest worthwhile difference in National Collegiate Athletic Association Division-I football players. J Strength Cond Res. 2016; 30(4):893–900.
17. Loturco I, Nimphius S, Kobal R, Bottino A, Zanetti V, Pereira LA, et al. Change-of direction deficit in elite young soccer players. Ger J Exerc Sport Res. 2018; 48(2):228–34.
18. Sporis G, Jukic I, Milanovic L, Vucetic V. Reliability and factorial validity of agility tests for soccer players. J Strength Cond Res. 2010; 24(3):679–86.
19. Taylor J, Macpherson T, Spears I, Weston M. The effects of repeated-sprint training on field-based fitness measures: a meta-analysis of controlled and non-controlled trials. Sport Med. 2015; 45(6):881–91.
20. Torreblanca-Martínez V, Nevado-Garrosa F, Otero-Saborido FM, Gonzalez-Jurado JA. Effects of fatigue induced by repeated-sprint on kicking accuracy and velocity in female soccer players. PLoS One. 2020; 15(1):e0227214.
21. Buchheit M. The 30–15 intermittent fitness test: accuracy for individualizing interval training of young intermittent sport players. J Strength Cond Res. 2008; 22(2):365–74.
22. Cvetković N, Stojanović E, Stojiljković N, Nikolić D, Scanlan AT, Milanović Z. Exercise training in overweight and obese children: Recreational football and high-intensity interval training provide similar benefits to physical fitness. Scand J Med Sci Sports. 2018; 28:18–32.
23. Randell RK, Clifford T, Drust B, Moss SL, Unnithan VB, De Ste Croix M, et al. Physiological characteristics of female soccer players and health and performance considerations: a narrative review. Sport Med. 2021; 51(7):1377–99.
24. Vandorpe B, Vandendriessche J, Vaeyens R, Pion J, Matthys S, Lefevre J, et al. Relationship between sports participation and the level of motor coordination in childhood: a longitudinal approach. J Sci Med Sport. 2012; 15(3):220–5.
25. Mäkiniemi JK, Savolainen EHJ, Finni T, Ihalainen J. Position specific physical demands in different phases of competitive matches in national level women's football. Biol Sport. 2022; 40(3):629–37.
26. Stanković M, Đorđević D, Aleksić A, Lazić A, Lilić A, Čaprić I, et al. The relationship between jump performance,

speed and cod speed in elite female soccer players. Facta Univ Ser Phys Educ Sport. 2022; 47–59.
27. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle. Sport Med. 2013; 43(5):313–38.
28. Manolopoulos E, Papadopoulos C, Salonikidis K, Katartzi E, Poluha S. Strength training effects on physical conditioning and instep kick kinematics in young amateur soccer players during preseason. Percept Mot Skills. 2004; 99(2):701–10.
29. Sheppard JM, Young WB. Agility literature review: Classifications, training and testing. J Sports Sci. 2006; 24(9):919–32.
30. Buchheit M, Mendez-Villanueva A, Quod M, Quesnel T, Ahmaidi S. Improving acceleration and repeated sprint ability in well-trained adolescent handball players: speed versus sprint interval training. Int J Sports Physiol Perform. 2010; 5(2):152–64.
31. Toumi H, Best TM, Martin A, Poumarat G. Muscle plasticity after weight and combined (weight+ jump) training. Med Sci Sports Exerc. 2004; 36(9):1580–8.
32. Lockie RG, Dawes JJ, Jones MT. Relationships between linear speed and lower-body power with change-of-direction speed in national collegiate athletic association divisions I and II women soccer athletes. Sports. 2018; 6(2):30.
33. Pyne DB, Saunders PU, Montgomery PG, Hewitt AJ, Sheehan K. Relationships between repeated sprint testing, speed, and endurance. J Strength Cond Res. 2008; 22(5):1633–7.
34. Kaplan T. Examination of repeated sprinting ability and fatigue index of soccer players according to their positions. J Strength Cond Res. 2010; 24(6):1495–501.
35. Blangsted AK, Sjøgaard G, Madeleine P, Olsen HB, Søgaard K. Voluntary low-force contraction elicits prolonged low-frequency fatigue and changes in surface electromyography and mechanomyography. J Electromyogr Kinesiol. 2005; 15(2):138–48.
36. Søgaard K, Blangsted AK, Jørgensen LV, Madeleine P, Sjøgaard G. Evidence of long term muscle fatigue following prolonged intermittent contractions based on mechano-and electromyograms. J Electromyogr Kinesiol. 2003; 13(5):441–50.
37. Pajić Z, Simović S, Dopsaj M. Standardized planned agility tests in young football players: Mathematical modeling in the function of defining physical potential. Facta Univ Ser Phys Educ Sport. 2022; 245–56.
38. Dolci F, Kilding AE, Spiteri T, Chivers P, Piggott B, Maiorana A, et al. High-intensity Interval Training Shock Microcycle Improves Running Performance but not Economy in Female Soccer Players. Int J Sports Med. 2021; 42(08):740–8.
39. Savolainen E, Vänttinen T, Ihalainen J, Walker S. Physical qualities and body composition predictors of running performance in national level women's official soccer matches. Biol Sport. 2023; 40(3):619–27.
40. Viaño-Santasmarinas J, Rey E, Carballeira S, Padrón-Cabo A. Effects of high-intensity interval training with different interval durations on physical performance in handball players. J Strength Cond Res. 2018; 32(12):3389–97.
41. Padulo J, Bragazzi NL, Nikolaidis PT, Dello Iacono A, Attene G, Pizzolato F, et al. Repeated sprint ability in young basketball players: multi-direction vs. one-change of direction (Part 1). Front Physiol. 2016; 7:133.
42. Armendáriz MLP, Spyrou K, Alcaraz PE. Match demands of female team sports: a scoping review. Biol Sport. 2023; 41(1):175–99.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.134756
© Institute of Sport – National Research Institute

Characterizing the most demanding passages of kinematic and mechanical activity in elite football: a multifactorial approach

AUTHORS: Farzad Yousefian[1,2], Abdullah Zafar[3], Dan Fransson[4], Magni Mohr[5,6], João Brito[2], Bruno Travassos[1,2]

[1] Research Centre in Sports Sciences, Health Sciences and Human Development (CIDESD), Department of Sport Sciences, University of Beira Interior, Covilhã, Portugal
[2] Portugal Football School, Portuguese Football Federation, Oeiras, Portugal
[3] Department of Kinesiology, University of Waterloo, Waterloo, Canada
[4] Center for Health and Performance, Department of Food and Nutrition and Sports Science, University of Gothenburg, Gothenburg, Sweden
[5] Department of Sports Sciences and Clinical Biomechanics, SDU Sport and Health Science Cluster (SHSC), University of Southern Denmark, Odense, Denmark
[6] Center of Health Science, Faculty of Health, University of the Faroe Islands, Tórshavn, Faroe Islands

ABSTRACT: This study investigated the 5-minute most demanding passages (MDP) of kinematic (distance covered) and mechanical (acceleration and deceleration) activities in elite male football according to multifactorial criterion performance variables. Global positioning systems data were collected from 39 players across 45 matches in the Swedish first division (n = 329 observations). The multifactorial kinematic variable (MDPk) was composed of the concurrent distances covered at moderate-speed running, high-speed running, and sprinting distances, and the multifactorial mechanical (MDPm) considered the concurrent occurrences of high-intensity acceleration and deceleration activities. A moving average method was used to identify the MDP across a 5-minute period. The frequency distribution of the multifactorial variables, and differences in the time of occurrence and magnitude between multifactorial performance variables and their univariate constituent variables were investigated. Frequency distribution analysis revealed MDPk and MDPm peaked in the first 5 min of the match (MDPk: χ^2 (15, $N = 329$) = 135.88, $p \leq 0.001$, *W*: 0.64, 115.99 ± 32.7 s; MDPm: χ^2 (15, $N = 329$) = 31.02, $p \leq 0.001$, *W*: 0.31, 101.21 ± 25.1 s; $p \leq 0.0004$). Within each half, differences in the MDP commencement time between the multifactorial variables and their respective discrete univariate constituent variables were trivial to small (MDPk effect size (ES): 0.04–0.21; MDPm ES: 0.02–0.11). Linear mixed model analysis demonstrated that the MDP magnitude of multifactorial variables were approximately 8–28% and 8–21% lower across the match and halves, respectively, compared to the MDP of their respective univariate constituent variables ($p \leq 0.001$; $r = 0.26–0.62$). The greatest differences between the respective multifactorial and discrete constituent variables were observed for sprinting (-28%) and high-intensity acceleration (-22%). The results reveal that the MDP is distinguished based on peak kinematic and mechanical demands, which occur at discrete periods and exhibit distinct locomotor profiles across the match and within each half. Practitioners should consider the methods of identifying the MDP, as the selection of univariate and multifactorial kinematic and mechanical performance variables can impact MDP characterization, which can qualify the designing of bespoke training protocols.

CITATION: Yousefian F, Zafar A, Fransson D et al. Characterizing the most demanding passages of kinematic and mechanical activity in elite football: a multifactorial approach. Biol Sport. 2024;41(4):41–50.

Received: 2023-08-23; Reviewed: 2023-09-12; Re-submitted: 2023-11-04; Accepted: 2024-01-29; Published: 2024-03-17.

Corresponding author:
Farzad Yousefian
Research Centre in Sports Sciences, Health Sciences and Human Development (CIDESD), Department of Sport Sciences, University of Beira Interior, Covilhã, Portugal
E-mail: Farzad.yousefian@ubi.pt

ORCID:
Farzad Yousefian
0000-0001-7894-3728

Abdullah Zafar
0000-0002-7872-7715

Dan Fransson
0000-0002-1798-0338

Magni Mohr
0000-0002-1749-8533

João Brito
0000-0003-1301-1078

Bruno Travassos
0000-0002-2165-2687

Key words:
Most intense periods
GPS
Match demands
Performance
Team sports

INTRODUCTION

In recent years, numerous studies have employed tracking system microtechnologies, such as global positioning systems (GPS), to describe the physical demands of elite football players during matches [1], offering insights for training design [2]. Given the stochastic nature of football, physical demands on players continuously fluctuate in magnitude, effort, and time due to changing game dynamics [3, 4], leading to differential intensity patterns and the most demanding passages (MDP) of physical activity [5–8]. Thus, a comprehensive understanding of the MDP can inform effective training design to ensure optimized performance and minimized risk to injury when preparing players for competition [6, 9].

Current research supports the use of a continuous moving average method for robust MDP identification during matches compared to fixed length method [5, 8, 9, 10]. A fixed length method splits the match into fixed periods (e.g., for 5 min periods: 0–5 min, 5–10 min, etc.), while a moving average method considers the

maximal load across a given time point second by second (e.g., a 5 min period at 1Hz sampling frequency would include 300 data points: 0–299, 1–300, 2–301, etc.). For instance, Varley et al. [8] found a 25% underestimation of peak high-intensity running (HIR; > 15 km/h) distance using fixed length windows compared to a moving average approach. Similarly, more recent studies have revealed significant underestimations of the MDP of total distance and high-speed running distance by as much as 7% and 22%, respectively by fixed length compared to a moving average method [5, 7].

Several researchers have explored MDP of external load performance variables (running distances and accelerations/decelerations) across various thresholds (e.g., > 15 km/h, > 19.8 km/h, > 25.2 km/h, > 3 m/s^2, < -3 m/s^2) and time windows (1 to 10 min) [5, 7, 8, 9, 11]. For example, the 5 min MDP in elite male football have been reported for total distance (~130–150 m/min), moderate-speed running (> 15 km/h; 35.4 ± 18.2 m/min), high-speed running (> 19.8 km/h; ~20 m/min), average acceleration/deceleration (~0.60 m/s^2), and the number of high-intensity acceleration (> 3 m/s^2; 2 n/min) and deceleration (< -3 m/s^2; 2 n/min) [5, 7, 8, 11, 12, 13]. The temporal distribution of MDP has also been investigated recently, with the authors of the studies reporting that highest frequencies of peak total distance and acceleration load (average acceleration/deceleration) occur within the first 15 min of the match and each half, across peak 1 min to 10 min durations, whereas HSR distribution is uniformly distributed [12, 14, 15]. When analyzed according to 3 min durations, Novak et al. [16] reported peak total distance and sprinting distance were associated with earlier and later occurrences within the half, respectively, while no association with match half was observed for HSR [16]. However, methodological differences, including the use of different performance variables and moving average time windows limit direct comparisons between studies.

More specifically, existing research examines MDP individually as discrete univariate metrics, limiting their application in training session design and neglecting MDP periods whereby multiple variables interact and may occur concurrently [9, 16, 17]. Translating findings to training is thus restricted, particularly to ensure the intended transfer to the context of performance. Thus, it may be relevant to identify the MDP by using a multifactorial criterion variable which encompasses the concurrent occurrence of different high-intensity velocity-based (kinematic) or mechanical (rate of change in velocity; acceleration and deceleration) external load constituent variables simultaneously. This approach may be supported by a theoretical framework proposed by Vanrenterghem et al., [18], whereby kinematic (measures of distance across speed thresholds) and mechanical (measures of acceleration/deceleration magnitudes) loads are uncoupled to better understand their relative contributions underpinning different load-adaptation pathways. In effect, targeting the specific pathways, in terms of training prescription, and monitoring their relative contributions to the locomotor profile of players during the match, could better inform player performance monitoring and preparation. The relationship between the multifactorial most demanding kinematic (MDPk) and mechanical (MDPm) variables and the MDP of their respective constituent variables as discrete variables can be investigated in terms of their timing, interaction, and magnitude. In fact, studies highlight the effectiveness of sport-specific conditioning drills (e.g., small-sided games) for high transfer of demands between training sessions and performance context according to coach-intended game dynamics compared to specific/isolated running drills (e.g., interval and repeated sprint training) [9, 17, 19, 20]. Therefore, a multifactorial analysis of MDP may be more relevant in performance settings through enhancing performance monitoring strategies of players during such commonly applied training drills and provide further insight towards improving the methodologies and application of the MDP in elite football.

Thus, a multifactorial analysis approach based on capturing concurrent MDP of discrete high-intensity kinematic (MDPk) and mechanical (MDPm) variables within match dynamics is suggested. This study proposes and tests a multifactorial analysis to identify and characterize 5-minute MDP of high-intensity activity in elite male football based on concurrent kinematic and mechanical performance variables. Based on this approach, the aims of the study were to describe the frequency distribution of the respective multifactorial performance variables MDPk and MDPm; and to understand the relationship between the MDP of the multifactorial metrics and their respective discrete univariate variables in terms of their timing of occurrence and relative magnitude. We hypothesize a similar temporal distribution for MDPk and MDPm, with a greater frequency of MDP cases occurring at the start of the match and within each half. Furthermore, we hypothesize that there will be small differences in terms of timing and magnitude between univariate and multivariate constituent variables, with the MDP instances occurring within relatively close proximity.

MATERIALS AND METHODS

Study Design

A retrospective study was conducted using tracking data collected from two teams in the Swedish first division (*Allsvenskan*) during the 2020 and 2021 seasons. Prior to the start of the investigation, players were verbally informed of the aims of the study and permission to use collected data was obtained from the participating players and clubs. Ethical approval of the study was obtained from the ethics review committee of the University of Gothenburg (#2021-05974-01), and the study was conducted in accordance with the principles of the Declaration of Helsinki.

Participants

A total of 39 professional male football players (mean ± standard deviation: age: 27.9 ± 4.5 years; height: 182. 6 ± 5.9 cm; weight: 74.7 ± 6.0 kg) participated in the study. Data were collected from 45 competitive matches of the 2020 (7 matches) and 2021 (38 matches) seasons, resulting in 329 match observations (mean ± standard deviation: 8.4 ± 6.8 observations per player; range: 1–24). Only

outfield players who completed the total duration of the match were included in the study.

Procedure

Match-play locomotor data was collected using 10-Hz GPS devices (Catapult Vector S7, Catapult Sports, Melbourne, Australia). The GPS devices have been reported as valid and reliable to measure force-velocity profiles [21] and the inter-device reliability for distance, peak velocity and average acceleration was reported as *good* (%CV: 0.1–3.9%) [22]. The 10 Hz devices demonstrated to be reliable and acceptable for tracking soccer specific movement including instantaneous velocity, maximum instantaneous velocity, as well acceleration and decelerations [23, 24]. Prior to the start of every match, all devices were calibrated according to the manufacturer's instructions, and placed between the players' shoulder blades in tightly fitted vests during the match. Throughout the study, each player wore the same GPS unit to avoid inter-unit variation. Following each match, raw GPS data were downloaded using the manufacturer's proprietary software and analyzed using customized Microsoft Excel spreadsheets and Python 3.9 software. Data underwent satellite connectivity check before raw data analysis; instances with fewer than eight connected satellites were excluded.

Performance Variables

A moving average method was used to identify the MDP across 5 min considering univariate kinematic (running distance covered) and mechanical (acceleration/decelerations) performance variables including moderate-speed running (MSR; 15–19.8 $km \times h^{-1}$), high-speed running (HSR; > 19.8–25.2 $km \times h^{-1}$), and sprinting (SPR; > 25.2 $km \times h^{-1}$) distances, as well as high-intensity acceleration (ACC; ≥ 3 $m \times s^{-2}$) and high-intensity deceleration (DEC; ≤ -3 $m \times s^{-2}$) metrics, in accordance with previous studies [11, 25]. The MDPk metric was identified based on the total distance covered at running speed > 15 km $h^{-}1$, thus consisting of the maximal sum of the moving average across a 5 min period of MSR, HSR, and SPR. Alternatively, the MDPm metric was identified based on the maximal absolute sum of the moving average across a 5 min period of high-intensity acceleration and deceleration efforts (≥ 3 $m \times s^{-2}$). The selected 5 min duration, as well as the kinematic velocity thresholds and mechanical acceleration thresholds were selected in accordance with previous related studies [11, 15]. Any additional time at the end of each half was removed prior to the analysis. The moving average included a 300 s window, based on the 10 Hz sampling frequency of the GPS devices, therefore, any period at the end of each half with less than 300 s was not included in the analysis [12]. The frequency distribution of MDPk and MDPm were analyzed based on their respective peak period commencement time and binned into discrete 5 min periods for each half and the match. Differences in the commencement time between MDPk and MDPm and their respective univariate constituent variables were investigated within halves and the match. Subsequently, magnitude differences between MDPk and MDPm and their respective constituent variables were analyzed across halves and the match.

Statistical Analyses

The frequency distribution of MDPk and MDPm across the match and for each half were assessed using Pearson chi-square Goodness-of-Fit tests. The magnitude of statistical difference from a hypothetical equal distribution was assessed using Cohen's *W* effect size. Binomial tests conducted pairwise comparisons of 5 min intervals following chi-square analysis. Bonferroni adjustments were applied to control for multiple comparisons and type I error, yielding adjusted α-levels of $p \leq 0.0004$ for across match and $p \leq 0.002$ for within-half analyses. Magnitude of significance was evaluated using Cohen's *h* effect size [26].

Subsequently, the MDP of univariate metrics were compared with the MDPk and MDPm regarding their occurrence in the period within each half and across the match using standardized mean differences and ± 95% confidence intervals (± 95%CI). The magnitude of the differences was interpreted according to Cohen's *d* effect size criteria: 0.2–0.5, small; 0.5–0.8, medium; and > 0.8, large.

Finally, differences in magnitude between the MDPk and MDPm and their respective constituent variables for each half and the match were assessed using linear mixed models. For each model, normality of the residuals was evaluated using a combination of the Kolgomorov-Smirnoff test and inspection of the Q-Q plots. In all models, the 'player' and 'match' were specified as random effects and fixed effects included match half, and 'period' (i.e., the peak performance variable as either a univariate or multifactorial constituent variable) [16]. Non-normally distributed data were log-transformed to reduce the non-uniformity of error and back-transformed in the presented results. Where significance was detected, multiple pairwise comparisons were assessed using Bonferroni *post-hoc* tests. Effect size correlations (*r*) were calculated from the linear mixed model *t* statistics and interpreted based on the following criteria: < 0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large [27]. The % coefficient of variation (%CV) was also calculated as the standard deviation divided by the mean multiplied by 100%. Data are presented as mean ± SD, and the α-level was set at $P \leq 0.05$, unless otherwise stated. All statistical analyses were performed using IBM SPSS for Windows statistics version 25.0 (IBM Corp., Armonk, NY, United States).

RESULTS

Frequency distribution

The frequency distributions of MDPk and MDPm across the match and for each half are presented in Figure 1. MDPk showed large significant differences across the match (χ^2 (15, N = 329) = 135.88, $p \leq 0.001$, W: 0.64) and in the first half (χ^2 (7, N = 329) = 86.05, $p \leq 0.001$, W: 0.51). Medium effect size differences were observed in the second half (χ^2 (7, N = 329) = 68.40, $p \leq 0.001$, W: 0.46). MDPm showed medium effect size differences across the match

(χ^2 (15, N = 329) = 31.02, p ≤ 0.001, W: 0.31) and small differences only in the first half (first half: χ^2 (7, N = 329) = 22.78, p ≤ 0.001, W: 0.26; second half: χ^2 (7, N = 329) = 11.26, p = 0.26).

The highest frequency of MDPk and MDPm was observed in the first 5 min of the match (MDPk: ~18% of total cases; 101.21 ± 25.1 s; MIPm: ~11%; 115.99 ± 32.7 s. Within the halves, the highest MDPk frequency was observed in the first 5 min of each half (first half: ~28%; 111.47 ± 19.8 s; second half: ~26%; 3159.17 ± 19 s), with ~54% and ~52% of total cases occurring in the first 15 min of each half. Regarding the MDPm, the highest frequency occurred in the first 5 min of the first half (~20%; 105.18 ± 23.3s), and in the second 5 min period of the second half (~16%; 3152.14 ± 22.4s), with ~44% and ~42% of total cases occurring in the first 15 min of each respective half.

Timing of occurrence

Figure 2 presents the mean ±95%CI differences in the timing of occurrence between MDPk, MDPm and the MDP of their respective univariate constituent variables, across the match and within each half. Differences in the timing of occurrence considered the reference point (time 0) as the commencement time of either MDPk and MDPm, with positive and negative values indicating the occurrence of each univariate variable MDP after and before either MDPk or MDPm, respectively.

Overall, the timing of occurrence between MDPk and MDPm revealed small effect size differences in the overall match analysis (-3 75.67 ± 222.4 s (d:0.25 ± 0.15)). Trivial differences were observed in the analysis of the first half (-122.14 ± 109.1 s (d: 0.17 ± 0.15)), and second half (-101.0 ± 97.8 s (d:0.15 ± 0.14)). The results indicate that overall MDPm tend to occur after MDPk with the ± 95%CI range differences of 444.8 s across the match and ~218 s for the first half and ~196 s for the second half.

The MDPk constituent variables SPR and HSR occurred outside of the 5 min periods surrounding the timing of occurrence of MDPk, while the MSR occurred within the 5 min periods. Small significant differences were observed between MDPk and SPR (496.99 ± 224.2 s (d: 0.33 ± 0.2–0.5)), and HSR (379.01 ± 177.98 s (d: 0.26 ± 0.13–0.38)). No significant differences were observed between MDPk and MSR (Figure 2a). The MDPm constituent variables occurred within the 5 min periods surrounding the timing of occurrence of MDPm. Trivial differences were observed between MDPm

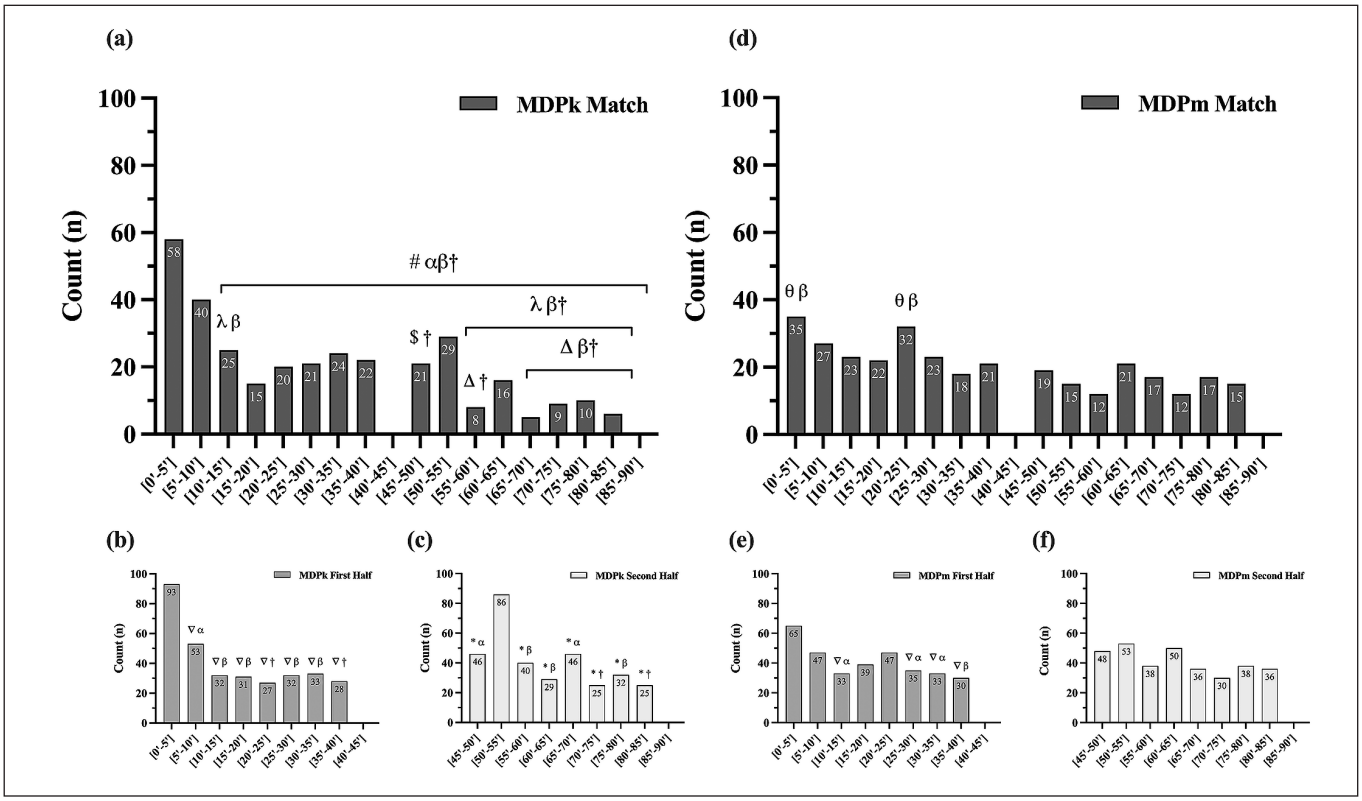


FIG. 1. Frequency distribution of MDPk across the (a) match, (b) first half, and (c) second half, and MDPm across the (d) match, (e) first half, and (f) second half. # Significantly different to [0'-5'] (p ≤ 0.0004), λ Significantly different to [5'-10] (p ≤ 0.0004), $ Significantly different to [65'-70'] (p ≤ 0.0004); Δ Significantly different to [50'-55'] (p ≤ 0.0004); θ Significantly different to [55'-60'] and [70'-75'] (p ≤ 0.0004), ∇ Significantly different to [0'–5'] (p ≤ 0.002). * Significantly different to [50'-55'] (p ≤ 0.002). Effect size (h): 0.2–0.5, small (α); 0.5–0.8, medium (β), > 0.8, large (†).

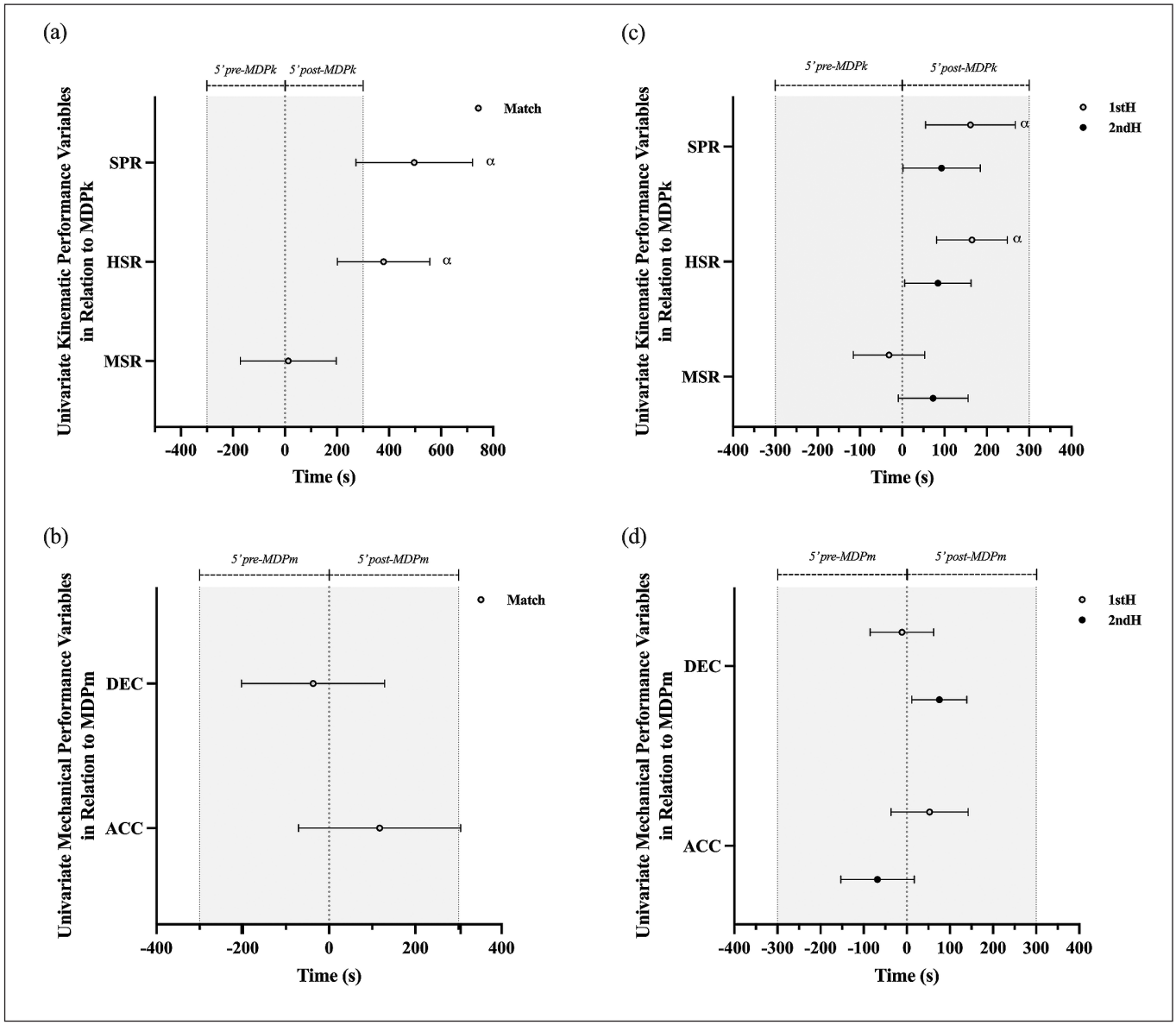


FIG. 2. Differences (mean ± 95%CI) between the peak period commencement time of univariate kinematic and mechanical performance variables and the perspective multifactorial metrics (shown as the reference point at time 0) for the match (a-b) and each half (c-d). Shaded areas represent the 5-min period *pre-* (occurring *before*) and *post-* (occurring *after*) peak period commencement time of the specific multifactorial variable (reference time 0 point). Effect size (*d*) 0.2–0.6, small (α).

and both ACC (117.19 ± 187.7 s (*d*: 0.08 ± -0.1–0.2) and DEC (-36.90 ± 66.1 s (*d*: 0.02 ± -0.1–0.13)) across the match (Figure 2b).

The analysis between halves revealed that the MDPk constituent variables occurred within the 5 min periods surrounding the timing of occurrence of MDPk, with differences in time smaller in the second half compared to the first half. Specifically, the 95%CI range of the time difference between MDPk and the respective kinematic constituent variables (MSR, HSR, and SPR) decreased from 383.3 s in the first half to 193.8 s in the second half, indicating closer proximity in their occurrences in the second half. Small significant differences were observed between MDPk and HSR (first half: 165.14 ± 83.6 s (*d* ± 95%CI: 0.21 ± 0.1–0.3); second half: 84.42 ± 78.4 s (*d*: 0.12 ± 0.01–0.2)) and SPR (first half: 161.22 ± 106.2 s (*d*: 0.21 ± 0.1–0.4); second half: 93.14 ± 91.2 (*d*: 0.14 ± 0.00–0.3)) (Figure 2c).

In line with previous results, the MDPm constituent variables occurred within the 5 min periods surrounding the timing of occurrence of MDPm, with differences in time smaller in the second half compared to the first half. The 95%CI range of the time difference

between MDPm and the respective mechanical constituent variables (ACC and DCC) slightly increased between halves (first half: 226.9 s; second half: 292.3 s). However, no significant differences were observed between the time of MDPm and ACC (first half: 52.78 ± 89.4 s (*d*: 0.07 ± -0.1–0.20); second half: -67.96 ± 85.2 s (*d*: 0.09 ± -0.0–0.2)) and DEC (first half: -11.26 ± 73.49 s (*d*: 0.02 ± -0.1–0.12); second half: 75.38 ± 63.80 s (*d*: 0.11 ± 0.02–0.2)) within each half (Figure 2d).

Magnitude

Differences in magnitude between MDPk, MDPm and the MDP of their respective univariate variables are presented in Table 1. Generally, the magnitude of the MDPk and MDPm in comparison with MDP univariate variables were small ($p \leq 0.001$; *r*: 0.14–0.30) across the match. The percentage differences between multifactorial and discrete performance variables were approximately MSR: 15.0%; HSR: 19%; SPR: 39%; ACC: 29%; and DEC: 8%, with greater values observed for the univariate MDP metrics. MDPk was composed of approximately ~58% MSR, ~30% HSR, and ~12% SPR, while the percentage composition of MDPm was approximately ~36% acceleration and ~64% deceleration.

The magnitudes of MDPk and MDPm decreased significantly between halves (~9–10%), with small to moderately greater values observed in the first half ($p \leq 0.001$; $r = 0.24$–0.30). There were no significant interaction effects for *half* × *period* across all performance variables. However, small to moderately significant ($p \leq 0.001$; $r = 0.26$–0.44) main effects were observed for periods, indicating that the peak magnitude of the MDPk and MDPm were lower than their respective univariate metrics across halves. Differences between the MDPk and MDPm and the MDP of their respective univariate metrics were approximately: MSR: 12%; HSR: 21%; SPR: 20%; ACC: 26%, and DEC: 9%.

Significant ($p \leq 0.001$) main effects were also observed for halves, with small significant decreases ($p \leq 0.001$; $r = 0.11$–0.28) observed in the second half for all variables, except for SPR ($p > 0.05$) and ACC ($p = 0.01$, $r = 0.07$). Differences between halves were similar for MDPk and MDPm, by approximately 9%.

DISCUSSION

In this study, a multifactorial analysis approach based on capturing concurrent MDP of discrete high-intensity kinematic (MDPk) and mechanical (MDPm) variables within match dynamics, is suggested. This study proposes and tests a multifactorial analysis to identify and characterize 5 min MDP of high-intensity activity in elite male football based on the concurrent occurrences of kinematic (MDPk) and mechanical (MDPm) performance variables. To the best of our knowledge, this study is the first to attempt the identification of MDPk and MDPm periods within multifactorial MDP performance variables. Our key findings demonstrate that the 5 min MDP are distinguished through peak kinematic and mechanical demands, which occur at distinct periods with unique locomotor profiles across both the match and each half. In line with our hypotheses the temporal distribution for MDPk and MDPm revealed greater frequency of MDP cases occurring at the start of the match and within each half. Regarding the timing of the MDP between multifactorial and respective univariate constituent variables, a closer proximity of occurrences was observed

TABLE 1. Comparison (mean ± standard deviation (%CV)) between the MDP of multifactorial variables and their respective constituent variables for the match and each half.

Metric	Period	Match	First Half	Second Half
MDPk (m)		221.05 ± 53.62 (24.30%)	210.91 ± 56.37 (26.70%)	191.51 ± 51.55 (26.90%) **β
MSR	**MDPk (m)**	129.34 ± 40.27 (31.10%) ##α	126.52 ± 40.33 (31.90%)	112.20 ± 34.18 (30.50%) **β
	MDP (m)	148.74 ± 35.85 (24.10%)	141.63 ± 36.14 (25.50%)	126.51 ± 33.09 (26.20%) **β
HSR	**MDPk (m)**	69.64 ± 31.46 (45.20%) ##α	60.87 ± 27.32 (44.90%)	57.45 ± 27.26 (47.40%) **α
	MDP (m)	83.19 ± 27.98 (33.60%)	73.46 ± 26.00 (35.40%)	69.09 ± 24.89 (36.00%) **α
SPR	**MDPk (m)**	29.78 ± 18.81 (63.16%) ##α	28.76 ± 22.6 (78.56%)	28.34 ± 22.49 (79.35%)
	MDP (m)	41.30 ± 22.28 (53.94%)	35.57 ± 23.71 (66.68%)	32.64 ± 21.97 (67.31%)
MDPm ($m \cdot s^{-2}$)		0.066 ± 0.019 (29.50%)	0.061 ± 0.019 (31.70%)	0.055 ± 0.017 (31.30%) **α
ACC	**MDPm ($m \cdot s^{-2}$)**	0.024 ± 0.012 (50.00%) ##α	0.021 ± 0.011 (50.50%)	0.020 ± 0.010 (53.10%) *
	MDP ($m \cdot s^{-2}$)	0.031 ± 0.010 (32.80%)	0.026 ± 0.010 (37.50%)	0.025 ± 0.009 (37.70%) *
DEC	**MDPm ($m \cdot s^{-2}$)**	-0.044 ± 0.016 (35.62%) ##α	-0.039 ± 0.014 (36.80%)	-0.036 ± 0.013 (37.60%) **α
	MDP ($m \cdot s^{-2}$)	-0.047 ± 0.015 (31.31%)	-0.043 ± 0.013 (29.70%)	-0.039 ± 0.013 (33.30%) **α

$p \leq 0.001$; # $p \leq 0.05$, significantly different than discrete univariate MDP. ** $p \leq 0.001$; * $p \leq 0.05$, significantly different than the first half. Effect size (*r*): 0.1–0.3, small (α) and 0.3–0.5, moderate (β). Data presented as mean ± standard deviation (%CV).

for mechanical than kinematic variables across the match. The magnitude of univariate MDP were greater than their respective constituent counterparts within the multifactorial MDP, however only by small effect size differences. Overall, our results highlight that the selection of multifactorial MDP criterion variables has implications in terms of its distribution throughout the match, as well as the timing and magnitude differences between its constituent variables and their univariate MDP counterparts.

The frequency analysis of multifactorial MDP aligns with previous research that explored the temporal distribution of MDP in elite football, although our approach considered kinematic and mechanical MDP as multifactorial performance variables, MDPk and MDPm respectively [4, 10, 12, 14, 15, 16]. Both MDPk and MDPm frequencies peak in the initial first 5 minutes of the match and the first half, however, the distribution patterns differ markedly in the second half. Notably, MDPk frequency peaks in the second 5 minutes of the second half. The MDPk distribution may be related to decreased muscle temperature during half-time intervals [28], impacting activities requiring a high rate of force development [29], such as sprinting. Accordingly, research by Novak et al. [16] associated 3 minute peak total distance and sprinting distance with earlier and later occurrences in the match and half, respectively, while peak high-speed running distance was more uniformly distributed. Fransson et al. [10] also observed similar distribution patterns for high velocity running distances across varying time periods. Collectively, these findings suggest that high velocity kinematic thresholds distribute more uniformly compared to lower-velocity thresholds [4, 10, 12, 14, 15, 16].

In contrast, MDPm demonstrates a more uniform distribution in the second half, potentially linked to the elevated metabolic cost and mechanical load associated with intense acceleration and deceleration efforts [19, 25, 30–32]. Players might strategically pace themselves and perform such efforts based on match context and at lower velocities (< 15 km/h), which might not coincide with the high velocity running efforts encompassed in MDPk. Correspondingly, a study of elite Australian soccer players demonstrated that ~85% of maximal accelerations did not surpass high-velocity thresholds (> 15 km/h) [25]. Therefore, variations in match running performance distribution could stem from the association of high-intensity actions with critical moments in the game, such as the creation or defense of goal-scoring opportunities [4]. Moreover, player-adapted pacing strategies may prioritize energy conservation for high-intensity runs at the expense of lower-velocity efforts [33]. As such, greater running distances at moderately high speeds early in the match may be strategic, while higher-velocity threshold efforts could be context-dependent throughout the game.

Comparisons of the timing occurrences between multifactorial (MDPk and MDPm) and their respective univariate constituent variables (MSR, HSR, SPR, ACC and DEC) revealed a decrease in the differences between kinematic variables between halves. Conversely, the time of occurrence between mechanical variables remained relatively consistent within each half and the match. Therefore, unlike kinematic variables, mechanical univariate peak periods aligned within the 5 min windows surrounding MDPm across the match and halves. However, the greater alignment of kinematic variables in the second half suggests that their clustering may be related to changes in match context, pacing strategies, or exercise tolerance, which may enable players to conserve energy for high-intensity activity [4, 33].

Comparative analysis between multifactorial and univariate performance variables indicated that the peak 5 min MDP magnitude was slightly greater when analyzed discretely, displaying small to moderate effect sizes, with reductions across the match and halves. Such difference could potentially be attributed to variations in MDP match dynamics between kinematic and mechanical variables. Discrete activities may be performed with greater intensity when examined individually rather than as multifactorial variables. For example, the higher magnitude of HSR may be due its occurrence at a greater intensity (or perhaps duration) elsewhere during the match to when the specified HSR (> 19.8–25.2 km/h) thresholds are concurrently considered with MSR (15–19.8 km/h) and SPR (≥ 25.2 km/h) thresholds within MDPk. This observation is further supported by the timing differences between MDPk and HSR, throughout the match. Such discrepancies might arise from methodological differences in identifying the MDP match running performance, especially concerning threshold selection, and moving average durations [7, 11, 10, 15]. These outcomes necessitate further investigation into the practical significance of magnitude differences between univariate and multifactorial performance variables.

Interestingly, the magnitude of all multifactorial and univariate constituent variables, except for SPR, decreased significantly between halves. The relative maintenance of SPR between halves may indicate that observed reductions in variables might not be solely due to physiologically mediated fatigue alone but may also be influenced by pacing strategies and match context [33]. The decrease in the magnitude of peak kinematic and mechanical performances between halves should be approached cautiously, as factors such as variations in effective playing time and periods of inactivity can influence these reductions [34, 35]. To attribute any performance reductions to fatigue in relation to observed changes, future studies should account for the specific relative time of play and players' work rate [34].

The analysis also reveals high variability associated with the timing and magnitude of the presented variables. Examination of time differences between the commencement of multifactorial and univariate MDP variables demonstrates exceptionally high variability. For example, the variability between MDPk and the MDP of univariate kinematic constituent variables in the first half, across 45 matches, were 1660% (MSR), 757% (HSR), and 533% (SPR). In terms of magnitude, the variability for MDPk and MDPm across the match, and the halves, were similar. However, multifactorial constituents exhibit greater variability compared to their univariate counterparts across the match and halves, with SPR displaying the highest

variability. Despite differences in the window durations investigated, our results are comparable with and exhibit similar trends to previously reported variability of peak 3 min univariate variables [16], such as HSR and SPR. These disparities likely result from distinct match-specific contextual variables and tactical roles that underlie players' unique locomotor patterns. The high variability observed in time differences between the times of occurrence of the 5 min peak multifactorial and their respective univariate constituent variables underscores the non-concurrent nature of MDP across players, a notion previously highlighted [16].

The distinct approach of the study lies in considering the concurrent occurrence of univariate kinematic and mechanical performance variables as multifactorial variables, providing a robust means of identifying the 5 min peak locomotor performance during match play. However, the selection of multifactorial constituent variables may be related to the specific team or individual players analyzed, as they may differentially influence the distribution, magnitude, and composition of the respective multifactorial variables. For instance, while the peak multifactorial kinematic performance variable (MDPk) consisted of approximately ~58% MSR, ~30% HSR, and ~12% SPR running distances, and the peak multifactorial mechanical variable (MDPm) was composed of ~36% acceleration and ~64% deceleration, this may not remain constant across the match, for all players, and all observed MDP. Our findings, indicating changes between halves across all variables, reinforce the notion that the degree of constituent variable contribution to the respective MDPk and MDPm composition may fluctuate throughout the match, and may be influenced by other contextual factors. Differences and changes in terms of constituent variables could potentially influence their match distribution. Thus, future investigations should analyze the temporal distribution and percentage composition of peak multifactorial locomotor activities across the match to gain a more comprehensive understanding of dynamic locomotor performance patterns and how specific contextual variables can influence the distribution and magnitude of multifactorial constituent variables. Moreover, the practical significance of magnitude differences between univariate and multifactorial performance variables requires further exploration. The trade-off is that while our multifactorial analysis provides a robust approach to identifying the MDP through the concurrent occurrence of specific high-intensity kinematic and mechanical demands – which more accurately reflects competitive match scenarios – the discrete univariate analysis of MDP may be more relevant for precisely targeting specific locomotor activities.

Consequently, future studies and practitioners should consider adopting a multifactorial approach to identify kinematic and mechanical MDP across different durations and univariate constituent variables. The influence of univariate constituent variables on multifactorial MDP distribution profiles requires further investigation. It is plausible that the composition and degree of contribution of specific univariate constituent variables within multifactorial variables may vary temporally and be influenced by tactical and contextual variables during the match. For example, recent studies have highlighted that peak locomotor activities are significantly influenced by various contextual factors (e.g., tactical positions, match half, match outcome, tactical formation, possession, and phases of the game), which were not considered in the current study [13, 35–38]. Understanding the dynamics of multifactorial MDP composition profiles could further inform training prescription by enhancing ecological validity and representative design. Such adjustments may facilitate the implementation of specific task constraints in conditioning games to replicate match demands more accurately [9, 17, 20]. The incorporation internal load response (e.g., heart rate and sessional rate of perceived exertion (s-RPE) and individualized locomotor thresholds, which were not considered in our study, would further our understanding of the individualized performance and response to peak periods during competition [2, 16]. It is also imperative to acknowledge and account for sources of variability in future studies, incorporating a larger number of teams and players to enhance the generalizability of the findings. An additional limitation of our study was the analysis of two teams from the same professional league, and thus practitioners should take caution when interpreting the results. Lastly, the proposed approach underscores that kinematic and mechanical MDP in football are multifactorial and can be holistically analyzed to provide more effective insights for team and player performance monitoring and training prescription.

Therefore, the current study supports the use of multifactorial kinematic and mechanical MDP performance variables composed of relevant univariate performance variables to enhance the monitoring and prescription of training sessions. Such an approach allows the monitoring of several relevant independent (univariate) variables simultaneously. Practitioners may benefit from such an approach as the multifactorial MDP variables reflect the concurrent occurrence of demands across multiple velocity thresholds (kinematics) or considers both high-intensity accelerations and decelerations (mechanical). Prescribing training based on the MDP of match play through conditioning drills, such as small to large-sided games, may therefore be more effectively monitored as changes in the respective multifactorial MDP composition can be assessed to better target specific locomotor activities [9, 17, 18, 20, 35]. For example, a recent study by Martin-Garcia et al., [20] reported that specific locomotor activities are differentially trained (stimulated) depending on the format of conditioning drills based on match MDP, whereby small format games stimulate mechanical activity (acceleration and deceleration), while high-speed running and sprinting activities are stimulated in large format games. Practitioners may extend the findings in this study to better understand how the multifactorial MDP and its corresponding composition, regarding the constituent variables, change through consecutive drills. Monitoring the timing and changes in the magnitude and composition of kinematic and mechanical multifactorial MDP can provide further insight surrounding the development of transient fatigue during the match and residual fatigue and recovery strategies following the match.

CONCLUSIONS

In conclusion, this study introduces a novel approach that considers the concurrent occurrence of univariate kinematic and mechanical performance variables as multifactorial variables, namely MDPk and MDPm. Our findings contribute to understanding that peak locomotor demands can be distinguished based on kinematic and mechanical profiles which are multidimensional, reflecting the concurrence of various locomotor activities. The influence of univariate constituent variables on multifactorial metrics' frequency distribution as well as the composition may shift over time. Thus, the selection of univariate metrics could influence the contribution and composition of peak multifactorial kinematic and mechanical performance variables throughout the match. Identifying changes in the multifactorial metrics' constituent variables may be relevant for targeting specific locomotor activities and identifying their influence on transient and residual fatigue development. Ultimately, this approach contributes to a more precise understanding of peak locomotor activity patterns, informing player performance monitoring and training design.

Conflict of Interest

The authors declared no conflict of interest.

REFERENCES

1. Reynolds J, Connor M, Jamil M, et al. Quantifying and comparing the match demands of U18, U23, and 1ST team English professional soccer players. Front Physiol. 2021; 12:706451.
2. Rago V, Brito J, Figueiredo P, et al., Methods to collect and interpret external training load using microtechnology incorporating GPS in professional football: a systematic review. Res Sports Med. 2020; 28(3):437–458.
3. Bradley P, Ade J. Are current physical match performance metrics in elite soccer fit for purpose or is the adoption of an integrated approach needed? Int J Sport Physiol. 2018; 13(5):656–664.
4. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sport Sci. 2003; 21(7):519–528.
5. Fereday K, Hills, SP, Russell M, et al. A comparison of rolling averages versus discrete time epochs for assessing the worst-case scenario locomotor demands of professional soccer match-play. J Sci Med Sport. 2020; 23(8):764–769.
6. Gabbett TJ, Kennelly S, Sheehan J, et al. If overuse injury is a 'training load error', should undertraining be viewed the same way? Brit J Sport Med. 2016; 50(17):1017–1018.
7. Oliva-Lozano JM, Martín-Fuentes I, Fortes V, et al. Differences in worst-case scenarios calculated by fixed length and rolling average methods in professional soccer match-play. Biol Sport 2021; 38(3):325–331.
8. Varley MC, Elias GP, Aughey RJ. Current match-analysis techniques' underestimation of intense periods of high-velocity running. Int J Sport Physiol. 2012; 7(2):183–185.
9. Whitehead S, Till K, Weaving D, et al. The use of microtechnology to quantify the peak match demands of the football codes: a systematic review. Sports Med. 2018; 48:2549–2575.
10. Fransson D, Krustrup P, Mohr M. Running intensity fluctuations indicate temporary performance decrement in top-class football. Sci Med Footb. 2017; 1(1):10–17.
11. Delaney JA, Thornton HA, Rowell AE, et al. Modelling the decrement in running intensity within professional soccer players. Sci Med Footb. 2018; 2(2):86–92.
12. Schimpchen J, Gopaladesikan S, Meyer T. The intermittent nature of player physical output in professional football matches: an analysis of sequences of peak intensity and associated fatigue responses. Eur J Sport Sci. 2021; 21(6):793–802.
13. Casamichana D, Castellano J, Diaz AG, et al. The most demanding passages of play in football competition: a comparison between halves. Biol Sport. 2019; 36(3):233–240.
14. Thoseby B, Govus A, Clarke A, et al. Temporal distribution of peak running demands relative to match minutes in elite football. Biol Sport. 2021; 39(4):985–994.
15. Oliva-Lozano, J. M., Martínez-Puertas, H., Fortes, V., et al. When do soccer players experience the most demanding passages of match play? A longitudinal study in a professional team. Res Sports Med 2021; 31(2):101–111.
16. Novak AR, Impellizzeri FM, Trivedi A, et al. Analysis of the worst-case scenarios in an elite football team: Towards a better understanding and application. J Sport Sci. 2021; 39(16):1850–1859.
17. Weaving D, Young D, Riboli A, et al. The Maximal Intensity Period: Rationalising its Use in Team Sports Practice. Sports Med. 2022; 8(1):1–9.
18. Vanrenterghem J, Nedergaard NJ, Robinson MA, et al. Training load monitoring in team sports: a novel framework separating physiological and biomechanical load-adaptation pathways. Sports Med. 2017; 47:2135–2142.
19. Dalen T, Sandmæl S, Stevens T, et al. Differences in acceleration and high-intensity activities between small-sided games and peak periods of official matches in elite soccer players. J Strength Cond Res. 2021; 35(7):2018–2024.
20. Martin-Garcia A, Castellano J, Diaz AG, et al. Positional demands for various-sided games with goalkeepers according to the most demanding passages of match play in football. Biol Sport. 2019; 36(2):171–180.
21. Clavel P, Leduc C, Morin JB, et al. Concurrent validity and reliability of sprinting force–velocity profile assessed with GPS devices in elite athletes. Int J Sport Physiol. 2022; 17(10):1527–1531.
22. Crang ZL, Duthie G, Cole MH. The inter-device reliability of global navigation satellite systems during team sport movement across multiple days. J Sci Med Sport. 2022; 25(4):340–344.
23. Varley MC, Fairweather IH, Aughey RJ. Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. J Sport Sci. 2012; 30(2):121–127.
24. Cormier P, Tsai MC, Meylan C, et al. Concurrent validity and reliability of different technologies for sprint-derived horizontal force-velocity-power profiling. J Strength Cond Res. 2023; 37(6):1298–1305.
25. Varley MC, Aughey RJ. Acceleration profiles in elite Australian soccer. Int J Sports Med. 2012; 34(3):34–39.
26. Rosnow RL, Rosenthal R. Effect sizes for experimenting psychologists. Can J Exp Psychol. 2003; 57(3):221–237.
27. Hopkins W, Marshall S, Batterham A, et al. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1):3–12.
28. Mohr M, Krustrup P, Nybo L, et al. Muscle temperature and sprint performance during soccer matches–beneficial effect of re-warm-up at half-time. Scand J Med Sci Spor. 2004; 14(3):156–162.
29. Asmussen, E.; Bøje, O. V. E., "Body temperature and capacity for work.," Acta Physiol Scand. 1945; 10(1):1–22.
30. Sonderegger K, Tschopp M, Taube W. The challenge of evaluating the intensity of short actions in soccer: A new

methodological approach using percentage acceleration. PloS One. 2016; 11(11):e0166534.
31. Akenhead, R, Hayes PR, Thompson KG, et al. Diminutions of acceleration and deceleration output during professional football match play. J Sci Med Sport. 2013; 16 (6):556–561.
32. Osgnach C, Poser S, Bernardini R, et al. Energy cost and metabolic power in professional soccer: a new match analysis approach. Med Sci Sports Exerc. 2010; 42(1):170–178.
33. Bradley PS, Noakes TD. Match running performance fluctuations in elite soccer: indicative of fatigue, pacing or situational influences? J Sport Sci. 2013; 31(15):1627–1638.
34. Mernagh D, Weldon A, Wass J, et al. A comparison of match demands using ball-in-play versus whole match data in professional soccer players of the english championship. Sports. 2021; 9(6):76–84.
35. Riboli A, Semeria M, Coratella G, et al. Effect of formation, ball in play and ball possession on peak demands in elite soccer. Biol Sport. 2021; 38(2):195–205.
36. Ju W, Doran D, Hawkins R, et al. Contextualised peak periods of play in English Premier League matches. Biol Sport. 2021; 39(4):973–983.
37. Oliva-Lozano JM, Rojas-Valverde D, Gómez-Carmona CD, et al. Worst case scenario match analysis and contextual variables in professional soccer players: a longitudinal study. Biol Sport. 2020; 37(4):429–436.
38. Oliva-Lozano JM, Gómez-Carmona CD, Rojas-Valverde D, et al. Effect of training day, match, and length of the microcycle on the worst-case scenarios in professional soccer players. Res Sports Med. 2022; 30(4):425–438.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.136087
© Institute of Sport – National Research Institute

Influence of contextual factors on most demanding scenarios in under-19 professional soccer players

AUTHORS: Rubén-Cipriano Romero-Rodríguez[1], Enrique Alonso-Pérez-Chao[2,3], Carlos Ribas[3], Daniel Memmert[4], Miguel-Ángel Gómez-Ruano[1]

[1] Facultad de Ciencias de la Actividad Física y del Deporte, Universidad Politécnica de Madrid, 28040 Madrid, Comunidad de Madrid, España
[2] Department of Physical Activity and Sports Science, University Alfonso X el Sabio, 28691 Villanueva de la Cañada, Community of Madrid, Spain
[3] Faculty of Sport Sciences, European University of Madrid, 28670, Madrid, Spain
[4] German Sport University Cologne, Department of Computer Science in Sports and Team/Racket Sport Sciences, Germany, 50933, Köln, Germany

ABSTRACT: This study aimed to compare the most demanding scenarios (MDS) of under-19 professional soccer players during official matches, controlling for contextual factors such as playing position, the level of opponent teams, playing venue, match status, playing surface, pitch size, and playing status of players. A total of 42 players were monitored across 27 games using Global Positioning System (GPS) technology to collect the external loads, including total distance covered, high-speed running, sprint distance, accelerations, and decelerations. MDS were calculated across 1-minute, 5-minute, and 10-minute time windows for each variable. Significant differences were found based on the contextual factors. (i) Opponent level did not show significant differences; (ii) full-backs covered more distance at 1 minute in home games; (iii) midfielders in winning vs. drawing scenarios exhibited higher decelerations at 1 minute but less distance at 10 minutes; (iv) in drawing vs. losing scenarios, central defenders had greater distance at 5 minutes and accelerations at 5 minutes, while midfielders showed greater distances at 1 minute, 5 minutes, and 10 minutes; (v) offensive midfielders and forwards displayed specific performance differences; (vi) no significant differences were found for the playing surface; (vii) regarding pitch size, full-backs covered more distance at 5 minutes on larger pitches, while midfielders covered more distance at 5 minutes and 10 minutes; and (viii) starters generally outperformed non-starter players across various variables depending on the playing positions. The findings suggest that contextual factors have a significant impact on soccer player performance across different playing positions.

CITATION: Romero-Rodríguez RC, Alonso-Pérez-Chao E, Ribas C et al. Influence of contextual factors on most demanding scenarios in under-19 professional soccer players. Biol Sport. 2024;41(4):51–60.

Received: 2023-04-24; Reviewed: 2023-10-17; Re-submitted: 2023-12-20; Accepted: 2024-02-26; Published: 2024-03-06.

Corresponding author:
Rubén-Cipriano Romero-Rodríguez
Facultad de Ciencias de la Actividad Física y del Deporte, Universidad Politécnica de Madrid, 28040 Madrid, Comunidad de Madrid
España
E-mail: rubencipri@gmail.com

ORCID:
Ruben-Cipriano Romero-Rodriguez
0009-0005-9032-1493

Enrique Alonso Pérez-Chao
0000-0002-8678-8702

Carlos Ribas
0000-0003-2961-4383

Daniel Memmert
0000-0002-3406-9175

Miguel A. Gómez
0000-0002-9585-3158

Key words:
Team sports
Peak demands
Most demanding scenarios
Load monitoring
Game demands
Contextual factors

INTRODUCTION

Several studies have investigated the game demands experienced by soccer players, focusing on the average intensity across entire games [1, 2]. However, expressing match intensities as an average disguises the peak intensity period of match play and represents a simplistic perspective [3, 4]. To approach the intensity experienced by players at specific times during the competition, the analysis of shorter epoch durations (e.g., 1 minute and 5 minutes) during match play has been developed [5–8]. Existing literature in this regard has concurred that as the duration of the analysed period increased, the relative intensity decreased for all variables and positions, although this decrease was not consistently linear [9].

The peak demand (PD), which refers to the highest level of activity that players experience for a specific variable during a defined period of time, has been measured in soccer players using various external load variables (e.g., distances and accelerations) and time periods (e.g., 1 minute and 5 minutes) [3, 10, 11]. To quantify the PDs experienced by under nineteen soccer players (< 19 years of age [U19]) during games is particularly important given that the intensities detected can guide optimal training prescription to best prepare players to cope with the most demanding scenarios (MDS) experienced during games [3] and to assist these young players in transitioning to senior-level competitions.

In this regard, various scenarios or conditions inherent in the game [12, 13] should be analysed because they have been shown to influence physical performance [12, 14]. Consequently, external PD may be influenced by numerous contextual factors, which should be taken into account when analysing physical demands [15]. Therefore, it is important to explore the impact of

several factors on the peak external values achieved by soccer players during games. This includes investigating the effects of playing position [10, 16], team formation [17, 18], passage duration [9], momentary outcome [19, 20], fixture congestion [21], the number of minutes played by the athlete [2], and the amount of activity completed in the period immediately preceding the MDS [22, 23].

Based on the current literature, the momentary match status was a significant factor in the peak values of a player's physical performance since, in general, teams when winning reported that players covered more distance, especially at high speeds, compared to drawing matches. Theoretically, achieving a higher external PD during games could indicate that players may be capable of attaining a superior playing pace at key stages across games. In turn, a superior playing pace may indicate an ability to outplay opponents from a physical perspective and improve the likelihood of making successful plays, contributing to team success [24]. In this regard, peak values appeared higher during favourable results (winning) for the total distance, high-speed distance (> 19.8 km/h), and sprint distance (> 25.2 km/h) in most sample durations analysed (1 and 3 minutes) compared to when drawing or losing [20]. Moreover, other studies reported higher peak values for relative distance and Player Load for non-starter players who were winning; the midfielders were those who had higher values in these variables [25]. Alternatively, higher external PD during games may be reflective of game contexts in which a team that is losing at the time might elevate playing intensity to improve the result [24]. Previous studies exploring the impact of team venue (home vs. away) on external PD have indicated higher values for total distance, high-speed distance (> 19.8 km/h), and sprint distance (> 25.2 km/h) across 1-minute, 3-minute, 5-minute, and 10-minute sampling durations when playing away compared to playing at home [20]. However, the existing research has presented conflicting findings. In turn, other studies suggest that home teams are likely to experience greater peak external intensities compared to away games [12, 26].

Nevertheless, research regarding the influence that these contextual factors may have on the peak values in professional football is scarce given the limited number of studies available to date. Based on the foregoing, the need to consider situational factors in the analysis of MDS and try to interpret how these variables can affect the responses of athletes would seem indispensable [27]. Therefore, this study aimed to quantify and compare the external PD encountered during official games based on various contextual variables including playing position (central defender, full-backs, midfielders, wide midfielders, and offensive midfielders, and forwards), opponent level (high, medium, and low level), team venue (home or away), momentary outcome (winning, drawing and losing), playing surface (artificial or natural grass), pitch size (large, medium, small) and player role (starter and non-starter). Based on existing data [20], it was hypothesized that external PD may be influenced by several contextual factors.

MATERIALS AND METHODS

Sample

Male professional soccer players from the same team competing in the highest national division of a U19 Spanish soccer competition (n = 42, mean ± standard deviation [SD]: age 18.0 ± 0.4 years, height 181.4 ± 6.8 cm, body mass: 70.1 ± 5.6 kg) were monitored during 34 official games. Players were considered to be professional as they had an exclusive dedication to this sport with a frequency of 6 weekly sessions (5 practices and 1 game).

For inclusion in the study, players had to complete at least a halftime (45 minutes of playing time). Then, each game only included data from those players who played at least 45 minutes, since substitutes can have higher outputs than starting players, likely because of pacing strategies [9]. Additionally, players who participated in 2 different positions during the same game (e.g., a player who started playing as a midfielder and ended up playing as a wide midfielder) were excluded from that specific game, since changes in positions have an impact on the physical performance of players [28]. In turn, goalkeepers were excluded from the analysis due to the distinct nature of their activity-demands profile. Any game in which any team played with numerical superiority, either due to player send-off, a red card, or injuries, as well as blowout games (a difference of more than five goals in favour of a team), were excluded from the analysis. These exclusion criteria have been justified in previous similar studies as these situations could potentially impact the demands and, particularly, the physical intensity of the match [29, 30]. As a result, four initially recruited players and seven monitored games did not meet the inclusion criteria and were therefore excluded from the final analyses. This led to a retained sample of 38 players and 27 games for the study. Considering entire game analyses, n = 289 game samples across the n = 38 players were included in the final analyses.

The team formation was 4-2-3-1. Players were deployed in each match as follows: two central defenders, two full-backs, two midfielders, two wide midfielders, one offensive midfielder, and one player in the forward position. Depending on the substitutions made by the coach in each match, and the timing of these substitutions, there might be variations in the number of records for each position. For instance, if a forward player was replaced at halftime by another of the same position, even though the game system only fielded one player of that position per game, that specific match could include the analysis of up to two players in the same position, given that both met the criteria by playing at least 45 minutes.

Procedures

This observational investigation was conducted across a 12-month period throughout the 2020–2021 season. The devices (Vector S7; Catapult Sports, Melbourne, Australia) were calibrated according to the manufacturer's instructions, which consisted of placing the device on a flat surface, turning the units on without surrounding magnetic devices, and finally, waiting for 60 s. Then, the units were placed in

the back of a specific chest vest. Each player wore a device in a bespoke pocket within a vest positioned on the upper thoracic spine between the scapulae. The devices contained a triaxial accelerometer (± 16 g, 100 Hz), magnetometer (± 4.900 μT, 100 Hz), gyroscope (up to 2,000 deg/s, 100 Hz), and a Global Positioning System (GPS) receptor (10 Hz), and all units were updated with the same firmware version (6.5.0). The technology used in this study has been supported as valid in measuring distance [31, 32], speed, accelerations, and decelerations [32, 33], while similar GPS technology is reliable (coefficient of variation (CV) < 5%) in measuring distance and speed variables [31]. All participants were familiarized with the devices as part of their day-to-day training and playing practices. Each device was turned on ~20–40 minutes before the warm-up preceding each game. Players wore the same assigned unit throughout the course of the data collection period to avoid inter-device variation in external load data outputs [34, 35].

To establish the external PD for each match observation, first, the raw data were extracted in 1-s intervals for each player. Data were then exported to a custom-built Microsoft Excel (version 16.0; Microsoft Corporation, Redmond, WA) spreadsheet for further analysis. Data were analysed across different time windows (1 minute, 5 minutes, and 10 minutes) using rolling averages to find the peak value for each variable across each duration. This rolling average method entails computing averages for a designated window or interval of consecutive data points as the window progressively moves through the dataset. This approach is frequently employed when assessing MDS [4] and has been previously used in several studies [6, 10, 19, 36, 37]. The data were analysed separately for the first and second halves of each game, with the highest values for each variable in a specific game used for game analysis (i.e., the highest value for each variable across any moment of the game in a specific game was taken as the value for that game).

Physical variables

Variables analysed were selected based on previous publications [6, 25]. Thus, external PDs were calculated for several external physical load variables including total distance (m) covered (TD) and distance (m) covered in different intensity zones including high-speed running (HSR) > 21 km/h, as previously used in soccer research [30, 38] and sprint distance (SD) > 24 km/h. Furthermore, accelerations (ACC) (count) performed > 2 $m \cdot s^{-2}$ (dwell time: 0.3 seconds), and decelerations (DEC) (count) performed < -2 $m \cdot s^{-2}$ (dwell time: 0.3 s) were also measured. These dwell times were chosen given that values between 0.3 and 0.4 s have been identified as the most readily used in team sports settings [39].

Contextual variables

The contextual variables analysed were playing position (e.g., central defender, full-backs, midfielders, wide midfielders, offensive midfielders, and forwards), opponent level (e.g., high, medium, and low level), team venue (e.g., home, and away), match status (e.g., winning, drawing, and losing), playing surface (e.g., artificial, or natural grass), pitch size (large, medium, small) and player role (starter and non-starter).

- **Playing position:** To explore potential differences based on playing positions, the total sample was categorized into six typical soccer roles: central defender (CD) (n = 6, 65 samples), full-backs (FB) (n = 8, 77 samples), midfielders (MF) (n = 9, 69 samples), wide midfielders (WMF) (n = 8, 55 samples), offensive midfielders (OMF) (n = 6, 62 samples) and forwards (FW) (n = 5, 59 samples).
- **Opponent level:** Concerning the opponent level, we examined differences in peak values when the reference team played against high-level teams (ranked in the top 6 league positions), medium-level teams (ranked 7th to 13th in the league), and low-level teams (ranked in the bottom 7 of the league). These categories are similar to those reported previously [13, 14, 40].
- **Team venue:** Comparisons according to playing venue were made between games that were played at home (13 games, 76 samples) and away (14 games, 84 samples).
- **Match status:** Match status was defined as winning, drawing, or losing in relation to the number of goals scored and conceded by the sampled team at the time of data entry [41].
- **Playing surface:** Comparisons according to playing surface were made between games that were played on natural grass (14 games, 82 samples) and games that were played on artificial grass (13 games, 78 samples).
- **Pitch size:** Pitch dimensions were classified as large size (≥ 106 × 68 m; 7208 m^2); medium size (> 93 × 55 m; 5115 m^2 and < 106 × 68 m; 7208 m^2), and small size (< 93 × 55 m; 5115 m^2).
- **Player role:** was established as a starter (156 samples) or non-starter (83 samples). For inclusion in the study, players had to complete at least a half-time (45 minutes of playing time). Then, only benching players who started from the beginning of the second half were considered non-starter players and accordingly included in the study.

Statistical analysis

The Kolmogorov-Smirnov normality test was performed to check data normality assumptions. The linear mixed model (LMM) was used to detect significant differences within groups (high level vs. medium level vs. low level; drawing vs. winning vs. losing; large vs. medium vs. small) and to test significant differences within the other conditions (playing position, opponent level, team venue, match status, playing surface, pitch size and player role) depending on players' position. Cohen's effect size (ES) and the mean difference with 95% confidence intervals (CI) were determined for all pairwise comparisons and interpreted as trivial = < 0.20; small = 0.20–0.59; moderate = 0.60–1.19; large = 1.20–1.99; and very large = > 2.00 [42]. All analyses were conducted using IBM SPSS for Windows (version 23, IBM Corporation, Armonk, New York), except ES, which was calculated using

a customized Microsoft Excel spreadsheet (version 16.0, Microsoft Corporation, Redmond, WA). The significant level was set at $p < 0.05$.

RESULTS

Mean comparisons according to the condition for each time window depending on players' position are presented in Figure 1.

Opponent level

No significant differences ($p > 0.05$) were observed in the comparison between varying opponent levels (high vs. medium vs. low).

Team venue

In the comparison between home and away games, FB notably covered a greater distance (DIST) at 1' ($p = 0.04$; ES = 1.40). Conversely, no significant differences ($p > 0.05$) were observed in the other comparisons between home and away games.

Match status

In the comparison between winning and drawing statuses, MF showed significantly higher DEC 1' ($p = 0.04$; ES = 0.79) and notably lower DIST 10' ($p = 0.02$; ES = -0.88).

Regarding the comparison between drawing and losing statuses, CD demonstrated significantly greater DIST 5' ($p = 0.02$; ES = 1.15), and ACC 5' ($p = 0.01$; ES = 1.31). Meanwhile, MF displayed notably higher DIST at 1' ($p = 0.01$; ES = 0.84), DIST 5' ($p < 0.01$; ES = 1.13), and DIST 10' ($p < 0.01$; ES = 1.28). OMF exhibited higher DIST at 1' ($p = 0.01$; ES = 1.11) and DIST 5' ($p = 0.04$; ES = 1.06). FW showed significantly greater SD 1' ($p = 0.03$; ES = 1.09), ACC 5' ($p < 0.01$; ES = 1.13), DEC 5' ($p < 0.01$; ES = 1.23), and DEC 10' ($p < 0.01$; ES = 1.01) for drawing games compared to losing. However, WMF displayed notably lower DEC 1' ($p = 0.03$; ES = -0.09) when comparing drawing to losing status.

In reference to the comparison between winning vs. losing status, FB disclosed considerably higher DIST 1' ($p = 0.02$; ES = 0.93) and DEC 1' ($p = 0.02$; ES = 1.31); MF revealed substantially higher ACC 1' ($p = 0.01$; ES = 1.26); WMF revealed significantly greater DEC 1' ($p < 0.01$; ES = 0.44), DIST 10' ($p = 0.01$; ES = 0.21), HSR 10' ($p = 0.01$; ES = 1.57), and SD 10' ($p = 0.03$; ES = 1.49); OMF expressed substantially larger DIST 1' ($p < 0.01$; ES = 0.73) and DEC 5' ($p = 0.04$; ES = 1.02); and FW exhibited considerably higher SD 1' ($p = 0.02$; ES = 1.12), ACC 5' ($p < 0.01$; ES = 1.47), DEC 5' ($p < 0.01$; ES = 1.82), HSR 10' ($p = 0.01$; ES = 1.44), SD 10' ($p = 0.01$; ES = 1.46), ACC 10' ($p < 0.01$; ES = 1.22) and DEC 10' ($p < 0.01$; ES = 1.50) during winning games compared to losing (Figure 1). No significant ($p > 0.05$) differences were observed in the remaining comparisons.

Playing surface

Regarding the comparison between different playing surfaces (natural grass vs. artificial grass), no significant differences were observed ($p > 0.05$).

Pitch size

When comparing different pitch sizes (large vs. small), FB revealed significantly larger DIST 5' on larger pitches ($p = 0.04$; ES = 2.32), while MF showed greater DIST 5' ($p = 0.03$; ES = 2.38) and DIST 10' ($p = 0.01$; ES = 2.82).

In the comparison between large vs. medium pitch size, WMF revealed appreciably higher DIST 1' ($p = 0.03$; ES = 1.83) and HSR 5' ($p = 0.03$; ES = 2.04).

No significant ($p > 0.05$) differences were observed in the remaining comparisons.

Starting status

Regarding the comparison between starter vs. non-starter role, CD displayed significantly higher values for DIST 1' ($p < 0.01$; ES = 1.99), ACC 1' ($p < 0.01$; ES = 2.53), DEC 1' ($p < 0.01$; ES = 1.76), DIST 5' ($p < 0.01$; ES = 1.97), ACC 5' ($p < 0.01$; ES = 2.09), DEC 5' ($p = 0.03$; ES = 1.17), DIST 10' ($p = 0.00$; ES = 1.66), ACC 10' ($p < 0.01$; ES = 1.64); FB expressed significantly larger values for DIST 1' ($p = 0.02$; ES = 0.95), HSR 1' ($p < 0.01$; ES = 1.37), SD 1' ($p = 0.01$; ES = 1.11), ACC 1' ($p = 0.03$; ES = 0.87), DEC 1' ($p < 0.01$; ES = 1.04), DIST 5' ($p < 0.01$; ES = 1.37), HSR 5' ($p = 0.01$; ES = 1.01), ACC 5' ($p = 0.01$; ES = 0.93), DEC 5' ($p < 0.01$; ES = 0.82), DIST 10' ($p < 0.01$; ES = 1.50), ACC 10' ($p < 0.01$; ES = 0.91); MF showed significant differences for all variables across all time windows; WMF showed substantially higher SD 1' ($p = 0.02$; ES = 0.93), DIST 5' ($p = 0.04$; ES = 0.92), HSR 5' ($p = 0.01$; ES = 0.99), SD 5' ($p = 0.04$; ES = 0.86), ACC 5' ($p = 0.01$; ES = 0.97), HSR 10' ($p < 0.01$; ES = 1.16), SD 10' ($p = 0.01$; ES = 1.01), ACC 10' ($p = 0.03$; ES = 0.88); OMF got significantly greater HSR 1' ($p < 0.01$; ES = 1.55), SD 1' ($p < 0.01$; ES = 1.79), HSR 5' ($p < 0.01$; ES = 1.42), SD 5' ($p < 0.01$; ES = 1.70), DIST 10' ($p = 0.03$; ES = 1.05), HSR 10' ($p < 0.01$; ES = 1.31) and SD 10' ($p < 0.01$; ES = 1.76); and FW reached significantly higher HSR 1' ($p < 0.01$; ES = 1.49), SD 1' ($p < 0.01$; ES = 1.67), HSR 5' ($p < 0.01$; ES = 1.05), SD 5' ($p < 0.01$; ES = 1.05), HSR 10' ($p < 0.01$; ES = 1.20) and SD 10' ($p < 0.01$; ES = 1.26) when starting the games compared to when not starting (Figure 1). No significant ($p > 0.05$) differences were found in the remaining positions across each variable.

DISCUSSION

This study aimed to quantify and compare the external peak demands (PD) encountered by under-19 professional soccer players during official games according to different contextual variables such as playing position, opponent level, team venue, momentary outcome, playing surface, and player role. Based on the results obtained, it can be confirmed that contextual variables had a relevant influence on PD in official matches, in the different variables studied, and for different playing positions, as had already been suggested in previous research [27]. In addition, our results corroborate the previously

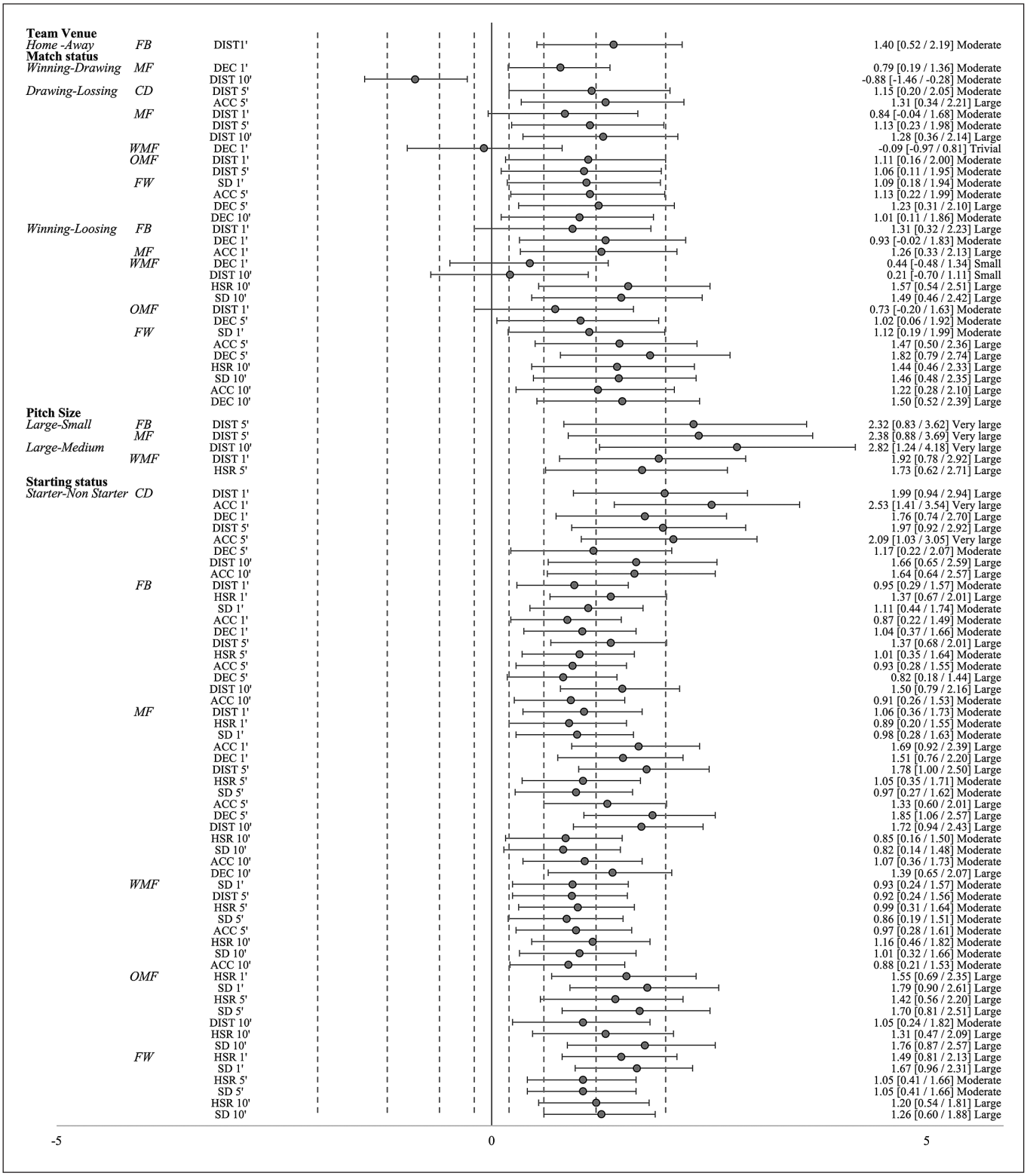


FIG. 1. Standardized effect size magnitude [95% confidence interval] between conditions for all variables depending on playing position and time window (1', 5' and 10').

Notes: The dotted lines represent the effect size magnitude thresholds from trivial to large (see Methods), playing positions: CD = central defender, FB = full- backs, MF = midfielders, WMF = wide midfielders, OMF= offensive midfielders and FW = forwards.

External physical load variables: TD = total distance covered, HSR = high-speed running (> 21 km/h), SD = sprint distance (> 24 km/h), ACC = accelerations (> 2 m · s^{-2}) and DEC = decelerations (< -2 m · s^{-2})

demonstrated differences in PD concerning playing position, as explored in previous research [9, 10, 37].

Regarding the team venue (home or away matches), playing as the home team resulted in higher values in the PD of total distance covered and distance covered at different speed ranges (> 21 and > 24 km/h) compared to playing away, especially in the position of FB for the period of 1 minute. This aligns with the findings of other studies that confirmed the higher physical demands in games played at home compared to away games, primarily for the variable TD and in the absolute values of completed matches [12, 43, 44]. However, some studies specifically analysed PD and reported the opposite [20, 45]. For instance, higher values for PD in TD, HSR, and SPD were reported during away games compared to home games in periods of 1', 5', and 10'. Nevertheless, the results are in line with previous findings [45] where PD for ACC and DEC were significantly higher in away games, especially for FW in periods of 1' and 10', coinciding with the 1' periods. These differences could be attributed to the interacting effects of contextual factors, such as match status, field dimensions, and spectator influence [46].

Concerning the playing surface, no significant differences were observed ($p > 0.05$). Although we lack comparable data in the literature specifically related to PD regarding this factor, what appears evident is that the two surfaces have different mechanical properties, and the playing surface can alter the demands of the competition and the physiological response in football-specific activity [47]. Research suggests that physical performance in terms of specific efforts [48] and agility tests [49] was better on artificial turf compared to natural grass, accompanied by lower physiological load, and perceived fatigue [47]. As for the physical performance of full games, it was found that TD and very high-intensity running (VHIR; running speed from 16.1 to 19 km/h) covered by players on artificial turf were significantly higher compared to natural grass [50]. However, it should be noted that this study did not analyse PD, and the sample consisted of U14 players in a different competition, which could potentially explain these variations. Based on these findings, it could be assumed that playing on natural grass could increase fatigue, impacting a player's running activity and reducing their performance in the game. This may lead to a slower pace of play and fewer high-intensity runs [2], although these can also be influenced by other contextual factors (e.g., the level of opponent teams) [51].

The distinction between being a starter or a non-starter in a match also resulted in differences in the PD for most of the analysed variables and positions. Noticeable differences (large or very large) between starters and non-starters were observed for CD positions in the variables ACC (1', 5' and 10'), DECC (1', and 5'), DIST (1', 5' and 10'); FB in DIST (1', 5' and 10'), HSR (1' and 5'), SD (1'), ACC (1'. 5' and 10') and DEC (1' and 5'); MF (all variables across all time windows); OMF in HSR (1', 5' and 10') and SD (1', 5' and 10'); FW in HSR (1', 5' and 10'), and SD (1', 5' and 10'); WMF in DIST (5'), HSR (5' and 10') and SD (1', 5' and 10'), favouring the starting players. This suggests that starting players, by completing more uptimes, are more exposed and likely to be exposed to PD. These results are partially consistent with previous research [19], where starter players showed higher PD for TD for all playing positions when compared with non-starter players. However, in this research, non-starter players showed higher peak values for HSR PD for the 5' period compared to starter players [19].

Previous studies found that the status of playing as a starter or non-starter did not have an impact on total distance, but it did have an influence on the high-speed distance (> 19.8 km/h) and sprinting distance (> 25.2 km/h), with starting players having higher values in 1', 3', 5', and 10' periods [9]. The data from the present study support this notion, although the threshold values differ. On the other hand, in a recent study non-starters tended to produce higher peak values for the TD variable in the 3' window. However, this same research also reflected that the lowest values of PD in TD happened in the final part of the matches for most players, although these are the minutes in which non-starting players usually participate [36]. Nevertheless, one of the findings was that the SD variable tended to appear in those final moments, possibly due to the presence of players who entered the field without fatigue or the influence of contextual factors and/or tactical considerations that would keep them with an orderly participation [25]. An example of this influence was reflected in the position of MFs, who had higher values of PD for TD and Player Load when the team was winning for non-starting players compared to starters [25].

Based on the analysis of PD regarding the standard of teams, the present study demonstrated that PD for TD was higher when playing against high-level teams, especially for WMF and OMF (5' and 10' minutes), SD, and MF (1' and 5' minutes). However, FB showed higher peak values for ACC (5' minutes) when playing against medium-level teams. These results correspond to most research on this factor [43, 52, 53] where higher average values for TD and HSR were also found when playing against medium or high-level teams compared with low-level teams [26, 54]. The opposite has also been reflected. Apart from the maximum speed reached, the high-level team showed greater distance covered in matches against low-level opponents, in the variables total TD, average speed (km/h), low intensity running (LIR = > 11.01, and < 14 km/h), medium intensity running (MIR = > 14.01 and < 19 km/h) and high intensity running (HIR = > 19.01 and < 23 km/h) than against high-level opponents [26].

When comparing opponent levels, no significant differences ($p > 0.05$) were observed in the comparison between varying opponent levels (high vs. medium vs. low). These results do not align with the findings of previous research [43, 55] where higher values for TD and HIR were observed against high-level teams as opposed to low-level teams. These results diverge from earlier studies [e.g. 53], particularly concerning variables related to ACC and DEC. Varley, Gregson, et al. (2017) also reported higher demands in HSR without the ball for medium-level teams compared to low-level teams, along with higher demands in HSR with the ball for low-level teams

compared to medium-level teams [56]. The exploration of the relationship between ball possession and the physical demands of the game in this research is novel, as previous studies have not considered this factor. Additionally, there is a lack of research on how the level of the opposing team influences the physical demands, making this study potentially ground-breaking in addressing this gap.

Based on the match status, our results showed that MF exhibited a significant increase in deceleration (DEC 1') during winning games compared to drawing games. However, they showed notably lower distance covered at 10 minutes (DIST 10') during winning games. This suggests that midfielders contribute more to the deceleration aspect in winning scenarios but cover less ground over an extended period. These results deviate from the findings of previous research [45] which which pointed out larger distances covered during PD windows of 1', 3', and 5', being significantly higher during moments when the team was drawing compared to moments when they were winning.

Concerning tied versus losing scenarios, the PDs were also notably higher during tied results for almost all playing positions and variables. This aligns with previous findings, where PDs were observed to be elevated during tied situations for TD (1', 3', and 5') [20, 45]. In the comparison between winning and losing, our analysis revealed higher PDs across almost all variables and playing positions when the team was in a winning position. Particularly significant differences were noted for the FW, WMF, and OMF (HSR 5' and 10'). This may suggest that, during winning situations, attacking positions adopt a more aggressive pressing attitude and exert increased efforts in the opponent's field. This aligns with a recent study indicating that attacking players (FW, WMF, and MF) exhibited higher demands in HSR (> 21 km/h), very HSR (VHSR = > 21 and < 24 km/h), and SD (> 24 km/h) when their team was winning [57]. To date, research has commonly shown that there is greater physical performance in terms of total game demands when the result is unfavourable compared to drawing or winning [14]. In terms of PD, teams demonstrated higher game demands in the variables of TD, HSR, and SD when they won, as opposed to drawn games [20]. In this regard, peak values appeared to be higher during favourable results (winning) for total distance covered, HSR (> 19.8 km/h), and SD (> 25.2 km/h) in most of the analysed sample durations (1' and 3') compared to drawn or lost games [20].

Regarding the size of the playing pitch, the results reveal notable variations in performance metrics across different pitch sizes. When comparing large versus small pitches, FB demonstrated significantly larger DIST 5' on larger pitches (ES = 2.32), whereas MF exhibited greater DIST 5' (ES = 2.38) and DIST 10' (ES = 2.82) on larger playing areas. The factor of playing pitch size is mainly related to the "individual playing area" or "area per player" (ApP) [58], which has been widely studied and shown to directly affect the conditioning demands of the players [59, 60]. In our analysis, when comparing a large-sized pitch with a medium-sized one, WMF showed significantly higher DIST 1' (ES = 1.83) and HSR 5' (ES = 2.04) on larger pitches, indicating a consistent trend towards enhanced performance in these variables. When comparing large-sized pitches vs. small-sized pitches, no significant differences ($p > 0.05$) were observed. This suggests that the transition from a medium-sized pitch to a small-sized pitch may not have a pronounced effect on the observed performance metrics.

Despite this, the overall trend continues to suggest a correlation between pitch size and performance metrics, with larger pitches generally favouring higher PD across various playing positions and variables. These results align with the findings of previous studies [60, 61], indicating that a larger playing area corresponds to increased demands for HSR. To meet these demands, playing areas with larger ApP are necessary, with the order of importance being SD > HSR > TD. Notably, this heightened demand associated with larger playing areas did not have a significant impact on measures of ACC and DEC [61]. Furthermore, in line with earlier research conducted in various small sided games (SSGs) [62], MFs exhibited higher values in medium-sized dimensions (SSG 7v7+3; ApP 61.4 m^2) and large dimensions (SSG 8v8+3; ApP 73.7 m^2) compared to small dimensions (SSG 4v4+3 ApP 21 m^2 & SSG 5v5+3 ApP 38.5 m^2). These consistent findings across different studies provide additional support to the idea that pitch dimensions, particularly the individual playing area, play a crucial role in influencing player performance and conditioning demands.

To our knowledge, there is no existing research specifically related to PD or official match demands concerning this factor. Considering the competitive regulations established by federations, it might not seem logical to consider this aspect, as these regulations typically mandate standardized measurements for playing surfaces, assumed to be equal or meeting minimum standards. However, this situation differs for the top national U-19 soccer category in Spain. In this case, the dimensions of the fields where official matches are played vary significantly, ranging from large to medium or small dimensions. This leads to a notable alteration of the relative area per player, resulting in a potential fluctuation of over 100 m^2 per player between different playing fields within the same league. Such variations can have significant implications due to the conditioning differences they introduce. A recent meta-analysis [59] showed that, in spaces larger than 100 m^2 per player, each increase of 25 m^2 of ApP increased the exposure to HSR by an average of 2.8 to 1.9 $m \cdot min^{-1}$, in VHSR it increased between 0.6 and 0.9 $m \cdot min^{-1}$ and in SD it increased between 0.1 and 0.3 $m \cdot min^{-1}$. Hence, disparities in the playing area exceeding 100 m^2 per player will lead to significant distinctions, as our results identified.

The limitations of this study should be considered when interpreting our results. First, only external load variables were monitored, and therefore internal PDs (e.g., heart rate, rating of perceived exertion) were not explored; they may show different patterns to those observed in our study for external demands. Secondly, the sample size employed in this study was relatively small, as it involved recruiting only one soccer team. Consequently, these findings may not

be applicable to all soccer teams due to potential variations in success rates, tactical strategies, playing pace, and player fitness likely to vary within and between competitions.

Practical applications

Based on the obtained results, several practical applications can be suggested depending on the orientation, games per week, individual necessities, objectives, and different contextual variables. Coaches and strength conditioning professionals should devise strategies to expose players to the MDS during practice sessions, aiming to prepare athletes to handle the most intense demands of the game. Moreover, by analysing the physical demands of different playing positions, coaches can discern the strengths and weaknesses of individual players. This information allows them to make informed decisions when selecting players for specific games. Additionally, understanding the specific physical demands associated with different playing positions and opponent levels empowers coaches to design training programmes tailored to the specific needs of the team.

Concerning return-to-performance processes, considering the higher PD when a player is returning to play allows coaches and medical staff to implement necessary precautions. Gradually reintroducing the player to the physical demands of the game may involve strategies such as reducing playing time, increasing rest periods, and implementing a structured tapering programme. This approach aims to enhance the physical conditioning and reduce the risk of re-injury. In this context, natural grass surfaces seem to demand additional muscular and metabolic capacity from players in football practice. Therefore, it is advisable for coaches to tailor specific player training regimens to the characteristics of the field surface. This adaptation could be a crucial consideration in the decision-making process.

CONCLUSIONS

Numerous contextual factors, including the playing surface, starting status, opponent level, and match status, can exert a significant influence on the performance of soccer players across various playing positions.

Conflic of interest

The authors declared no conflict of interest.

REFERENCES

1. Díez A, Lozano D, Arjol-Serrano JL, Mainer-Pardos E, Castillo D, Torrontegui-Duarte M, et al. Influence of contextual factors on physical demands and technical-tactical actions regarding playing position in professional soccer players. BMC Sports Sci Med Rehabil. 2021; 13(1).
2. Bradley PS, Di Mascio M, Peart D, Olsen P, Sheldon B. high-intensity activity profiles of elite soccer players at different performance levels. J Strength Cond Res. 2010; 24(9):2343–51.
3. Alonso E, Miranda N, Zhang S, Sosa C, Trapero J, Lorenzo J, et al. Peak match demands in young basketball players: Approach and applications. Int J Environ Res Public Health. 2020; 17(7):1–10.
4. Cunningham DJ, Shearer DA, Carter N, Drawer S, Pollard B, Bennett M, et al. Assessing worst case scenarios in movement demands derived from global positioning systems during international rugby union matches: Rolling averages versus fixed length epochs. PLoS One. 2018; 13(4):1–14.
5. Bortnik L, Burger J, Rhodes D. The mean and peak physical demands during transitional play and high pressure activities in elite football. Biol Sport. 2023; 1055–64.
6. M. Oliva-Lozano J, Riboli A, Fortes V, M. Muyor J. Monitoring physical match performance relative to peak locomotor demands: implications for training professional soccer players. Biol Sport. 2023; 553–60.
7. Thoseby B, D. Govus A, Clarke A, J. Middleton K, Dascombe B. Positional and temporal differences in peak match running demands of elite football. Biol Sport. 2023; 40(1):311–9.
8. Alonso Pérez-Chao E, Portes R, Gómez MÁ, Parmar N, Lorenzo A, Jiménez Sáiz SL. A Narrative Review of the Most Demanding Scenarios in Basketball: Current Trends and Future Directions. J Hum Kinet. 2023; 89:231–45.
9. Martín-Fuentes I, Oliva-Lozano JM, Fortes V, Muyor JM. Effect of playing position, passage duration and starting status on the most demanding passages of match play in professional football. Res Sports Med. 2021; 29(5):417–26.
10. Martín-García A, Casamichana D, Gómez Díaz A, Cos F, Gabbett TJ. Positional differences in the most demanding passages of play in football competition. J Sports Sci Med. 2018; 17(4):563–70.
11. Ju W, Doran D, Hawkins R, Gómez-Díaz A, Martin-Garcia A, Ade J, et al. Contextualised peak periods of play in English Premier League matches. Biol Sport [Internet]. 2022; 39:973–83. Available from: https://www.termedia.pl/doi/10.5114/biolsport.2022.112083.
12. Lago C, Casais L, Dominguez E, Sampaio J. The effects of situational variables on distance covered at various speeds in elite soccer. Eur J Sport Sci. 2010; 10(2):103–9.
13. Taylor J, Mellalieu S, James N, Shearer D. The influence of match location, quality of opposition, and match status on technical performance in professional association football. J Sports Sci. 2008; 26(9).
14. Castellano J, Blanco-Villaseñor A, Álvarez D. Contextual Variables and Time-Motion Analysis in Soccer. Int J Sports Med. 2011 Jun 17; 32(06):415–21.
15. Gómez-Ruano MA, Pollard R, Lago-Peñas C. Home Advantage in Sport. Home Advantage in Sport. 2021.
16. Fahey JT, Aldred K, Greig M, Rhodes D. Peak Running Speeds in Professional Male Football: Influence of Division and Playing Position. J Strength Cond Res. 2023; 37(3).
17. Calder A, Gabbett T. Influence of Tactical Formation on Average and Peak Demands of Elite Soccer Match-Play. J Strength Cond Res. 2022; 2(1):1–10.
18. Riboli A, Semeria M, Coratella G, Esposito F. Effect of formation, ball in play and ball possession on peak demands in elite soccer. Biol Sport. 2021; 38(2):195–205.
19. Fereday K, Hills SP, Russell M, Smith J, Cunningham DJ, Shearer D, et al. A comparison of rolling averages versus discrete time epochs for assessing the worst-case scenario locomotor demands of professional soccer match-play. J Sci Med Sport [Internet]. 2020; 23(8):764–9. Available from: https://doi.org/10.1016/j.jsams.2020.01.002.

20. Oliva-Lozano JM, Rojas-Valverde D, Gómez-Carmona CD, Fortes V, Pino-Ortega J. Worst case scenario match analysis and contextual variables in professional soccer players: A longitudinal study. Biol Sport. 2020; 37(4):429–36.
21. Castellano J, Martin-Garcia A, Casamichana D. Most running demand passages of match play in youth soccer congestion period. Biol Sport. 2020; 37(4):367–73.
22. Schimpchen J, Gopaladesikan S, Meyer T. The intermittent nature of player physical output in professional football matches: An analysis of sequences of peak intensity and associated fatigue responses. Eur J Sport Sci. 2021; 21(6).
23. Bradley PS, Noakes TD. Match running performance fluctuations in elite soccer: Indicative of fatigue, pacing or situational influences? J Sports Sci. 2013; 31(15):1627–38.
24. Pérez-Chao E, Gómez M, Scanlan A, Ribas C, Trapero J, Lorenzo A. Influence of game and quarter results on external peak demands during games in under-18 years, male basketball players. Biol Sport. 2023; 365–75.
25. Hills SP, Barrett S, Thoseby B, Kilduff LP, Barwood MJ, Radcliffe JN, et al. Quantifying the Peak Physical Match-Play Demands of Professional Soccer Substitutes Following Pitch-Entry: Assessing Contextual Influences. Res Q Exerc Sport. 2020; 00(00):1–12.
26. Aquino R, Carling C, Palucci Vieira LH, Martins G, Jabor G, Machado J, et al. Influence of Situational Variables, Team Formation, and Playing Position on Match Running Performance and Social Network Analysis in Brazilian Professional Soccer Players. J Strength Cond Res. 2018; 0(0):1.
27. Rico-González M, Oliveira R, Palucci Vieira LH, Pino-Ortega J, Clemente F. Players' performance during worst-case scenarios in professional soccer matches: a systematic review. Biol Sport. 2022; 39(April):695–713.
28. Schuth G, Carr G, Barnes C, Carling C, Bradley PS. Positional interchanges influence the physical and technical match performance variables of elite soccer players. J Sports Sci. 2016; 34(6).
29. Fransson D, Krustrup P, Mohr M. Running intensity fluctuations indicate temporary performance decrement in top-class football. Sci Med Footb. 2017; 1(1):10–7.
30. Palucci Vieira LH, Carling C, Barbieri FA, Aquino R, Santiago PRP. Match Running Performance in Young Soccer Players: A Systematic Review. Sports Med. 2019; 49(2):289–318.
31. Hoppe MW, Baumgart C, Polglaze T, Freiwald J. Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. PLoS One. 2018; 13(2).
32. Hodder RW, Ball KA, Serpiello FR. Criterion validity of catapult clearsky t6 local positioning system for measuring inter-unit distance. Sensors. 2020; 20(13):3693.
33. Serpiello FR, Hopkins WG, Barnes S, Tavrou J, Duthie GM, Aughey RJ, et al. Validity of an ultra-wideband local positioning system to measure locomotion in indoor sports. J Sports Sci. 2018; 36(15).
34. Johnston RJ, Watsford ML, Kelly SJ, Pine MJ, Spurrs RW. Validity and interunit reliability of 10 Hz and 15 Hz GPS units for assessing athlete movement demands. J Strength Cond Res. 2014; 28(6):1649–55.
35. Castellano J, Casamichana D, Calleja-González J, Román JS, Ostojic SM. Reliability and accuracy of 10 Hz GPS devices for short-distance exercise. J Sports Sci Med. 2011; 10(1):233–4.
36. Novak AR, Impellizzeri FM, Trivedi A, Coutts AJ, McCall A. Analysis of the worst-case scenarios in an elite football team: Towards a better understanding and application. J Sports Sci. 2021; 00(00):1–10.
37. Riboli A, Esposito F, Coratella G. The distribution of match activities relative to the maximal intensities in elite soccer players: implications for practice. Res Sports Med. [Internet]. 2021; 00(00):1–12. Available from: https://doi.org/10.1080/15438627.2021.1895788.
38. Whitehead S, Till K, Weaving D, Jones B. The Use of Microtechnology to Quantify the Peak Match Demands of the Football Codes: A Systematic Review. Sports Med. 2018; 48(11):2549–75.
39. Varley MC, Jaspers A, Helsen WF, Malone JJ. Methodological considerations when quantifying high-intensity efforts in team sport using global positioning system technology. Int J Sports Physiol Perform. 2017; 12(8):1059–68.
40. Rampinini E, Impellizzeri FM, Castagna C, Coutts AJ, Wisløff U. Technical performance during soccer matches of the Italian Serie A league: Effect of fatigue and competitive level. J Sci Med Sport. 2009; 12(1):227–33.
41. Lago-Peñas C. The Role of Situational Variables in Analysing Physical Performance in Soccer. J Hum Kinet. 2012; 35(1):89–95.
42. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1):3–12.
43. Aquino R, Munhoz Martins GH, Palucci Vieira LH, Menezes RP. Influence of match location, quality of opponents, and match status on movement patterns in Brazilian professional football players. J Strength Cond Res. 2017; 31(8):2155–61.
44. Oliva-Lozano JM, Rojas-Valverde D, Gómez-Carmona CD, Fortes V, Pino-Ortega J. Impact of contextual variables on the representative external load profile of Spanish professional soccer match-play: A full season study. Eur J Sport Sci. 2021; 21(4):497–506.
45. Augusto D, Brito J, Aquino R, Figueiredo P, Eiras F, Tannure M, et al. Contextual Variables Affect Running Performance in Professional Soccer Players: A Brief Report. Front Sports Act Living. 2021; 3:350.
46. Wunderlich F, Weigelt M, Rein R, Memmert D. How does spectator presence affect football? Home advantage remains in European topclass football matches played without spectators during the COVID-19 pandemic. PLoS One. 2021; 16(3 March 2021).
47. Wundersitz DWT, Staunton CA, Gordon BA, Kingsley MIC. The influence of playing surface on external demands and physiological responses during a soccer match simulation. J Sports Sci. 2021; 39(24).
48. Ammar A, Bailey SJ, Hammouda O, Trabelsi K, Merzigui N, Abed K EI, et al. Effects of Playing Surface on Physical, Physiological, and Perceptual Responses to a Repeated-Sprint Ability Test: natural Grass Versus Artificial Turf. Int J Sports Physiol Perform. 2019; 14(9).
49. López-Fernández J, Sánchez-Sánchez J, Garciá-Unanue J, Felipe JL, Colino E, Gallardo L. Physiological and physical responses according to the game surface in a soccer simulation protocol. Int J Sports Physiol Perform. 2018; 13(5):612–9.
50. Brito Â, Roriz P, Silva P, Duarte R, Garganta J. Effects of pitch surface and playing position on external load activity profiles and technical demands of young soccer players in match play. Int J Perform Anal Sport. 2017; 17(6):902–18.
51. Trewin J, Meylan C, Varley MC, Cronin J. The influence of situational and environmental factors on match-running in soccer: a systematic review. Sci Med Footb [Internet]. 2017; 1(2):183–94. Available from: https://doi.org/10.1080/24733938.2017.1329589.
52. Gonçalves LGC, Clemente F, Palucci Vieira LH, Bedo B, Puggina EF, Moura F, et al. Effects of match location, quality of opposition, match outcome, and playing position on load parameters and players' prominence during official matches in professional soccer players. Hum Mov. 2021; 22(3):35–44.
53. Rago V, Silva J, Mohr M, Randers M, Barreira D, Krustrup P, et al. Influence of opponent standard on activity profile and fatigue development during preseasonal friendly soccer matches: a team study. Res Sports Med. 2018; 26(4):413–24.

54. Lago C. The influence of match location, quality of opposition, and match status on possession strategies in professional association football. J Sports Sci. 2009; 27(13):1463–9.
55. Rampinini E, Coutts AJ, Castagna C, Sassi R, Impellizzeri FM. Variation in top level soccer match performance. Int J Sports Med. 2007; 28(12):1018–24.
56. Varley MC, Gregson W, McMillan K, Bonanno D, Stafford K, Modonutti M, et al. Physical and technical performance of elite youth soccer players during international tournaments: influence of playing position and team success and opponent quality. Sci Med Footb. 2017; 1(1):18–29.
57. Lago-Peñas C, Kalén A, Lorenzo-Martinez M, López-Del Campo R, Resta R, Rey E. Do elite soccer players cover longer distance when losing? Differences between attackers and defenders. Int J Sports Sci Coach. 2021; 16(3):840–7.
58. Casamichana D, Castellano J. Time-motion, heart rate, perceptual and motor behaviour demands in small-sides soccer games: Effects of pitch size. J Sports Sci. 2010; 28(14):1615–23.
59. Dello Iacono A, McLaren SJ, Macpherson TW, Beato M, Weston M, Unnithan VB, et al. Quantifying Exposure and Intra-Individual Reliability of high-Speed and Sprint Running During Sided-Games Training in Soccer Players: A Systematic Review and Meta-analysis. Sports Med. 2023; 53(2):371–413.
60. Riboli A, Coratella G, Rampichini S, Ce E, Esposito F. Area per player in small-sided games to replicate the external load and estimated physiological match demands in elite soccer players. PLoS One. 2020; 15:1–15.
61. Riboli A, Esposito F, Coratella G. Small-Sided Games in Elite Football: Practical Solutions to Replicate the 4-min Match-Derived Maximal Intensities. J Strength Cond Res. 2023; 37(2):366–374.
62. Martín-García A, Castellano J, Méndez Villanueva A, Gómez-Díaz A, Cos F, Casamichana D. Demands of Ball Possession Games in Relation to the Most Demanding Passages of a Competitive Match. 2020; (March):1–9.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.134753
© Institute of Sport – National Research Institute

Predictive analysis of ratings of perceived exertion in elite Gaelic football

AUTHORS: Dermot Sheridan[1], Aidan J. Brady[2], Dongyun Nie[1], Mark Roantree[1,2]

[1] School of Computing, Dublin City University, Dublin, Ireland
[2] Insight Centre for Data Analytics, Dublin City University, Dublin, Ireland

ABSTRACT: This study aimed to compare the predictive accuracy of absolute and relative external load indices (ELI) across three machine learning models, and predict the rating of perceived exertion (RPE) of elite Gaelic football players using ELI, personal characteristics, wellness scores, and training workloads. ELI and related variables were collected from 49 elite Gaelic football players over three competitive seasons resulting in 1617 observations. ELI included total distance, high speed running distance ($\geq 4.72\ m \cdot s^{-1}$), and number of accelerations and decelerations ($n \pm 3\ m \cdot s^{-2}$), expressed in both absolute and relative terms. Variables related to personal characteristics, wellness scores, and training workloads were also included. Data were analysed using decision tree, random forest (RF), and bootstrap aggregation (BS) models. The RF model had the highest predictive accuracy using absolute and relative ELI only, at 54.3% and 48.3%, respectively. Total and relative distance were the strongest predictors of RPE in the RF model, accounting for 38.8% and 27.9% of the normalised importance. The BS model had the highest accuracy at 67.0% and 65.2% for absolute and relative ELI when performed in conjunction with the related variables, respectively. The current models demonstrate potential to predict RPE and subsequently optimise training load in Gaelic football.

CITATION: Sheridan D, Brady AJ, Nie D, Roantree M. Predictive analysis of ratings of perceived exertion in elite Gaelic football. Biol Sport. 2024;41(4):61–68.

Received: 2023-05-11; Reviewed: 2023-11-23; Re-submitted: 2023-12-03; Accepted: 2024-01-27; Published: 2024-03-06.

Corresponding author:
Dermot Sheridan
School of Computing
Dublin City University
Glasnevin, Dublin 9
Ireland
E-mail: dermot.sheridan36@mail.dcu.ie
Tel.: +353 1 7008980

ORCID:
Dermot Sheridan
0000-0003-3687-1943

Aidan Brady
0000-0002-9427-5771

Dongyun Nie
0000-0003-3109-5762

Mark Roantree
0000-0002-1329-2570

Key words:
Athlete monitoring
External load
Global positioning systems
Machine learning
Team sports

INTRODUCTION

Effective monitoring and manipulation of an athletes training load is central to eliciting improvements in physical performance, and limiting the risk of injury and/or illness [1]. In invasion field-based team sports (IFTS) such as soccer, Gaelic football, and rugby, training load is typically quantified using external, internal, or a combination of external and internal load indices [2, 3]. External load represents the physical work performed by a player during training or match-play [4]. Internal load represents the psycho-physiological response incurred in response to an external stimulus during training or match-play [1]. Global positioning system technology (GPS) provides large quantities of valid and reliable data pertaining to a players speed and distance that can be quantified in real-time and is the most common method of external load monitoring in IFTS [5, 6]. Internal load can be quantified objectively using blood lactate and/or heart rate, or subjectively using ratings of perceived exertion (RPE). In IFTS, a RPE-based approach is widely used as it is valid, non-invasive, and low cost [7, 8].

The collective nature of IFTS training and use of drill based scenarios such as small sided games [9] means players are regularly prescribed the same external load. Training prescription based on external load indices (ELI) can however, result in considerable inter-individual variation in RPE [10–12]. This is an important consideration when manipulating external load as it is the internal load that promotes adaptation [13]. Prescription of training using internal load indices such as RPE are therefore desirable. However, RPE can only be collected following the cessation of training or match-play, with large differences between coaches intended RPE and athletes subsequent RPE [14, 15].

A limited number of studies have attempted to predict RPE using machine learning models by incorporating a combination of ELI and related contextual factors such as the athletes physical fitness level, personal characteristics, wellness scores, and training and match history [11, 16–19]. Using artificial neural networks (ANN) RPE was more accurately predicted compared to traditional statistical approaches using total distance, relative distance, absolute high speed running ($> 4.0\ m \cdot s^{-1}$) and percentage of total distance at high speed [root mean square error (RMSE) 1.85 vs. 1.42] for a group of Australian football players [16]. Total distance was identified as having the highest importance score for predictive accuracy [16]. More recently, using eight relative ELI collected during soccer training in a decision tree (DT) model, RPE prediction had a RMSE of 1.62 with relative high speed running ($> 5.5\ m \cdot s^{-1}$) having the highest importance score [18]. Inclusion of heart rate percentages, and variables

pertaining to the athletes individual characteristics improved the predictive accuracy of a gradient boosting machine in soccer with a RMSE of 0.93 although only 47.6% of predictions were correct [17].

While these models demonstrate value for predicting RPE, lack of consistency in the variables incorporated in the models, in particular the lack of standardisation of the ELI, and differences in machine learning models between studies limit the generalisability of these results to other IFTS such as Gaelic football. Further, although soccer, Australian football, rugby and Gaelic football are IFTS, players in each sport have a unique activity profile due to several factors including differences in playing rules, pitch size and playing time [20]. For example, the relative playing area per player is ~425 m^2 in Gaelic football, compared to ~320 m^2 in soccer [21]. Further analyses are therefore required to examine differences between IFTS and which indices have the greatest influence on model accuracy.

The aims of this study were to compare the accuracy of absolute and relative ELI across DT, random forest (RF), and bootstrap aggregation (BS) models in predicting RPE for a cohort of elite Gaelic football players and to examine the predictive accuracy of these models using ELI, personal characteristics, wellness scores, and training workloads. It was hypothesised that accuracy would be higher using absolute ELI, and that inclusion of variables related to personal characteristics, wellness scores, and training workloads would improve the accuracy of the DT, RF, and BS models.

MATERIALS AND METHODS

Participants

Forty-nine elite Gaelic football players (mean ± standard deviation (SD), age, 25.6 ± 4.0 y; height, 1.82 ± 0.06 m; body mass, 82.0 ± 7.1 kg) from one inter-county team gave written informed consent to participate in this study. The team were competing in Division 2 or Division 3 of the National Football League during the data collection period. Inclusion criteria was limited to outfield players. Ethical approval was obtained from Dublin City University Research Ethics Committee (DCU/REC/2021/267) in accordance with the Declaration of Helsinki.

Experimental design

GPS technology was used to measure the activity levels of elite Gaelic football players during training and match-play in the 2020, 2021 and 2022 inter-county seasons. RPE was recorded from players on a one-to-one basis following the completion of each training session and match. Training sessions were limited to field-based sessions, and were completed on a grass playing surface of approximately 140 m in length and 80 m in width. A total of 1616 GPS data files and concomitant measures of RPE were recorded. This included 96 training sessions and 44 matches resulting in 1205 and 411 records, respectively. A total of 562, 575, and 479 records were collected during the 2020, 2021, and 2022 playing seasons. The median (range) number of observations per player was 29 (2–98) with a mean ± SD of 32.6 ± 22.9.

Data collection

RPE was measured using the modified Borg CR10 scale as outlined previously [8]. Ratings were recorded approximately 30 min after each training session and match using a mobile application (Smartabase, v.6.8.08, Fusion Sport, Milton, Australia). The use of a mobile application allowed ratings to be recorded privately, without the influence of peer presence or other related environmental factors [22]. All players were familiar with the use of the CR10 scale prior to participation in the present study. RPE was subsequently categorised as low (RPE ≤ 5, n = 461), moderate (RPE 6–7, n = 710), and high (RPE ≥ 8, n = 446). These categories have been used previously in IFTS [12, 23] and are associated with the three physiological exercise intensity domains [24].

External indices of activity were collected using GPS units sampling at a rate of 18 Hz (GPEXE LT, Exelio, Italy). During each training session and match, players wore an individual GPS unit that was positioned between the scapulae in a custom-made undergarment. These units have shown *good* to *moderate* (< 10% typical error of estimate) validity, and *good* (< 5% coefficient of variation) reliability for distance covered across a range of movement speeds in a team-sport specific circuit [5, 25]. Following each training session and match, data was downloaded to the manufacturers proprietary software (GPEXE Bridge v.6.9.25) to remove values unrelated to the training session or match. Forty-two distinct movement variables related to speed and distance were extracted from each GPS data file. Prior to inclusion in the models, multicollinearity tests were performed for all GPS variables. Where the variance inflation factor (VIF) exceeded 5, variables were sequentially removed in line with expert knowledge on the practical utility of each [2]. The remaining movement variables included in the models were total distance, high speed distance (≥ 4.72 $m \cdot s^{-1}$), and number of accelerations and decelerations (n ± 3 $m \cdot s^{-2}$) expressed both in absolute terms independent of playing time, and relative terms in metres and distance per unit time.

Stature was measured to the nearest 0.1 cm using a portable stadiometer (model 213, SECA, Hamburg, Germany). Body mass was measured to the nearest 0.1 kg using a portable digital scale (model 813, SECA < Hamburg, Germany). Lean mass index and body fat percentage were assessed using duel-energy x-ray absorptiometry (DEXA). Age, body mass index, playing position, and playing experience, classified as the number of years playing at the elite level of Gaelic football, were also included. Maximal aerobic speed (MAS) was determined using the time taken to complete a 1200 m time-trial (TT). The TT was performed at the beginning of each playing season. Where a player was unable to complete the TT (4%), the group mean was entered as their MAS.

Perceived wellness was examined prior to each training session and match using a 5 item questionnaire that was submitted through a mobile application (Smartabase, v.6.8.08, Fusion Sport, Milton, Australia). Each item was rated on a 10-point scale. The individual items were subsequently categorised as muscle soreness, sleep quality, or energy levels using the average score of each item in the

section. To provide greater information on the data and time of each training session or match, session time (am or pm), day of the week, month, and season were included in the models. Activity type and days to and from the next and previous training session or match, respectively, were also included. Acute:chronic workload ratio (ACWR) indices were used to monitor changes in workload over a given training period. A total of 21 indices were generated. After examination of multicollinearity, four ACWR variables remained which were 7-d total distance, 28-d total distance, ACWR total distance, and ACWR high speed distance.

Statistical analysis

To examine the performance of ELI, with and without the inclusion of related variables, in the prediction of RPE, three machine learning models were performed on four occasions each. The machine learning models were DT, which create a tree-like graph of decisions based on the values of features, RF, which creates an ensemble of DT where a combination of learning models increases the overall result, and BS, which is another ensemble method that combines the predictions from multiple machine learning algorithms to make more accurate predictions. The first two iterations of each model were used to examine the difference in predictive accuracy between the absolute and relative ELI, independent of related variables. The third and fourth iterations examined the predictive accuracy of the absolute and relative external load variables together with perceived wellness, ACWR, and athlete-specific variables, respectively.

The variable sets included in the third and fourth iteration of each model were examined for strength of association prior to inclusion in the models using the Spearman rank-order correlation coefficient. The magnitude of association was interpreted as trivial (0.0 to 0.1), small (0.1 to 0.3), moderate (0.3 to 0.5), large (0.5 to 0.7), very large (0.7 to 0.9), or almost perfect (0.9 to 1.0) [26]. Where the

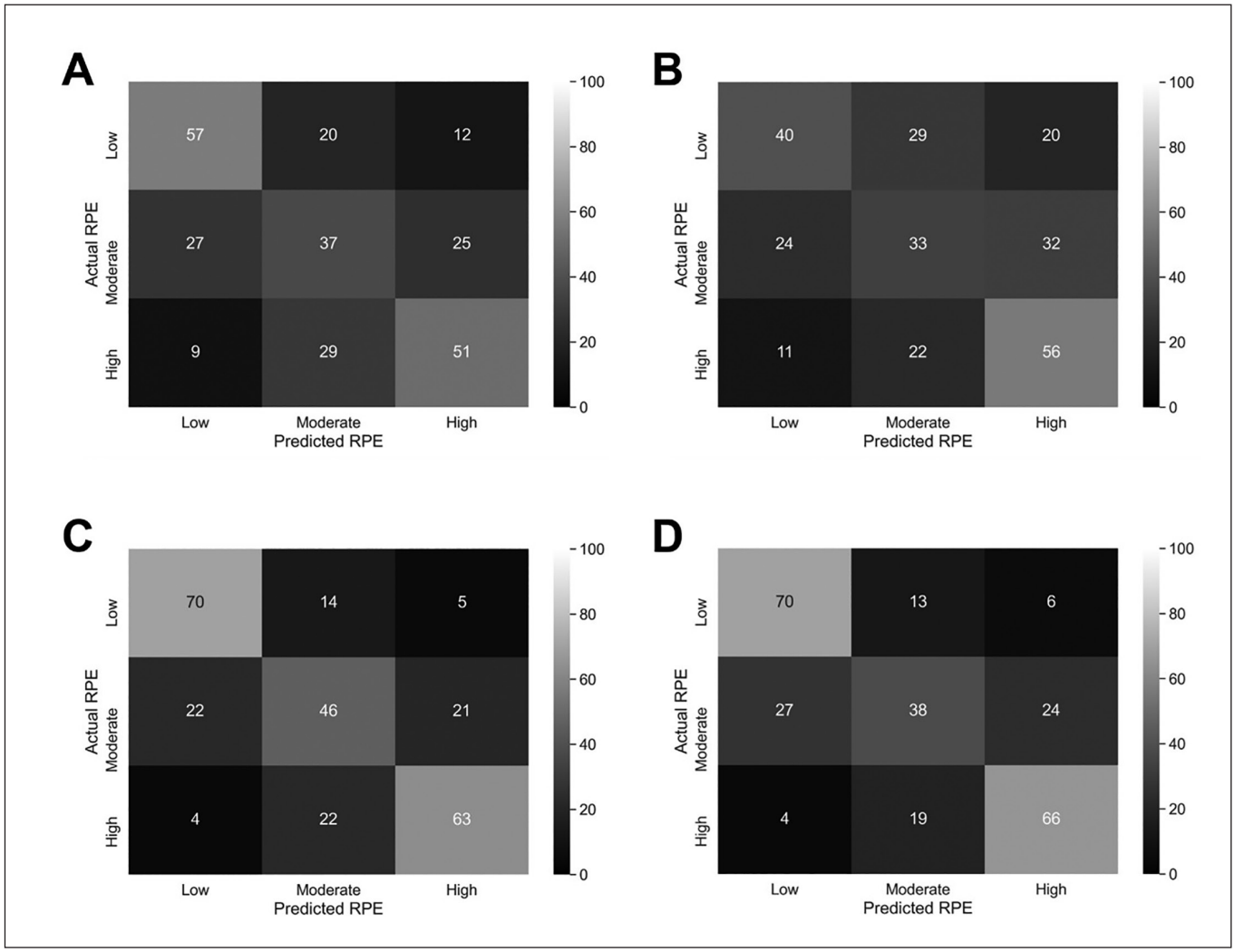


FIG. 1. Confusion matrix of the actual RPE and predicted RPE for the (A) RF model using absolute ELI only, (B) RF model using relative ELI only, (C) BS model using absolute ELI and related variables, and (D) BS model using relative ELI and related variables.

correlation coefficient exceeded 0.5, variables were removed in line with expert consensus on the practical importance of each. All variables were subsequently normalised prior to inclusion in the models. The categorisation of RPE resulted in an unbalanced number of records in each category. A down-sampling method was therefore employed to take the smallest number of records from each category and randomly select an equal number of records for the other RPE categories (n = 446).

The DT, RF, and BS models require a learning dataset to construct the model, and a testing set to evaluate the models performance. The learning set in the present study consisted of 80% of the data while the testing set contained the remaining 20%. Importance scores for each variable in making correct predictions were calculated from the DT and RF models. The importance score of each variable is a measure of the magnitude by which the model-predicted RPE differs between the values of each variable. The importance score was determined through the number of expressions of a variable in the created DT. All models were performed in Python (v.3.5) programming software (Python Software Foundation, Wilmington, DE, USA). A one-way analysis of variance was also performed to examine the differences in each model variable across the low, moderate, and high RPE categories. When a significant effect of group was indicated, *post hoc* testing was then performed with Bonferroni correction. Data are presented as mean ± SD, unless otherwise stated. The significance level was set at $\alpha \leq 0.05$ for all tests.

RESULTS

The mean ± SD of each model variable in the low, moderate, and high RPE categories is presented in Table 1. The accuracy of the DT, RF and BS models for predicting RPE for each dataset is presented in Table 2. The RF model had the highest accuracy score at 54.3% and 48.3% when using absolute and relative ELI, respectively. The normalised importance score for each absolute and relative external load measure in the RF models is presented in Table 3 and Table 4, respectively. For absolute ELI, total distance had the highest importance score at 0.388. Relative distance had the highest importance score of the relative ELI at 0.279. The BS model had the highest predictive accuracy after inclusion of variables related to personal characteristics,

TABLE 1. Descriptive analysis of each model variable

Variable	Low (RPE ≤4)	Moderate (RPE 5 – 7)	High (RPE ≥8)	P value
Age (yr)	26.1 ± 4.1	25.7 ± 4.2	24.4 ± 3.7[c]	0.018
Lean mass index ($m \cdot kg^2$)	21.0 ± 1.4	20.7 ± 2.3	20.6 ± 1.3	0.333
Body fat percentage (%)	14.3 ± 4.0	14.8 ± 3.6	14.2 ± 4.0	0.484
Maximal aerobic speed ($m \cdot s^{-1}$)	4.73 ± 0.20	4.75 ± 0.20	4.72 ± 0.24	0.595
Duration (min)	60.6 ± 21.0	72.1 ± 22.8[b]	83.5 ± 27.0[a,e]	< 0.001
Total distance (m)	4951 ± 1457	6128 ± 2000[b]	8140 ± 3131[a,d]	< 0.001
Relative distance ($m \cdot min^{-1}$)	84.3 ± 18.4	88.1 ± 22.0	98.7 ± 21.3[a,e]	< 0.001
High speed distance (≥4.72 $m \cdot s^{-1}$)	816 ± 478	921 ± 537	1234 ± 675[a,d]	< 0.001
Relative high speed distance (≥4.72 $m \cdot s^{-1}$)	14.1 ± 7.7	13.9 ± 8.6	15.3 ± 8.1	0.450
Accelerations (n)	9.8 ± 6.7	12.2 ± 8.3	12.1 ± 7.3	0.053
Relative accelerations ($n \cdot min^{-1}$)	0.2 ± 0.2	0.2 ± 0.2	0.2 ± 0.1	0.490
Decelerations (n)	6.2 ± 4.8	9.4 ± 6.1[b]	14.1 ± 8.0[a,d]	< 0.001
Relative decelerations ($n \cdot min^{-1}$)	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1[a]	< 0.001
Muscle soreness (AU)	5.0 ± 2.7	5.4 ± 2.8	5.3 ± 2.7	0.651
Sleep quality (AU)	7.9 ± 1.3	8.2 ± 1.0	8.0 ± 1.0	0.082
Energy level (AU)	7.8 ± 1.2	7.9 ± 1.0	7.7 ± 1.5	0.633
7-d total distance	14031 ± 6880	15958 ± 5889	17115 ± 6882[b]	0.007
28-d total distance	47846 ± 23520	44207 ± 21012	38291 ± 22223[c]	0.016
ACWR total distance	0.95 ± 0.19	1.03 ± 0.17[b]	1.05 ± 0.15[a]	< 0.001
ACWR high speed distance	1.03 ± 0.33	1.03 ± 0.37	1.08 ± 0.25	0.463
Days to last match	5.2 ± 5.4	3.5 ± 4.7[c]	1.1 ± 3.2[a,d]	< 0.001
Days to next match	4.1 ± 3.4	7.1 ± 5.5[a]	9.4 ± 5.7[a,e]	< 0.001

ACWR, acute:chronic workload ratio. [a], $P < 0.001$ vs. Low; [b], $P < 0.01$ vs. Low; [c], $P < 0.05$ vs. Low; [d], $P < 0.001$ vs. Moderate; [e], $P < 0.01$ vs. Moderate.

TABLE 2. Accuracy of the decision tree, random forest, and bootstrap aggregation models for each dataset

	Decision tree	Random forest	Bootstrap aggregation
Absolute ELI	48.7%	54.3%	52.8%
Relative ELI	47.6%	48.3%	42.3%
Absolute ELI and related variables	57.7%	61.0%	67.0%
Relative ELI and related variables	58.4%	61.0%	65.2%

ELI, external load indices.

TABLE 3. Normalised importance scores from the random forest model for absolute external load indices.

Variable	Importance score
Total distance (m)	0.388
High speed distance (≥ 4.72 m·s^{-1})	0.259
Decelerations (n)	0.193
Accelerations (n)	0.160

TABLE 4. Normalised importance scores from the random forest model for relative external load indices.

Variable	Importance score
Relative distance (m·min^{-1})	0.279
Relative accelerations (n·min^{-1})	0.256
Relative decelerations (n·min^{-1})	0.249
Relative high speed distance (≥ 4.72 m·s^{-1})	0.216

wellness scores, and training workloads alongside the absolute and relative ELI at 67.0% and 65.2% accuracy, respectively. The accuracy of the RF and BS models for the low, moderate and high RPE categories are presented in a confusion matrix in Figure 1.

DISCUSSION

The aims of the present study were to compare the accuracy of absolute and relative ELI across three machine learning models when predicting RPE, examine the predictive accuracy of the three models using ELI alongside variables related to personal characteristics, wellness scores, and training workloads, and compare the accuracy between RPE categories. The RF model had the highest accuracy for predicting RPE at 54.3% and 48.3% using only absolute and relative ELI, respectively. Inclusion of related variables alongside the ELI improved the predictive accuracy of the three models, which was highest using the BS model at 67.0% and 65.2% for the absolute and relative datasets, respectively.

Previous studies that have attempted to predict RPE from external load have used absolute [17], relative [18], or a combination of both absolute and relative ELI [11] yet none have compared the predictive accuracy between absolute and relative indices. Comparison of these indices will enable a more objective approach to variable selection in future predictive models. A DT, RF, and BS model were run on absolute ELI, followed by relative ELI resulting in six different results sets for comparison. In all models, ELI expressed in absolute terms had a greater accuracy by 1.1–10.5%. The RF model, which had the best accuracy for both absolute and relative ELI, was 6% higher using the absolute indices. A recent examination of the contribution of training intensity and duration to training load in rugby league and rugby union reported that session duration accounted for a larger proportion of the total variance in training load than session intensity [27]. This supports the findings of the present study in that ELI, expressed in absolute terms, appear to be more influential on RPE although relative ELI are more commonly reported in IFTS [6].

In the present study, RPE was divided into three categories. This approach has been used previously when examining factors influencing RPE in IFTS [12], and with other cohorts, including endurance athletes [28]. The boundaries of these categories are reflective of the first and second ventilatory thresholds [24], and may be used to demarcate entry into the three distinct physiological exercise intensity domains [29]. This approach may be more practically relevant given the differing physiological adaptations that can occur across the exercise intensity domains, and provide coaches with a larger target window when using RPE for training prescription [23].

The RF model in the present study correctly predicted 64%, 42% and 57% of cases in the low, moderate and high RPE categories using absolute ELI. When using relative ELI, the predictive accuracy in the low, moderate, and high RPE categories was 45%, 37%, and 63%, respectively. The width of the moderate category may have contributed to the lower predictive accuracy compared to the low and high RPE categories. It is difficult to compare the results of the present study with previous research as most other models have attempted to predict the specific RPE value rather than a distinct class [11, 17, 18]. However, one study reported an accuracy of 47.6% for single RPE values which was increased to 91.7% when using a 'loose accuracy' approach, where predictions within a range of ± 1 unit of the actual value were marked correct [17]

demonstrating the similarities of predictions at the boundary values. Notably, the latter study used a combination of ELI and a range of related variables yet had a lower accuracy score than both RF models in the present study using ELI only.

The accuracy score across RPE categories was lowest in the moderate category. This is likely due to the boundary overlap with the low and high RPE categories and the moderate category having the narrowest range. A surprising finding of the present study was that accuracy in the high category considerably outperformed the low category in the relative model. It is plausible that the relative model performed better in the high category as the differences between the ELI were more pronounced. For example, relative distance differed by 3.8 $m \cdot min^{-1}$ between the low and moderate categories but differed by 10.6 $m \cdot min^{-1}$ between the moderate and high category. By contrast, the low category outperformed the high category in the absolute model, although the difference was less pronounced.

Machine learning allows for the extraction of importance scores for the variables included in the RF models. As variable importance is calculated on the number of variables used in the model, there is a direct effect on the calculation of importance with the complexity of the algorithm and the number of variables considered. An understanding of the contribution of each variable to the predictive accuracy of RPE can allow more effective planning and control of training loads. In the present study, total distance had the highest importance score of the four absolute and the four relative ELI. This is in agreement with a recent meta-analysis where total distance had the strongest association with RPE [3] and the abovementioned analysis in rugby league and rugby union [27]. Equally, total distance was the strongest predictor of RPE using ANN [16]. By contrast, relative high speed running (> 5.5 $m \cdot s^{-1}$) was the strongest predictor of RPE, accounting for 61%, with relative distance having the lowest score in youth soccer when using a DT model [18]. These differences may be due, at least in part, to differences in the activity profile of Gaelic football and soccer, and the role of player age as youth players report higher RPE values in training than adult players [30, 31]. The type of machine learning model and high speed running thresholds may also have contributed to these differences.

The inclusion of a range of variables alongside ELI provided six additional results sets. This improved the predictive accuracy of all three models in the present study. Of note, the BS model improved by 14.2% and 12.9% using variables related to personal characteristics, wellness scores, and training workloads alongside the absolute and relative ELI, respectively. The BS model outperformed both the DT and RF models after inclusion of related variables although the DT and RF models improved by an average of 9.9% and 9.7%, respectively. The inclusion of a wide variety of variables related to athletic performance has been recommended to provide a more holistic approach [17, 19]. Those chosen for inclusion in the present study were factors shown to influence RPE and the activity performed during Gaelic football, such as body composition, player experience, physical fitness levels, accumulated training load, and sleep quality and muscle soreness [32–34], and those which have improved the predictive accuracy of previous models, such as individual characteristics and supplementary variables that contributed 4.5–33% accuracy in soccer [17]. The accuracy in the low RPE category improved to 78.7% in both BS models. In the high RPE category, accuracy improved to 70.8% and 74.2% alongside the absolute and relative ELI, respectively. These findings demonstrate the importance of including variables beyond ELI to predict RPE and highlight the potential practical application to IFTS.

Unlike the RF models, the contribution of each variable in the BS models cannot be quantified making it difficult to discern which factors are of greatest importance and should be prioritised during training and match-play, particularly those which were significantly different between groups such as days to/from last match and cumulative distance. However, the variables included in the present study can be collected in a relatively low cost, time-efficient manner and are already routine practice within many IFTS [1]. The relatively small number of training observations is a limitation of the present study. A larger dataset in machine learning can potentially improve the accuracy of the model by providing more representative data, reducing variance, and improving feature representation, but the quality and relevance of the data are also important factors that must be considered. The data collection was limited to a single team over a three-season period which occurred during a global pandemic that disrupted the normal training schedule and may have influenced the fitness levels of participants due to restricted movements and limited collective training.

Practical applications

The findings of the present study highlight that for both absolute and relative ELI, distance covered has the greatest contribution to the predictive accuracy while the contribution of high speed running, accelerations and decelerations is largely similar. Coaches and practitioners should however, be cognisant of the differences in predictive accuracy between absolute and relative ELI and the subsequent changes in the importance score of each variable, particularly when using these variables to prescribe training and develop training programmes. The improved accuracy scores following inclusion of variables related to personal characteristics, wellness scores, and training workloads demonstrates that ELI alone do not adequately capture or predict RPE. A more holistic approach is therefore recommended. The higher accuracy scores in the low and high RPE categories compared to the moderate category suggests that when using RPE to predict a players response to training, a polarised training approach consisting of low volume, high intensity efforts and high volume, low intensity efforts may be the most suitable approach and increase the likelihood of eliciting the desired physiological stimulus.

CONCLUSIONS

The accuracy of the three machine learning models to predict RPE in a cohort of elite Gaelic football players was higher when using

absolute ELI compared to relative ELI emphasising the importance of volume over intensity. The inclusion of variables related to personal characteristics, wellness scores, and training workloads increased the accuracy of all three models, in particular a BS model which performed strongly in the low and high RPE categories. These models may be used to assist coaches and practitioners in planning, monitoring, and evaluating the demands of training and match-play.

Funding

This work was conducted with the financial support of Science Foundation Ireland under grant numbers SFI/12/RC/2289_P2 and SFI/18/CRT/6223.

Declaration of interest

No conflict of interest, financial or otherwise, is declared by the authors.

Author contributions

DS, AB, and MR designed the study; DS collected the data; DS, AB, and DN were responsible for data cleaning and processing, DS and DN performed the statistical analysis; DS, AB and MR interpreted the results and drafted the first manuscript, all co-authors provided substantial edits and approved the final manuscript. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

REFERENCES

1. Bourdon PC, Cardinale M, Murray A, Gastin P, Kellmann M, Varley MC, Gabbett TJ, Coutts AJ, Burgess DJ, Gregson W, Cable NT. Monitoring Athlete Training Loads: Consensus Statement. Int J Sports Physiol Perform. 2017; 12(s2):161–70.
2. Akenhead R, Nassis GP. Training Load and Player Monitoring in High-Level Football: Current Practice and Perceptions. Int J Sports Physiol Perform. 2016; 11(5):587–93.
3. McLaren SJ, Macpherson TW, Coutts AJ, Hurst C, Spears IR, Weston M. The Relationships Between Internal and External Measures of Training Load and Intensity in Team Sports: A Meta-Analysis. Sports Med. 2018; 48(3):641–58.
4. Impellizzeri FM, Marcora SM, Coutts AJ. Internal and External Training Load: 15 Years On. Int J Sports Physiol Perform. 2019; 14(2):270–3.
5. Scott MTU, Scott TJ, Kelly VG. The Validity And Reliability Of Global Positioning Systems In Team Sport: A Brief Review. J Strength Cond Res. 2016; 30(5):1470–90.
6. Whitehead S, Till K, Weaving D, Jones B. The Use of Microtechnology to Quantify the Peak Match Demands of the Football Codes: A Systematic Review. Sports Med. 2018; 48(11):2549–75.
7. Coutts AJ, Rampinini E, Marcora SM, Castagna C, Impellizzeri FM. Heart rate and blood lactate correlates of perceived exertion during small-sided soccer games. J Sci Med Sport. 2009; 12(1):79–84.
8. Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, Doleshal P, Dodge C. A New Approach to Monitoring Exercise Training. J Strength Cond Res. 2001; 15(1):109–15.
9. Halouani J, Chtourou H, Gabbett T, Chaouachi A, Chamari K. Small-Sided Games in Team Sports Training: A Brief Review. J Strength Cond Res. 2014; 28(12):3594–618.
10. Gallo T, Cormack S, Gabbett T, Williams M, Lorenzen C. Characteristics impacting on session rating of perceived exertion training load in Australian footballers. J Sports Sci. 2015; 33(5):467–75.
11. Jaspers A, De Beéck TO, Brink MS, Frencken WGP, Staes F, Davis JJ, Helsen WF. Relationships Between the External and Internal Training Load in Professional Soccer: What Can We Learn From Machine Learning? Int J Sports Physiol Perform. 2018; 13(5):625–30.
12. Lovell TWJ, Sirotic AC, Impellizzeri FM, Coutts AJ. Factors Affecting Perception of Effort (Session Rating of Perceived Exertion) During Rugby League Training. Int J Sports Physiol Perform. 2013; 8(1):62–9.
13. Impellizzeri FM, Rampinini E, Coutts AJ, Sassi A, Marcora SM. Use of RPE-Based Training Load in Soccer. Med Sci Sports Exerc. 2004; 36(6):1042–7.
14. Brink MS, Frencken WGP, Jordet G, Lemmink KAPM. Coaches' and Players' Perceptions of Training Dose: Not a Perfect Match. Int J Sports Physiol Perform. 2014; 9(3):497–502.
15. Foster C, Heimann KM, Esten PL, Brice G, Porcari JP. Differences in perceptions of training by coaches and athletes. S Afri J Sports Med. 2001; 8:3–7.
16. Bartlett JD, O'Connor F, Pitchford N, Torres-Ronda L, Robertson SJ. Relationships Between Internal and External Training Load in Team-Sport Athletes: Evidence for an Individualized Approach. Int J Sports Physiol Perform. 2017; 12(2):230–4.
17. Geurkink Y, Vandewiele G, Lievens M, de Turck F, Ongenae F, Matthys SPJ, Boone J, Bourgois JG. Modeling the Prediction of the Session Rating of Perceived Exertion in Soccer: Unraveling the Puzzle of Predictive Indicators. Int J Sports Physiol Perform. 2019; 14(6):841–6.
18. Marynowicz J, Lango M, Horna D, Kikut K, Andrzejewski M. Predicting ratings of perceived exertion in youth soccer using decision tree models. Biol Sport. 2022; 39(2):245–52.
19. Rossi A, Perri E, Pappalardo L, Cintia P, Iaia F. Relationship between External and Internal Workloads in Elite Soccer Players: Comparison between Rate of Perceived Exertion and Training Load. Appl Sci. 2019; 9(23):5174.
20. Varley MC, Gabbett T, Aughey RJ. Activity profiles of professional soccer, rugby league and Australian football match play. J Sports Sci. 2014; 32(20):1858–66.
21. Brady AJ, Moyna NM, Scriney M, McCarren A. Activity profile of elite Gaelic football referees during competitive match play. Sci Med Football. 2023; 7(1):57–63.
22. Minett GM, Fels-Camilleri V, Bon JJ, Impellizzeri FM, Borg DN. Peer Presence Increases Session Ratings of Perceived Exertion. Int J Sports Physiol Perform. 2022; 17(1):106–10.
23. Moreira A, Bilsborough JC, Sullivan CJ, Cianciosi M, Aoki MS, Coutts AJ. Training Periodization of Professional Australian Football Players During an Entire Australian Football League Season. Int J Sports Physiol Perform. 2015; 10(5):566–71.
24. Seiler KS, Kjerland GØ. Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? Scand J Med Sci Sports. 2006; 16(1):49–56.
25. Hoppe MW, Baumgart C, Polglaze T, Freiwald J. Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. PLoS ONE. 2018; 13(2):e0192708.
26. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive Statistics for Studies in Sports Medicine and Exercise Science. Med Sci Sports Exerc. 2009; 41(1):3–12.
27. Weaving D, Dalton-Barron N, McLaren S, Scantlebury S, Cummins C, Roe G, Jones B, Beggs C, Abt G. The relative contribution of training intensity and duration to daily measures of training

load in professional rugby league and union. J Sports Sci. 2020; 38(14):1674–81.
28. Stellingwerff T. Case Study: Nutrition and Training Periodization in Three Elite Marathon Runners. Int J Sport Nutr Exerc Metab. 2012; 22(5):392–400.
29. Jamnick NA, Pettitt RW, Granata C, Pyne DB, Bishop DJ. An Examination and Critique of Current Methods to Determine Exercise Intensity. Sports Med. 2020; 50(10):1729–56.
30. Gaudino P, Iaia FM, Strudwick AJ, Hawkins RD, Alberti G, Atkinson G, Gregson W. Factors Influencing Perception of Effort (Session Rating of Perceived Exertion) During Elite Soccer Training. Int J Sports Physiol Perform. 2015; 10(7):860–4.
31. Marynowicz J, Kikut K, Lango M, Horna D, Andrzejewski M. Relationship Between the Session-RPE and External Measures of Training Load in Youth Soccer Training. J Strength Cond Res. 2020; 34(10):2800–4.
32. Cullen BD, McCarren AL, Malone S. Ecological validity of self-reported wellness measures to assess pre-training and pre-competition preparedness within elite Gaelic football. Sport Sci Health. 2021; 17(1):163–72.
33. Malone S, Hughes B, Roe M, Mangan S, Collins K. Factors that Influence Session-Rating of Perceived Exertion in Elite Gaelic Football. J Strength Cond Res. 2020; 34(4):1176–83.
34. Daly LS, Catháin CÓ, Kelly DT. Do players with superior physiological attributes outwork their less-conditioned counterparts? A study in Gaelic football. Biol Sport. 2024; 41(1):163–74.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.134754
© Institute of Sport – National Research Institute

Effects of an 8-week pre-season targeted training on sprinting performance, agility and lower limb muscular asymmetries in elite soccer players

AUTHORS: Artur Gołaś[1], Przemysław Pietraszewski[1], Robert Roczniok[1], Artur Terbalyan[1], Adam Maszczyk[1], Rafał Opaliński[2], Adam Zając[1]

[1] Institute of Sport Sciences, The Jerzy Kukuczka Academy of Physical Education, Katowice, Poland
[2] InnoGIO, Warszawa, Poland

ABSTRACT: The purpose of this study was to determine the effects of an 8 week targeted training program on speed, agility, and muscle asymmetries in soccer players. 32 elite soccer players were recruited for the study. Their age, body mass, and body height were 25.8 ± 7.3 years, 77.4 ± 11.1 kg, and 177.5 ± 9.8 cm, respectively. After the warm-up, participants performed two maximum 30 m sprints with a 5-minute rest interval between trials. After the linear sprint test, performed two repetitions of the COD randomized ZigZag test. The tests were performed at the beginning and at the end of the pre-season, which lasted for 8 weeks. EMG was measured bilaterally from the quadriceps, hamstrings, and gluteal muscles with shorts made of knitted fabric similar to elastic clothes. Athletes in the experimental group performed sport-specific targeted strength training based on movement patterns 4 times per week (Monday, Tuesday, Thursday, and Friday). The training included 6 bodyweight exercises (Bird Dog, Single-Leg Glute Bridge, Dead Bug, Side Plank, Reverse Lunge, and Clamshell), performed unilaterally in 5 sets of 10 repetitions of each exercise. The load progression included an additional set in each successive week of the experiment. The data analysis showed significant improvement in 5 m and 30 m sprints after applying the 8-week targeted training protocol. A statistically significant improvement in performance was also observed after the 8-week training period in case of COD, while the speed deficit also decreased significantly. The greatest improvements were observed during the COD test. As a result of repeated COD training over a period of 8 weeks, its technique was improved. Implementation of training methods, which target specific aspects of soccer in the pre-season training routines can improve key motor abilities for that sports discipline. A comprehensive training approach including speed, agility, and resistance training based on specific movement patterns should be applied by strength and conditioning practitioners in soccer teams to achieve peak physical performance and reduce injury risk due to the partial elimination of muscular asymmetries.

CITATION: Gołaś A, Pietraszewski P, Roczniok R et al. Effects of an 8-week pre-season targeted training on sprinting performance, agility and lower limb muscular asymmetries in elite soccer players. Biol Sport. 2024;41(4):69–76.

Received: 2023-03-28; Reviewed: 2023-05-18; Re-submitted: 2024-01-12; Accepted: 2024-01-13; Published: 2024-03-06

Corresponding author:
Adam Maszczyk
Institute of Sport Sciences, The Jerzy Kukuczka Academy of Physical Education, Katowice, Poland
E:mail:
a.maszczyk@awf.katowice.pl

ORCID:
Artur Gołaś
0000-0002-6656-6993

Przemysław Pietraszewski
0000-0003-3371-9663

Robert Roczniok
0000-0001-6551-9151

Artur Terbalyan
0000-0002-3628-8849

Adam Maszczyk
0000-0001-9139-9747

Adam Zając
0000-0002-4374-4822

Key words:
Soccer
EMG
Running speed
Muscle patterns
Strength

INTRODUCTION

The game of soccer is constantly evolving. In terms of physical requirements, the game has become significantly faster. For example, statistics from the English Premier League indicate that players at all positions are covering greater distances, at higher speeds, than ever before. Often, a player performs 50 or more sprints in a match, and these actions can play a vital role in determining the outcome of the game [1, 2]. Players are also required to change direction more than a thousand times per game, or approximately every six or seven seconds. For modern players, speed and agility are two key components that contribute to the ultimate quality of performance [3, 4, 5]. Typical high-speed movements are performed in soccer within seconds and usually over a distance of 5 to 30 m. Considering the relatively short distance of soccer sprints it seems logical that coaches concentrate on developing acceleration rather than maximum sprinting speed. The ability to change direction (COD) while running at high speed is of great significance in team sports, such as soccer, because it better reflects match conditions [5, 6, 7, 8]. In football, the significance of preseason preparations cannot be overstated. Teams engage in rigorous training sessions, focusing on enhancing players' fitness, tactical understanding, and teamwork. These preparations lay the foundation for a successful season, helping players build chemistry, adapt to new strategies, and minimize the risk of injuries. Coaches meticulously plan drills, analyze opponents, and fine-tune strategies to ensure their squad is well-prepared for the challenges ahead. The preseason serves as a crucial time for players to sharpen their skills, cultivate cohesion, and foster a winning mentality that can propel them through the upcoming season.

The general adaptation syndrome (GAS) is one of the most significant principles applied in sports training. GAS describes the process the body of an athlete goes through when it is exposed to any kind of stress, positive or negative [9]. In a different sense, adaptation means the adjustment of the athlete's cells, tissues, organs and the whole body to the surrounding environment. If the environment changes, the organism also changes to survive and function under the new conditions. The training effects in the scientific literature are often presented in a two-dimensional manner, describing acute and delayed changes. Immediately after a training session, performance usually declines as a result of fatigue. An athlete should not expect to become stronger after 1 set of exercise or 1 training session. Exposing the athlete to systematic exposure to progressive training loads will allow for increased strength potential. From a practical point of view, there are four main variables that determine the course of the adaptation process: the size of stimuli, adjustment, specificity, and individualization.

In a nutshell, training loads can be dedicated to three types of stimuli. First of them – is overloading, in which the magnitude of the load is above the neutral level and positive adaptation can occur. The second one is sustaining, in which the load is in the neutral zone and the level of performance is maintained. The last type of stimulus is regenerative, in which the magnitude of the stimulus allows the implementation of repairing processes and provides opportunities for recovery [3].

Taking together, training adaptation can be classified by specific training effects into acute effects, chronic effects, cumulative effects, delayed effects, partial effects, and residual effects

Soccer matches require players to perform repetitive power-related activities such as sprinting, jumping, accelerating, decelerating, change of direction, and cutting interspersed with periods of low to medium-intensity activity (e.g., walking). Therefore, in soccer locomotion speed tests are most popular, e.g., covering a certain distance in a straight line (5–30 m) or with a change of direction [10]. The ability to COD while running at high speed is of great interest to soccer coaches and athletes as it reflects match conditions [7]. A measure that helps in assessing the isolated COD capacity is the COD deficit. The COD deficit corresponds to the difference in speed between the linear sprint and the task of an equal distance with a change of direction [11].

Analysis of movement patterns for optimizing athlete's development seems vital. Surface electromyography (sEMG) is a diagnostic tool in the field of clinical neurophysiology used to analyse the function of motor entities of a selected muscle or muscle groups by means of surface electrodes during exercise or at rest [12]. The data collected from EMG analysis provides information on whether a muscle is active or not, and informs about the fatigue and the activation or deactivation of a given muscle [13]

The advantage of EMG is displaying the results with speed and load data, which offers the opportunities for identification of the most involved muscle groups during the exercise [12]. Development of textile electrodes embedded in clothing that does not require careful placement of sensors or wires that restrict mobility may represent a new solution to the limitations of conventional surface electrodes [14].

Once the imbalance is identified, an intervention opportunity appears in the form of redefining the movement pattern. Thus, the introduction of direct intervention (ACUTE EFFECTS) before training, in the form of activating the weaker side or muscle group can be possible. The second option can be planning and implementing targeted resistance training over a specified period of time (TARGETED TRAINING), allowing for reduced imbalances and thus for long term improvement of the movement pattern (DELAYED EFFECTS). Such an intervention should be used both as an "activation warm-up" before the main training units or as a separate training session.

Functional asymmetry of the lower limbs (side-to-side asymmetry) greater than 15% [15] may increase the risk of knee injuries [13]. The dominance of one side of the body over the other may result in differences in the strength of particular muscle groups. Studies of soccer players have shown differences in strength and flexibility between the dominant and non-dominant limbs [16], and biomechanical asymmetries between each limb [17]. It has been proven that muscle strength deficiencies and asymmetries of lower limb muscles increase the risk of thigh muscle injury [18].

It has been documented that the lack of functional asymmetry between the muscles of the right and left leg occurs for results lower than 9% of their activity. When the difference in muscle activity between the right and left limbs or parts of the body is between 9% and 18%, a tendency for asymmetry can be observed. An asymmetry greater than 18% indicates a serious imbalance and its origin should be determined and corrected by appropriate measures to avoid [19].

Considering the above data, the purpose of this study was to determine the effects of an 8 week targeted training program on speed, agility, and muscle asymmetries in soccer players.

MATERIALS AND METHODS

Participants

32 elite soccer players were recruited for the study. Their age, body mass, and body height were 25.8 ± 7.3 years, 77.4 ± 11.1 kg, and 177.5 ± 9.8 cm, respectively. They were randomly divided into two 16-person control and experimental groups. The participants did not perform any strenuous exercises 48 hours prior to testing to avoid fatigue. The players were informed verbally and in writing about the procedures, possible risks, and benefits of the tests, and provided written consent before the start of the study. The study received the approval (nr.6/2021) of the Bioethics Committee at the Academy of Physical Education in Katowice, Poland.

Testing Procedures

The study was carried out on a treadmill at a multifunctional hall in The Jerzy Kukuczka Academy of physical education in Katowice.

The experimental session was conducted between 9:00 and 11:00 a.m. The session was preceded by a warm-up protocol, which included 5 minutes of jogging, several upper and lower body exercises like push-ups, body weight squats and split squats, 5- and 20-m sprints, and COD sprints. The running times were recorded by two pairs of dual-beam Witty Gate photocells (Microgate, Bolzano, Italy) with a measuring precision of 0.01 s. After the warm-up, participants performed two maximum 30 m sprints with a 5-minute rest interval between trials. After the linear sprint test, the soccer players rested for an additional 5 minutes and then performed two repetitions of the COD randomized ZigZag test [20]. The tests were performed at the beginning and at the end of the pre-season, which lasted for 8 weeks.

Training Procedures

The intervention consisted of an 8-week training program. Three types of training sessions were used: speed training, agility training, and targeted strength training. The speed session included 15 sprints over a distance of 30 m performed at submaximal or maximal intensity. The rest intervals between repetitions were 2 minutes. After 5 and 10 repetitions, the rest interval was extended to 5 minutes. The agility session included 15 30-m COD runs. The speed session was performed twice a week (Monday, and Thursday) while the agility session was performed 3 times a week (Tuesday, Wednesday, and Friday).

During this period athletes in the experimental group performed sport-specific targeted strength training based on movement patterns 4 times per week (Monday, Tuesday, Thursday, and Friday). The training included 6 bodyweight exercises (Bird Dog, Single-Leg Glute Bridge, Dead Bug, Side Plank, Reverse Lunge, and Clamshell), performed unilaterally in 5 sets of 10 repetitions of each exercise. The load progression included an additional set in each successive week of the experiment. Control group received regular circuit training with the same volume and intensity as the experimental group. In addition to speed, agility, and targeted strength training, the players carried out normal soccer training including technical and tactical drills. The training mentioned above was designed to reflect testing conditions as much as possible.

Electromyography

EMG was measured bilaterally from the quadriceps, hamstrings, and gluteal muscles with shorts made of knitted fabric similar to elastic clothes used for sports activities or functional underwear, with the exception of the possibility to measure EMG from the skin surface (Myontec Ltd, Kuopio and Suunto Ltd, Vantaa, Finland; [21]). To measure the average rectified EMG signal, bipolar electrode pairs were located on the distal part of the quadriceps, hamstrings, and glutes. The reference electrodes were located longitudinally along the left and right lateral sides (over tractus iliotibialis) providing valid and repeatable data [22]. The electrodes located on the quadriceps muscles collected data from vastus lateralis, vastus medialis and rectus femoris muscles. The vastus intermedius muscle is located deeply under the other muscles and thus was not included. The electrodes located on the hamstring muscles gathered the signal from the biceps femoris, semimembranosus, and semitendinosus muscles. The electrodes located on the glute muscles recorded signals from the gluteus maximus and gluteus medius muscles. The EMG signals were measured in a raw form with a sampling frequency of 1000 Hz and a frequency band of 50 Hz – 200 Hz (-3 dB). The raw EMG signals were first rectified and then averaged over each 100 ms interval without overlapping. Therefore, 10 consecutive samples from the raw signal formed one rectified averaged data sample. This 10 Hz data was stored in ASCII format in the module memory, and uploaded to the PC using custom software. From the 10 Hz EMG data, ARV was calculated from a 1 s window during a stable torque signal. Six channels (three from each leg) were recorded. To ensure proper signal conduction, the electrodes were moisturized with tap water before putting on the shorts. When wetted, a membrane covering the electrodes prevents the electrode-skin interface from drying.

Statistical analysis

Statistical analyses were performed using Statistica 13.1. The results are presented as means, standard deviations, and confidence intervals. Normality of the distribution was verified using the Shapiro-Wilk tests, while the Levene's test was used to examine homogeneity of variance and the Mauchley's test was used to verify sphericity assumption. The statistical differences were determined by conducting a two-factor analysis of variance. Effect sizes for main effects and interactions were determined using partial eta squared (η2) and Cohen's d (d) for pairwise comparisons. Partial eta squared values were classified as small (0.01–0.059), moderate (0.06–0.137), or large (> 0.137). Cohen's d was characterized as large ($d > 0.8$), moderate ($0.5 \leq d \leq 0.8$), small ($0.2 \leq d < 0.5$), or trivial ($d < 0.05$). Additionally, percent changes with 95% confidence intervals (95%CI) were calculated. The p-value was set at < 0.05 for statistical significance.

RESULTS

The analysis of the results in Table 1 and Table 2 allowed us to conclude that for all the variables there were no grounds to reject the null hypothesis of normality of the variables analyzed, so in subsequent analyses the statistics were based on parametric tools, namely analysis of variance with repeated measures and Tuckey's post hoc multiple comparison tests. .Analysis of the results for the 5 m [s] distance (Fig. 1) revealed significant differences for the main effects: differences between groups ($F = 6.61$; $p = 0.015$; $\eta^2 = 0.18$); differences for the main effects before and after ($F = 93.89$; $p < 0.0001$; $\eta^2 = 0.75$); and for the interaction group × measurement time ($F = 15.85$; $p = 0.0004$; $\eta^2 = 0.35$). To determine between which groups there were significant differences for the interactions, Tuckey's post hoc multiple comparison tests were used. No significant differences were found between the results of the 5 m [s] test in the groups

TABLE 1. Descriptive statistics for all measured variables, p-values for normality of the distribution

Variable	Experimental group		Control group	
	Pre	Post	Pre	Post
	M ± SD (-95%CI: 95%CI)	M ± SD (-95%CI: 95%CI)	M ± SD (-95%CI: 95%CI)	M ± SD (-95%CI: 95%CI)
5M [s]	1.064 ± 0.058 (1.03; 1.09)	0.98 ± 0.046 (0.96; 1.01)	1.078 ± 0.039 (1.058; 1.10)	1.044 ± 0.035 (1.025; 1.063)
30M [s]	4.24 ± 0.16 (4.15; 4.33)	4.08 ± 0.17 (3.98; 4.17)	4.24 ± 0.13 (4.16; 4.31)	4.19 ± 0.17 (4.10; 4.28)
Agility [s]	6.17 ± 0.29 (6.02; 6.33)	5.18 ± 0.29 (5.03; 5.34)	6.22 ± 0.19 (6.12; 6.32)	6.09 ± 0.24 (5.96; 6.22)
Deficit [s]	1.93 ± 0.24 (1.80; 2.06)	1.11 ± 0.21 (1.00; 1.22)	1.98 ± 0.13 (1.91; 2.05)	1.90 ± 0.15 (1.82; 1.98)
AQ	11.31 ± 1.89 (10.31; 12.32)	9.58 ± 1.36 (8.85; 10.30)	11.31 ± 1.85 (10.32; 12.29)	10.99 ± 1.84 (10.02; 11.97)
AH	18.04 ± 2.89 (16.50; 19.58)	13.66 ± 1.49 (12.87; 14.46)	17.90 ± 2.02 (16.82; 18.98)	17.25 ± 1.96 (16.20; 18.29)
AG	20.21 ± 4.11 (18.02; 22.40)	14.33 ± 3.26 (12.59; 16.06)	20.25 ± 3.61 (18.33; 22.17)	19.53 ± 3.40 (17.72; 21.34)

M – mean; Me ; SD – standard deviation, p S-W – p values for Shapiro-Wilk test, confidence intervals (95CI).

TABLE 2. Descriptive statistics for all measured variables, p-values for normality of the distribution

Variable	M	-95%CI	95%CI	SD	p S-W
5M [s] – before	1.064	1.03	1.09	0.058	0.42
5M [s] – after	0.98	0.96	1.01	0.046	0.44
30M [s] – before	4.24	4.15	4.33	0.16	0.50
30M [s] – after	4.08	3.98	4.17	0.17	0.30
Agility [s] – before	6.17	6.02	6.33	0.29	0.33
Agility [s] – after	5.18	5.03	5.34	0.29	0.21
Deficit [s] – before	1.93	1.80	2.06	0.24	0.51
Deficit [s] – after	1.11	1.00	1.22	0.21	0.62
AQ – before	11.31	10.31	12.32	1.89	0.15
AQ – after	9.58	8.85	10.30	1.36	0.29
AH – before	18.04	16.50	19.58	2.89	0.12
AH – after	13.66	12.87	14.46	1.49	0.96
AG – before	20.21	18.02	22.40	4.11	0.11
AG – after	14.33	12.59	16.06	3.26	0.10

M – mean; Me – median, SD – standard deviation, p S-W – p values for Shapiro-Wilk test.

analyzed before the experiment ($p = 0.80$). Significant differences were found between the pre and post results in the experimental group ($p = 0.0002$, $d = 1.61$) and in the control group ($p = 0.002$, $d = 0.89$). In both the experimental and control groups, the time required to run the distance after the experiment was statistically significantly shorter (Fig. 1). Significant differences were found between the experimental and control groups after the experiment ($p = 0.0023$; $d = 1.57$). After the experiment, the time needed to run the distance was statistically significantly shorter in the experimental group than in the control (Fig. 1).

The analysis of the results for the 30 m [s] distance presented in Figure 2 showed significant differences for the main effects only for

the pre-post effect ($F = 44.20$; $p < 0.0001$; $\eta^2 = 0.59$); and for the interaction group × measurement time ($F = 15.54$; $p = 0.00044$; $\eta^2 = 0.34$). No significant differences were found between the results of the 30 m [s] test in the analyzed groups before the experiment ($p = 0.99$). Significant differences were found only between the results before and after in the experimental group ($p = 0.0002$; $d = 0.97$). In the experimental group, the time needed to run a distance of 30 m was statistically significantly shorter after the experiment (Fig. 2).

The analysis of the agility test results included in Figure 3 revealed significant differences for the main effects: differences between groups ($F = 36.95$; $p = < 0.0001$; $\eta^2 = 0.55$); differences for the main effects before and after ($F = 150.94$; $p < 0.0001$; $\eta^2 = 0.83$); and for the interaction group × measurement time ($F = 91.15$; $p < 0.0001$; $\eta^2 = 0.75$). No significant differences were found between the pre-test agility test results [s] in the analyzed groups ($p = 0.96$). Significant differences between pre and post results were found only in the experimental group ($p = 0.0001$; $d = 3.41$). In the experimental group, the time required to perform the agility test was statistically significantly shorter after the experiment (Fig. 3). Significant differences were found between the experimental and control groups after the experiment ($p = 0.0001$; $d = 3.42$). After the experiment, the time required to perform the agility test was statistically significantly shorter in the experimental group than in the control group (Fig. 3).

Analysis of the "Deficit" scores in Figure 4 revealed significant differences for the main effects: differences between groups ($F = 62.98$; $p < 0.0001$; $\eta^2 = 0.67$); differences for the main effects before and after ($F = 125.21$; $p < 0.0001$; $\eta^2 = 0.81$); and for the interaction group × measurement time ($F = 83.95$; $p < 0.0001$; $\eta^2 = 0.74$). No significant differences were found between the pre-test deficit scores of the groups analyzed ($p = 0.88$). Significant differences between the pre and post scores were found only in the experimental group ($p = 0.00016$; $d = 3.64$). Deficit was statistically significantly lower in the experimental group after the experiment (Fig. 4). Significant differences were found between the experimental and control groups after the experiment ($p = 0.00016$; $d = 4.33$). The deficit was statistically significantly lower in the experimental group than in the control group after the experiment (Fig. 4).

The analysis of the results for AQ included in Figure 5 revealed significant differences for the main effects only for the pre and post effect ($F = 10.36$; $p = 0.0031$; $\eta^2 = 0.26$); and for the interaction group × measurement time ($F = 5.02$; $p = 0.032$; $\eta^2 = 0.14$). No significant differences were found between the pre-test AQs of the analyzed groups ($p = 0.99$). Significant differences were found only between pre/post results in the experimental group ($p = 0.0031$; $d = 1.05$). In the experimental group, the AQ score was statistically significantly lower after the experiment (Fig. 5).

The analysis of the AH results included in Figure 6 showed significant differences for the main effects: differences between groups ($F = 7.65$; $p = 0.009$; $\eta^2 = 0.20$); differences for the main effects for pre and post conditions ($F = 32.97$; $p < 0.0001$; $\eta^2 = 0.52$); and for the interaction group × measurement time ($F = 18.11$; $p = 0.00018$; $\eta^2 = 0.38$). No significant differences were found between the AH results of the groups analyzed before the experiment ($p = 0.99$). Significant differences between pre/post results were found only in the experimental group ($p = 0.00016$; $d = 1.91$).In the experimental group, AH scores were statistically significantly lower post experiment (Figure 6). Significant differences were found between the experimental and control groups after the experiment ($p = 0.00025$; $d = 2.06$). After the experiment, the AH score in the experimental group was statistically significantly lower than in the control group (Fig. 6).

Analysis of the AG results in Fig. 7 found significant differences for the main effects: differences between the groups ($F = 4.45$; $p = 0.043$; $\eta^2 = 0.13$) ; differences for the main effects before and after ($F = 130.76$; $p < 0.0001$; $\eta^2 = 0.81$) ; and for the interaction group × measurement time ($F = 106.88$; $p < 0.0001$; $\eta^2 = 0.72$). No significant differences were found between the AG results in the analyzed groups ($p = 0.99$) before the experiment. Significant differences were found between the results before and after only in the experimental group ($p = 0.0001$; $d = 1.59$) In the experimental group, AG scores were statistically significantly lower after the experiment (Fig. 7). Significant differences were found between the experimental and control groups after the experiment ($p = 0.0016$; $d = 1.56$). After the experiment, the AG score in the experimental group was statistically significantly lower than in the control group (Fig. 7).

DISCUSSION

Speed and agility are the result of multiple anatomical systems working together in highly coordinated manner, including the cross-body co-contractions of deep myofascial tissues that create core stiffness; the pulsing contract-and-release cycle of the nervous system that efficiently generates rapid, powerful ground contact; and the hormonal reactions that produce adrenaline, cortisol, and lactic acid. A comprehensive approach via combining speed, agility, and strength training significantly improved the results in all of the tested motor variables.

The data analysis showed significant improvement in 5 m and 30 m sprints after applying the 8-week targeted training protocol.

A statistically significant improvement in performance was also observed after the 8-week training period in case of COD, while the speed deficit also decreased significantly. The greatest improvements were observed during the COD test, what can best translate in soccer players into actions on the pitch. As a result of repeated COD training over a period of 8 weeks, its technique was improved. The changes focused on maintaining a low athletic stance with slight flexion at the hips, knees, and ankles with joint angles adjusted to allow for optimal power transfer and rapid re-acceleration.

The control group also achieved a statistically significant improvement in most of the motor variables tested, with the exception of 30 m, deficit, AQ, AH, AG. However, these changes were minor compared to the experimental group.

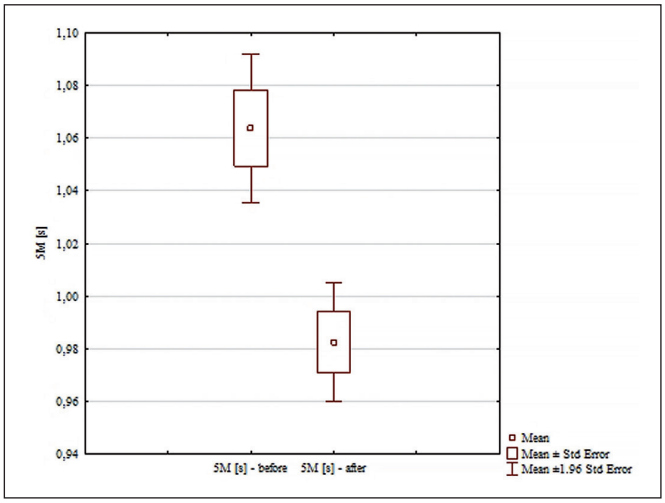


FIG. 1. Comparisons between paired values for 5 m [s].

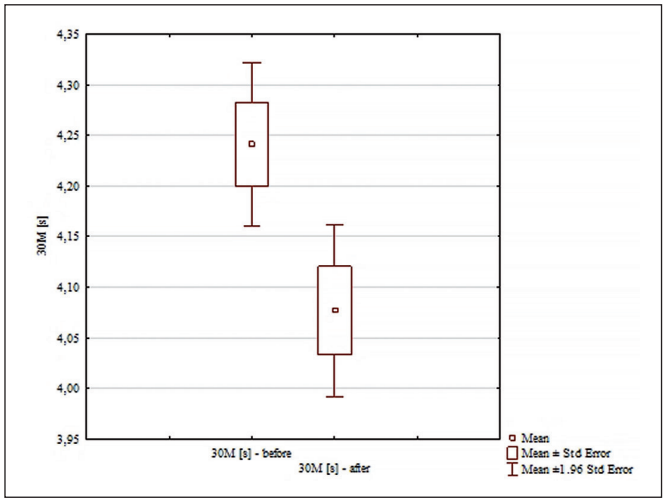


FIG. 2. Comparisons between paired values for 30 m [s].

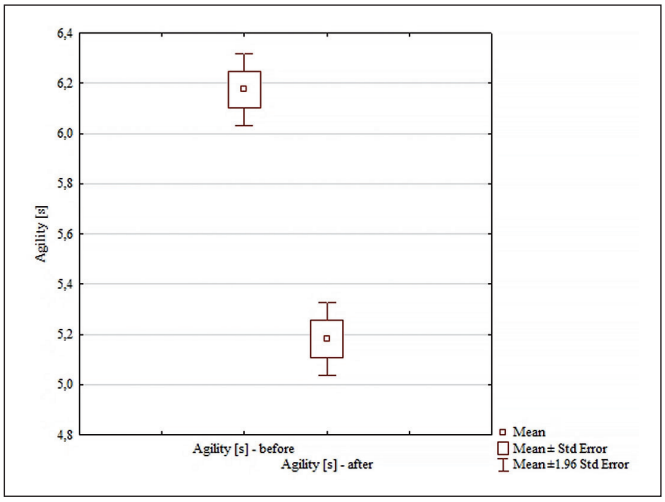


FIG. 3. Comparisons between paired values for agility [s].

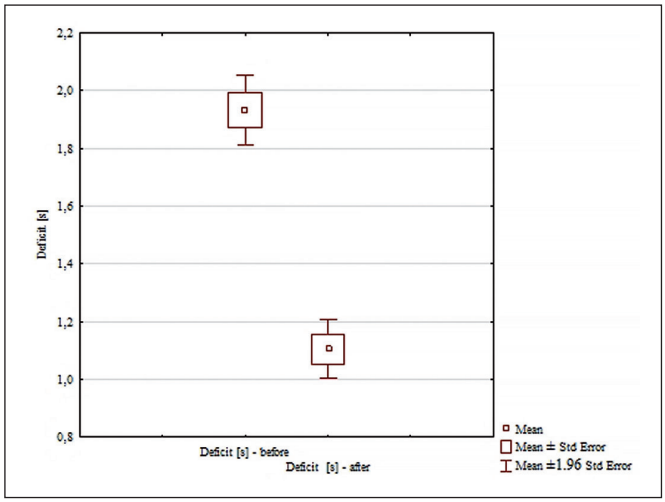


FIG. 4. Comparisons between paired values for deficit [s].

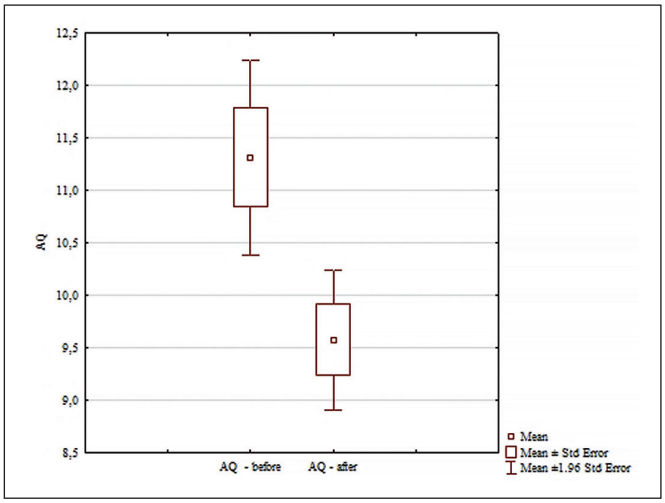


FIG. 5. Comparisons between paired values for AQ.

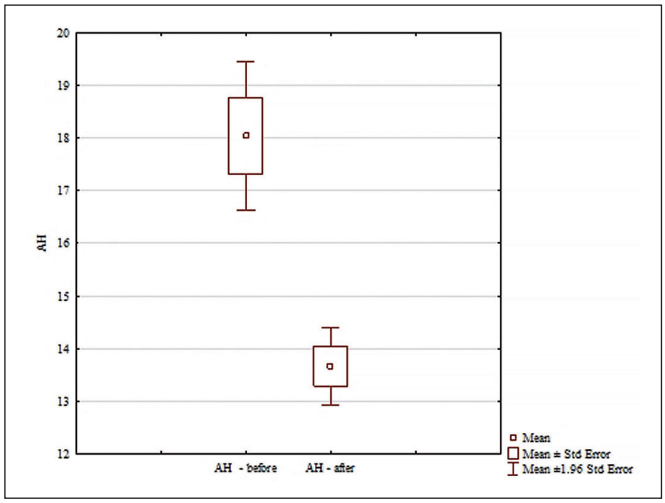


FIG. 6. Comparisons between paired values for 5 m AH.

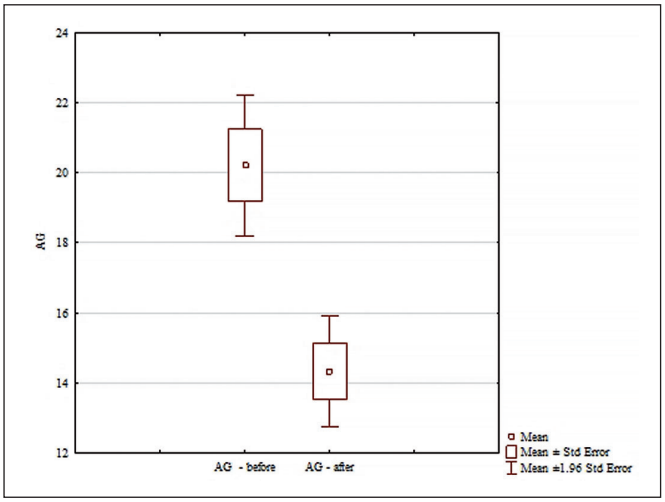


FIG. 7. Comparisons between paired values for AG.

Maintaining the lowered position, also known as the athletic stance, is crucial for cutting, sidestepping, pivoting, and other COD maneuvers during the match. The mechanics of COD can be separated into three phases: deceleration when the muscles primarily contract eccentrically, transition when the muscles primarily contract isometrically and reacceleration when concentric contractions of the muscles dominate. The 8 weeks of targeted strength training significantly translated into improvements in COD.

Significant differences were registered in the reduction of asymmetry between the muscle groups studied before and after the 8-week training intervention. The greatest effect was obtained for the gluteal muscles. Lower levels of asymmetry significantly translate into a reduced risk of injury and allow athletes to move cost-effectively. Movement patterns are the result of typical everyday activities, habits, leg dominance, and a history of injuries [23, 24]. A side-to-side asymmetry greater than 15% [15] may increase the risk of knee injuries. Soccer players are frequently characterized by unequal development of the right and left limbs due to certain technical actions performed in the sport, and such disproportions can cause functional or even structural asymmetries. In the present study, an 8-week specific movement pattern resistance training had a statistically significant effect on the reduction of these disproportions in the quadriceps, hamstring, and gluteal muscles, which may translate into a reduction of injury risk. The literature on muscle activity during running lacks data on the changes in the pattern of muscle activity following a specific period of resistance training. Furthermore, no studies have demonstrated differences in the activity of particular muscles and their comparison with each other. Comparisons of overall muscle activity of the right and left limbs often fail to show disproportions, whereas analysis of particular muscles with respect to each other (AQ, AH, AG) reveals significant statistical differences. This may result from the fact that the central nervous system compensates for the disturbances in the activity of particular muscles by transferring part of the load to other muscles. Consequently, the activity of the right lower limb can be taken over and controlled by a different muscle than in the left limb. Training based on movement patterns and activation of particular muscles can reduce the disproportion of (AQ, AH, AG) with respect to each other.

Most soccer players have a preferred foot for kicking the ball, and it is believed that this preference may lead to an asymmetry in the strength and flexibility of the lower extremities. Daneshjoo [25] attempted to determine whether asymmetry in strength and flexibility is present in the lower limbs of soccer players. They found significant differences between the preferred and non-preferred leg in the knee flexors and for the dynamic control ratio [26]. In both cases, the knee flexors of the preferred leg were weaker than those of the non-preferred leg. Almost 68% of players had significant musculoskeletal abnormalities (imbalance > 10%) in one or more specific muscle groups, while no significant differences were found in flexibility of the hip joint between the preferred and non-preferred leg. Our results indicate that the greatest disproportion between the right and left side occurs in the glute muscles and the smallest in the quadriceps muscles. These results indicate a greater need for activating the glute and hamstring muscles during resistance training for soccer players.

CONCLUSIONS

Implementation of training methods, which target specific aspects of soccer in the pre-season training routines can improve key motor abilities for that sports discipline. A comprehensive training approach including speed, agility, and resistance training based on specific movement patterns should be applied by strength and conditioning practitioners in soccer teams to achieve peak physical performance and reduce injury risk due to the partial elimination of muscular asymmetries. Future research should focus on other components of training, such as plyometrics with regard to muscle activity patterns to develop optimal pre-season training programs for soccer players. Different age, sex and competition levels should be considered as well.

Declarations

The research project was approved by the Committee of Bioethics at the Academy of Physical Education in Katowice.

Conflic of interest

The authors declared no conflict of interest.

REFERENCES

1. Haugen T, Tonnessen E, Hisdal J, Seiler S. The role and development of sprinting speed in soccer. Int J Sports Physiol Perform. 2014;9(3):432–41.
2. Konefał M, Chmura J, Zacharko M, Zając T, Chmura P. The Relationship among Acceleration, Deceleration and Changes of Direction in Repeated Small Sided Games. J Hum Kinet. 2022; 85(1):96–103.
3. Forster JW, Uthoff AM, Rumpf MC, Cronin JB. Training to Improve Pro-Agility Performance: A Systematic Review. J Hum Kinet. 2022; 85(1):35–51.
4. Small K, McNaughton L, Greig M, Lovell R. The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. J Sci Med Sport. 2010; 13(1):120–5.
5. Fasold F, Braun A, Klatt S. Effects of Arm Dominance and Decision Demands on Change of Direction Performance in Handball Players. J Hum Kinet. 2022; 85:127–135.
6. Lazić A, Andrašić S, Stanković M, Milanović Z, Trajković N. Change of Direction Deficit: A Promising Method to Measure a Change of Direction Ability in Adolescent Basketball Players. J Hum Kinet. 2022; 85:1–11.
7. Loturco I, Nimphius S, Kobal R, Bottino A, Zanetti V, Pereira LA. Change-of direction deficit in elite young soccer players: The limited relationship between conventional speed and power measures and change-of-direction performance. Ger J Exerc Sport Res. 2018; 48(2):228–34.
8. Prudholme DC, Coburn JW, Lynn SK, Lockie RG. Relationships between Sprint, Acceleration, and Deceleration Metrics with Training Load in Division I Collegiate Women's Soccer Players. J Hum Kinet. 2022; 85(1):53–62.
9. Gordan R, Gwathmey JK, Xie LH. Autonomic and endocrine control of cardiovascular function. World J Cardiol. 2015; 7(4):204–14.
10. Nimphius S, Mcguigan MR, Newton RU. Relationship Between Strength, Power, Speed, and Change of Direction Performance of Female Softball Players: J Strength Cond Res. 2010; 24(4):885–95.
11. Pereira LA, Nimphius S, Kobal R, Kitamura K, Turisco LAL, Orsi RC, et al. Relationship Between Change of Direction, Speed, and Power in Male and Female National Olympic Team Handball Athletes: J Strength Cond Res. 2018; 32(10):2987–94.
12. Enoka RM, Duchateau J. Inappropriate interpretation of surface EMG signals and muscle fiber characteristics impedes understanding of the control of neuromuscular function. J Appl Physiol. 2015; 119:1516–1518.
13. Stastny P, Tufano JJ, Golas A, Petr M. Strengthening the gluteus medius using various bodyweight and resistance exercises, Strength Cond J. 2016; 38:91–101.
14. Scilingo EP, Gemignani A, Paradiso R, Taccini N, Ghelarducci B, De Rossi D. Performance evaluation of sensing fabrics for monitoring physiological and biomechanical variables. IEEE. 2005; 9:345–352.
15. Croisier JL, Forthomme B, Namurois MH, Vanderthommen M, Crielaard JM. Hamstring muscle strain recurrence and strength performance disorders, Am J Sports Med. 2002; 30(2):199–203.
16. Rahnama N. Lees A. Bambaecichi E. A comparison of muscle strength and flexibility between the dominant and non-dominant leg in English soccer players. Ergonomics. 2005; 48(11–14):1568–1575.
17. Dörge HC, Andersen TB, Sørensen H, Simonsen EB. Biomechanical differences in soccer kicking with the preferred and the non-preferred leg. J Sports Sci. 2010; 20:293–299.
18. Croisier JL, Ganteaume S, Binet J, Genty M, Ferret JM. Strength imbalances and prevention of hamstring injury in professional soccer players, a prospective study. Am J Sports Med. 2008; 36(8):1469–75.
19. Alentorn-Geli E, Myer GD, Silvers HJ. Samitier G, Romero D, Lázaro-Haro C, Cugat R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. Knee Surg Sports Traumatol Arthrosc. 2009; 17(7):705–729.
20. Papla M, Krzysztofik M, Wojdala G, Rozcniok R, Oslizlo M, Golas A. Relationships between Linear Sprint, Lower-Body Power Output and Change of Direction Performance in Elite Soccer Players. Int J Environ Res Public Health. 2020; 22(17):6119.
21. Tikkanen O, Kärkkäinen S, Haakana P, Kallinen M, Pullinen T, Finni T, EMG, heart rate, and accelerometer as estimators of energy expenditure in locomotion. Med Sci Sports Exerc. 2014; 46:831–1839.
22. Van Dyk N, Bahr R, Whiteley R, Tol JL, Kumar BD, Hamilton B, Farooq A, Witvrouw E. Hamstring and quadriceps isokinetic strength deficits are weak risk factors for hamstring strain injuries: A 4-year cohort study. Am J Sports Med. 2016; 44(7):1789–95.
23. Cook G, Burton L. Functional movement screening. In: Voight ML, Hoogenboom BJ, Prentice WE, eds. Musculoskeletal Interventions: Techniques for Therapeutic Exercise. New York, NY: McGraw-Hill; 2007; 379–400.
24. Stastny P, Lehnert M, Zaatar A, Svoboda Z, Xaverova Z, Pietraszewski P. The gluteus medius vs. thigh muscles strength ratio and their relation to electromyography amplitude during a Farmer's walk exercise. J Hum Kinet. 2015; 45:157–165.
25. Daneshjoo A, Rahnama N, Mokhtar AH, Yusof A. Bilateral and Unilateral Asymmetries of Isokinetic Strength and Flexibility in Male Young Professional Soccer Players. J Hum Kinet. 2013; 36:45–53.
26. Delextrat A, Gregory J, Cohen D. The use of functional H:Q ratio to assess fatigue in soccer. Int J Sports Med. 2010; 31(3):192–197.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.135416
© Institute of Sport – National Research Institute

The relationships between distances covered above generic and relative speed thresholds by male soccer players in English Premier League matches across two competitive seasons. The effects of positional demands and possession

AUTHORS: Ronan Kavanagh[1], Rocco Di Michele[2], Rafael Oliveira[3,4,5], Kevin McDaid[6], David Rhodes[7], Ryland Morgans[8]

[1] Nottingham Forest FC, Nottingham, UK
[2] Department of Biomedical and Neuromotor Sciences, University of Bologna, Italy
[3] Sports Science School of Rio Maior-Polytechnic Institute of Santarém, 2040-413 Rio Maior, Portugal
[4] Research Centre in Sport Sciences, Health Sciences and Human Development, 5001-801 Vila Real, Portugal
[5] Life Quality Research Centre, 2040-413 Rio Maior, Portugal
[6] Dundalk Institute of Technology, Dundalk, Co Louth, Ireland
[7] Human Performance Department, Burnley Football Club, Burnley
[8] School of Sport and Health Sciences, Cardiff Metropolitan University, Cardiff

ABSTRACT: The aims of this study were to: a) examine the relationships between high-intensity distances covered above generic and relative speed thresholds in English Premier League (EPL) matches across two consecutive seasons and b) analyze the effects of playing position and team possession. Sixteen elite male soccer players (seven defenders, six midfielders and three forwards) participated in this study (age 27.8 ± 3.5 years, height 183.7 ± 5.4 cm, body mass 83.9 ± 7.1 kg). An Optical Tracking System was used to collect the following variables: total distance covered; high-speed running distance (HSRD) (> 5.5 m/s); high-intensity running distance (HIRD) (5.5–7 m/s); sprint distance (> 7 m/s); total distance covered above Maximal Aerobic Speed (MAS); distance covered > 85% peak speed (PS); and distance > 30% Anaerobic Speed Reserve (ASR). All measures were analyzed as whole match totals and as distances covered in the periods of the team in possession (TIP), opponent team in possession (OTIP), and ball out of play (BOP). Analysis by position based on defenders, midfielders and forwards was also performed. Distance > 30% ASR was almost perfectly correlated with HSRD ($r = 0.98$), while distances > MAS were highly correlated with both HIRD ($r = 0.91$) and HSRD ($r = 0.91$), and distance > 85% PS were highly correlated with SD ($r = 0.70$). Although the generic and relative speed thresholds show almost perfect correlation, the differences between HSRD, HIRD and distance > MAS indicate that players may be exposed to more HIRD when using relative thresholds.

CITATION: Kavanagh R, Di Michele R, Oliveira R et al. The relationships between distances covered above generic and relative speed thresholds by male soccer players in English Premier League matches across two competitive seasons. The effects of positional demands and possession. Biol Sport. 2024;41(4):77–86.

Received: 2023-02-13; Reviewed: 2023-11-23; Re-submitted: 2024-01-08; Accepted: 2024-02-16; Published: 2024-03-18.

Corresponding author:
David Rhodes
Football Performance Hub
Institute of Coaching
and Performance, University
of Central Lancashire, Preston
E-mail: drhodes2@uclan.ac.uk

ORCID:
Ronan Kavanagh
0009-0004-9695-4147

Rocco Di Michele
0000-0003-2771-7661

Rafael Oliveira
0000-0001-6671-6229

Kevin McDaid
0000-0002-0695-9082

David Rhodes
0000-0002-4224-1959

Ryland Morgans
0000-0003-2007-4827

Key words:
Match performance
Individualized speed zones
Performance analysis
Soccer
External load
External intensity

INTRODUCTION

Soccer is an intermittent field sport containing both high- and low-intensity running efforts [1]. The monitoring of physical performance in elite soccer has developed in recent years with advancements in suitable player tracking technologies [2]. Accurately quantifying players' match actions is required to improve the understanding of workloads during match-play [3]. When match-play physical demands are examined, load is often characterized by graduated speed thresholds ranging from motionless standing to maximal sprinting [4]. Player tracking has traditionally been reported using generic speed zones [5]. Currently, there is no consensus on the metrics that are most practically useful, specific and reliable [6]. For instance, a recent systematic review noted that there is a lack of uniformity to classify different speed thresholds which makes comparisons between studies or generalizations of results difficult [7]. Historically, generic speed thresholds have been applied to all squad athletes [8]. This allows the comparison of physical performance between players within and across teams and leagues to be conducted. However, these thresholds do not account for individual physical differences and the relative exertion imposed on the player to reach such generic speeds.

The disadvantages associated with generic speed thresholds have been documented, thus, researchers have attempted to individualize thresholds using physical performance markers [5, 9–11]. The aim of individualizing speed thresholds is to account for the individual nature of the exercise-intensity continuum and accurately represent the

relative intensity of an athlete when performing [8]. Varying methodological approaches employed to individualize high-speed thresholds, such as anaerobic threshold, have been reported, however, this can be difficult to implement in team environments with large squads [12]. Thus, another marker, namely percentage of peak speed (PS) has been utilized to underpin high-intensity running distance (HIRD) in team athletes [13]. However, Hunter, et al. [5] found that utilizing a single physical marker to determine multiple speed zones can lead to erroneous interpretations of players activities. Additionally, it has been suggested that a measure that describes the functional limits of endurance and an additional value that characterizes sprint capacity may be ideal [14].

Maximal Aerobic Speed (MAS) has been defined as a practical and time efficient method to assess the aerobic energy system in team sport athletes [12]. Time spent above MAS has been shown to correlate with improvements in aerobic fitness [14]. Recently several authors applied this to youth athletes, using field tests to assess MAS and PS [5, 10, 15]. This approach also allows for the estimation of an individual's Anaerobic Speed Reserve (ASR) and transition to sprint distances [5]. Therefore, an individualized approach to external load monitoring may also augment practitioners understanding of competition demands [5, 16]. The application of generic thresholds may also lead to an inaccurate external load quantification by sports science practitioners [17], whereas individualized thresholds have been proposed as a method to overcome this weakness [18]. Despite this rationale, individualized speed thresholds are not widely accepted in high-level soccer [19].

To date, no study has examined the differences in HIRD covered above generic and relative speed thresholds in English Premier League (EPL) matches. Examining league data is potentially key to improving the understanding of various methods of physical development [20]. These physical demands can also differ significantly depending on playing position and possession [21–25]. While in possession, players perform multiple high-speed and sprint activities in an attempt to create chances and score goals [26, 27]. Similarly, when not in possession, players still produce high-speed and sprint actions in an attempt to recover possession [26]. Indeed elite UEFA Champions League players produce greater efforts while not in possession across all positions [28]. It is therefore important to fully understand the differences in HIRD covered above generic and relative speed thresholds in and out of possession during match-play, to provide practitioners with detailed information on player exertion in order to design and deliver individually tailored sessions and weekly loads based on scientific principles. Further research is therefore warranted on the positional demands and effects of team possession on distance > MAS, ASR and distances > 85% PS.

Thus, the primary aim of this study was to examine the relationships between different generic and relative speed thresholds in EPL matches across two competitive seasons (2019–20 and 2020–2021). The secondary aim was to investigate the effect of playing position and team possession. The study hypothesis was that playing position and team possession will influence the quantity of distances covered above generic and relative speed thresholds in EPL match-play.

MATERIALS AND METHODS

Participants

Sixteen male professional outfield soccer players (mean ± standard deviation (SD), at the start of 2019–2020 season, age 27.8 ± 3.5 years, height 183.7 ± 5.4 cm, body mass 83.9 ± 7.1 kg) from an EPL team participated in the present study. The methodology to differentiate specialized positions was adapted from previous research [29] as various situational factors have an influence on the style of play that can be modulated by different tactical roles [30]. The small sample size is supported by previous studies in elite soccer cohorts [31–33], and consisted of three main positions, namely, defenders n = 7, midfielders n = 6, and forwards n = 3. Goal-keepers data were excluded due to their position-specific demands [34, 35]. Players' positional data were collected from 38 matches across two consecutive seasons (2019–2020 and 2020–2021). All data evolved as a result of employment where players were routinely monitored over the course of the competitive season [36]. Nevertheless, club approval for the study was obtained [37] and ethics was provided by the local Ethics Committee of University of Central Lancashire (BAHSS 646 dated 17/04/2019) and in accordance with the Helsinki Declaration. Moreover, all players provided written consent to participate in the study. To ensure confidentiality, all data were anonymized before analysis.

Procedure

In each season, only data from 19 home league matches and 19 away league matches from the EPL were included in the analysis. Participant data were only included in the analyses when time spent on the field exceeded 75-minutes of the match [38]. For each season, players were considered when an inclusion criterion of 75-minutes playing time, in eight (10.5%) or more league matches across the two-season examined period was fulfilled. Only players with match data from both examined seasons were included in the sample. The participants performed in a median of 60% (range = 20 to 97%) of league matches across both seasons. A total of 630 individual match data points were examined across both seasons, with a median of 40.5 matches per player (range = 8 to 74). No data from international camps (training or matches) was included.

Data collection

League match data across both study seasons was recorded and analyzed via an Optical Tracking System (Second Spectrum®, Los Angeles, USA). Second spectrum optical tracking has recently been detailed by the FIFA program to meet industry standards [39]. Data was collected via semi-automated HD cameras that were positioned around the stadium at a sampling frequency of 25-Hz. The Second

Spectrum match data was processed directly using the python programming language (Python 2.7) through the Spyder scientific development environment (https://www.spyder-ide.org/).

The metrics used for analysis across each season were: total distance covered; high-speed running distance (HSRD) (> 5.5 m/s); high-intensity running distance (HIRD) (5.5–7 m/s); sprint distance (> 7 m/s) [19]; total distance covered > MAS (MAS) [5, 14]; distance covered > 85% PS (PS) [40]; and distance > 30% ASR (ASR) [8]. All distances were examined as whole match totals and as distances covered in the periods of team in possession (TIP), opponent team in possession (OTIP), and ball out of play (BOP). All examined metrics were expressed both in meters and m/min (whole match, TIP, OTIP and BOP distances were respectively divided by the total, TIP, OTIP and BOP times). Before calculating these values, when individual match playing time was less than 90-minutes, distances were extrapolated to 90-minutes utilizing the meters per minute calculation. All variables obtained were calculated or pre-determined in the Second Spectrum System Software. These variables have been previously utilized by soccer practitioners to longitudinally track the external load undertaken by players [19]. The installation process, reliability and validity of Second Spectrum have been reported recently by FIFA Electronic Performance Tracking Systems (EPTS) programme [39].

Maximal aerobic speed test (MAS)

During the pre-season period, participants completed a MAS test to estimate velocity at the maximum oxygen consumption (vVO^2max). The MAS protocol was a 1200 m maximum effort shuttle test. The 1200 m shuttle test has previously shown a strong correlation with other MAS tests [12, 41]. Poles were set at the start point, and 20 m, 40 m and 60 m from the starting point (see Figure 1).

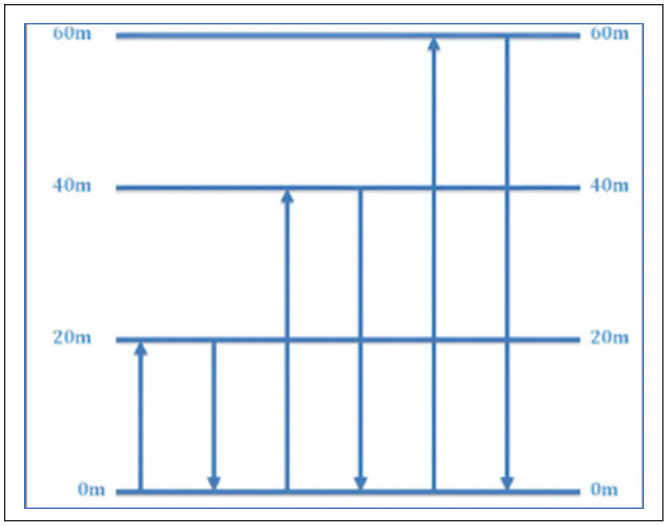


FIG. 1. Shows the Bronco 1200m shuttle test

Players were instructed to run from the start point to 20 m and return to the start point. Players then ran to the 40 m mark and returned to the start point before running to the 60 m mark and returning to the start point. This sequence was repeated as quickly as possible five times until the distance of 1200 m had been achieved [41]. Players were informed of how much time was remaining at 1-minute intervals until the test was complete to ensure players were performing maximally [42]. This verbal encouragement has been shown to be a motivational requirement for laboratory assessments of time to exhaustion and central fatigue [43]. Due to the change of direction within the test, a corrective equation was employed, 1200/(Time – 20.3 s (0.7 s for each turn) = MAS (m/s) [12].

Maximal peak speed (PS)

Each player's maximum PS during the season was collated using Optical Tracking System (Second Spectrum®, Los Angeles, USA). The researchers decided to use the individual maximum PS from match-play only, as an average PS per session may be influenced by positional demands and therefore would not be a true reflection of the players PS capacity. If a player produced a new PS during the season this was adjusted within the python programming language (Python 2.7), using the Spyder scientific development environment (https://www.spyder-ide.org/).

Anaerobic speed reserve (ASR)

Using MAS and PS scores, each athlete's theoretical ASR was calculated. ASR was defined as the difference between the MAS and PS score and reported in $m \cdot s^{-1}$. The MAS and PS protocols were previously utilised by Kavanagh et al. [36] to determine a soccer player's MAS and MSS. The 30% ASR measure employed a weighted MAS value and the MSS for each player using 70% and 30% respectively as previous reported [36].

Statistical analysis

The analyses were carried using the software R, version 4.2.0 (R Foundation for Statistical Computing, Vienna, Austria), with packages lme4 and rmcorr. All variables are shown as the mean ± SD. Repeated-measure correlations were calculated to examine the relationships between the examined physical performance variables, including distances covered between or above the selected generic and individualized speed thresholds. This technique allows the calculation of paired correlations using data obtained from repeated measures on multiple individuals as in the present data set, without violating the assumption of data independence. The repeated-measure correlation (rmcorr) represents the strength of the linear association between two variables, assessed as the common individual association [44]. The magnitude of rmcorr was interpreted as Pearson's r correlation coefficient as trivial (< 0.1), small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), and almost perfect (> 0.9) [45].

Linear mixed models with random intercept for individual players were used to compare the examined physical performance variables, standardized by time on pitch, across playing positions (defender, midfielder, forward), separately for each playing period (whole match, TIP, OTIP, BOP). When there was a significant ($p < 0.05$) effect for playing position, Tukey's tests were used to examine which positions differed. The differences were standardized by the between-subject standard deviation to determine the effect size (ES), and were evaluated as < 0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; 1.2–2.0, large; 2.0–4.0, very large; > 4.0 extremely large [45].

RESULTS

Table 1 shows the mean MAS, PS, and ASR in the present sample of players.

The average whole match playing time for the individual match data points was 95.5 ± 4.1-minutes, whereas TIP, OTIP and BOP times were 21.9 ± 3.6-minutes (22.9%), 30.6 ± 5.7-minutes (32%), and 43.1 ± 5.9-minutes (45.1%) respectively.

For descriptive purposes, the mean ± SD values of all examined physical performance variables are reported in Table 2.

The matrix of repeated-measure correlations with 95% confidence intervals for the examined variables is shown in Table 3.

All correlations were significant ($p < 0.05$) with exception of correlations between total distance and distance > 85% PS for the whole match and the non-possession period. For any given pair of variables, there were no relevant differences between correlations as calculated when considering the whole match or the periods of possession, non-possession or ball out of play. There were almost perfect correlations between HSRD and both HIRD (rmcorr = 0.93, $p < 0.001$) and distance > 30% ASR (rmcorr = 0.98, $p < 0.001$). Also, HSRD showed very large correlations with sprint distance (rmcorr = 0.72, $p < 0.01$) and distance > MAS (rmcorr = 0.91, $p < 0.001$). Very large correlations were observed between HIRD and distance > MAS (rmcorr = 0.91, $p < 0.001$) and distance > 30% ASR (rmcorr = 0.89, $p < 0.001$), as well as between distance > 30% ASR and sprint distance (rmcorr = 0.76, $p < 0.001$) and distance > MAS (rmcorr = 0.86, $p < 0.001$). Very large correlations were also evident between distance > 85% PS and sprint distance (rmcorr = 0.70, $p < 0.001$). All other correlations ranged from small to large.

Table 4 shows the mean ± SD values for all examined distances, divided by time on pitch, across playing positions in all the considered match periods.

When examining the whole match, midfielders covered greater total distance ($p = 0.037$, ES = 0.89, moderate) and distance > 85% PS ($p = 0.047$, ES = 1.74, large) than forwards. Compared to defenders, midfielders covered greater total distance ($p < 0.001$, ES = 1.91, large), HSRD ($p = 0.009$, ES = 1.33, large), HIRD ($p < 0.001$, ES = 1.59, large), distance > MAS ($p = 0.002$, ES = 1.36, large), and distance > 30% ASR ($p = 0.035$, ES = 1.19, moderate). Furthermore, forwards covered greater total distance ($p = 0.012$, ES = 1.01, moderate), HIRD ($p = 0.032$, ES = 1.23, large), and distance > MAS ($p = 0.003$, ES = 1.65, large) than defenders.

When the team was in possession of the ball, forwards, compared to both defenders and midfielders, covered greater HSRD ($p < 0.001$, ES = 2.13, very large, vs. defenders; and $p = 0.016$, ES = 1.28, large vs. midfielders), HIRD ($p < 0.001$, ES = 2.17, very large, vs. defenders; and $p = 0.030$, ES = 1.07, moderate vs. midfielders), sprint distance ($p = 0.030$, ES = 1.80, large, vs. defenders; and p = 0.012, 1.37, large vs. midfielders), distance > MAS ($p < 0.001$, ES = 2.26, very large vs. defenders and $p = 0.002$, ES = 1.36, large vs. midfielders), and distance > 30% ASR ($p < 0.001$, ES = 2.14, very large, vs. defenders; and $p = 0.005$, ES = 1.47 large, vs. midfielders). Also, forwards covered greater total distance than defenders ($p < 0.001$, ES = 1.90, large) and midfielders covered greater total distance ($p < 0.001$, ES = 1.74, large), HIRD ($p = 0.003$, ES = 1.10, moderate), and distance > MAS ($p = 0.012$, ES = 0.90, moderate), than defenders.

When the team was not in possession of the ball, midfielders, compared to defenders, covered greater distance ($p < 0.001$, ES = 1.53, large), HSRD ($p = 0.006$, ES = 1.20, large), HIRD ($p = 0.001$, ES = 1.32, large), and distance > MAS ($p = 0.006$, ES = 1.27, large). Compared to forwards, midfielders covered greater total distance ($p < 0.001$, ES = 1.96, large), HSRD ($p < 0.001$, ES = 2.09, very large), HIRD ($p = 0.001$, ES = 2.03, very large), distance > MAS ($p = 0.006$, ES = 1.93, large), distance > 30% ASR ($p < 0.001$, ES = 2.14, very large) and distance > 85% PS ($p = 0.004$, ES = 2.43, very large). Furthermore, defenders covered greater distance > 30% ASR ($p = 0.041$, ES = 1.25, large), and greater distance > 85% PS ($p = 0.047$, ES = 1.44, large) than forwards.

During the ball-out-of-play phases, midfielders covered greater total distance compared to defenders ($p < 0.001$, ES = 1.61, large), and greater distance > MAS ($p = 0.005$, ES = 2.04, very large) and distance > 30% ASR ($p = 0.022$, ES = 2.18, very large)

TABLE 1. Mean ± *SD* values for MAS, PS, and ASR

	All players (n = 16)	Defenders (n = 7)	Midfielders (n = 6)	Forwards (n = 3)
MAS (m/s)	4.63 ± 0.19	4.62 ± 0.19	4.75 ± 0.12	4.51 ± 0.25
PS (m/s)	9.53 ± 0.39	9.63 ± 0.35	9.37 ± 0.43	9.83 ± 0.32
ASR (m/s)	4.89 ± 0.45	5.01 ± 0.24	4.61 ± 0.50	5.32 ± 0.47

compared to forwards. No significant differences were observed between positions for the other variables (all $p > 0.05$, Table 4).

DISCUSSION

The study aimed to examine the relationships between different generic and relative speed thresholds in EPL matches across two competitive seasons, and to compare the effect of playing position and possession phase. Taken together, the present findings show low to almost perfect correlations between the examined absolute and relative distances. Distance > 30% ASR was almost perfectly correlated with HSRD, while distances > MAS were highly correlated with both HSRD and HIRD, and distance > 85% PS was highly correlated with sprint distance. During the entire match and when the team was not in possession of the ball, overall, midfielders covered greater distances than forwards and strikers, while forwards covered greater distances than the other two positions when in the ball possession phase. The average values for the generic-threshold distances measured in this study have similar magnitude to those previously reported in studies that assessed physical performance during EPL match-play [46–48].

The analysis of correlations between the examined variables revealed a close-to-perfect correlation between the distance covered > 30% ASR and HSRD. This is unsurprising, as individual 30% MAS in the present sample of players was on average equal to 5.76 ± 0.1 m/s (range 5.43–6.00 m/s), and thus very close to the generic 5.5 m/s threshold for high-speed running and, more importantly, with a low between-player variability (CV = 2.6%). It is worth noting that MAS (4.63 ± 0.19 m/s) and > 85% PS (8.10 ± 0.33 m/s)

TABLE 2. Mean ± *SD* values for the examined distance metrics

Variables	Positions	Whole match	TIP	OTIP	BOP
Total distance (m)	Defenders	9966 ± 515	2748 ± 504	4477 ± 713	2740 ± 405
	Midfielders	11594 ± 622	3531 ± 604	5089 ± 926	2974 ± 420
	Forwards	10710 ± 573	3579 ± 501	4303 ± 823	2829 ± 444
	Overall	10668 ± 945	3140 ± 673	4689 ± 871	2839 ± 429
High-speed running distance (> 5.5 m/s) (m)	Defenders	697 ± 275	182 ± 159	478 ± 157	37 ± 36
	Midfielders	992 ± 205	331 ± 145	627 ± 166	34 ± 31
	Forwards	941 ± 182	535 ± 130	363 ± 133	44 ± 30
	Overall	837 ± 280	279 ± 189	521 ± 181	37 ± 34
High-intensity running distance (5.5–7 m/s) (m)	Defenders	546 ± 195	135 ± 104	380 ± 121	31 ± 28
	Midfielders	834 ± 160	277 ± 111	526 ± 140	31 ± 26
	Forwards	740 ± 137	400 ± 86	303 ± 111	36 ± 24
	Overall	677 ± 223	219 ± 140	427 ± 151	32 ± 27
Sprint distance (> 7 m/s) (m)	Defenders	151 ± 95	47 ± 62	98 ± 55	6 ± 13
	Midfielders	158 ± 80	54 ± 50	101 ± 52	3 ± 8
	Forwards	202 ± 84	135 ± 61	60 ± 42	7 ± 11
	Overall	160 ± 89	60 ± 64	95 ± 54	5 ± 11
Distance > MAS (m)	Defenders	1414 ± 412	421 ± 244	896 ± 262	96 ± 60
	Midfielders	1868 ± 292	687 ± 202	1103 ± 270	78 ± 52
	Forwards	2010 ± 241	1110 ± 187	791 ± 219	110 ± 55
	Overall	1654 ± 431	601 ± 314	962 ± 284	91 ± 57
Distance > 30% ASR (m)	Defenders	589 ± 217	166 ± 133	393 ± 145	30 ± 30
	Midfielders	726 ± 163	250 ± 109	453 ± 142	23 ± 25
	Forwards	765 ± 150	460 ± 114	270 ± 102	35 ± 27
	Overall	661 ± 204	232 ± 152	401 ± 150	28 ± 28
Distance > 85% PS (m)	Defenders	24 ± 24	7 ± 13	16 ± 20	1 ± 4
	Midfielders	31 ± 27	10 ± 16	21 ± 20	0 ± 2
	Forwards	20 ± 18	16 ± 16	3 ± 7	1 ± 3
	Overall	26 ± 25	9 ± 15	16 ± 20	1 ± 3

TABLE 3. Repeated-measure correlations (with 95% CIs) between the examined distance metrics.

	Total distance	High-speed running distance (m)	High-intensity running distance (m)	Sprint distance (m)	Distance > MAS (m)	Distance > 30% ASR (m)
High-speed running distance	ALL: 0.41* (0.34–0.48)					
	TIP: 0.49* (0.43–0.55)					
	OTIP: 0.47* (0.41–0.53)					
	BOP: 0.40* (0.34–0.47)					
High-intensity running distance	ALL: 0.45* (0.39–0.51)	ALL: 0.93* (0.92–0.94)				
	TIP: 0.55* (0.49–0.60)	TIP: 0.94* (0.93–0.95)				
	OTIP: 0.51* (0.45–0.57)	OTIP: 0.95* (0.94–0.96)				
	BOP: 0.41* (0.34–0.47)	BOP: 0.95* (0.94–0.96)				
Sprint distance	ALL: 0.16* (0.08–0.24)	ALL: 0.72* (0.68–0.75)	ALL: 0.42* (0.36–0.49)			
	TIP: 0.23* (0.15–0.30)	TIP: 0.77* (0.73–0.80)	TIP: 0.49* (0.43–0.55)			
	OTIP: 0.17* (0.09–0.24)	OTIP: 0.68* (0.64–0.72)	OTIP: 0.41* (0.35–0.48)			
	BOP: 0.24* (0.16–0.31)	BOP: 0.72* (0.67–0.75)	BOP: 0.46* (0.39–0.52)			
Distance > MAS	ALL: 0.58* (0.52–0.63)	ALL: 0.91* (0.90–0.92)	ALL: 0.91* (0.90–0.92)	ALL: 0.54* (0.48–0.59)		
	TIP: 0.57* (0.52–0.63)	TIP: 0.86* (0.84–0.88)	TIP: 0.86* (0.83–0.88)	TIP: 0.58* (0.52–0.63)		
	OTIP: 0.61* (0.56–0.66)	OTIP: 0.88* (0.86–0.90)	OTIP: 0.88* (0.86–0.90)	OTIP: 0.50* (0.43–0.55)		
	BOP: 0.50* (0.44–0.56)	BOP: 0.90* (0.89–0.91)	BOP: 0.88* (0.86–0.89)	BOP: 0.58* (0.52–0.63)		
Distance > 30% ASR	ALL: 0.36* (0.29–0.43)	ALL: 0.98* (0.98–0.98)	ALL: 0.89* (0.87–0.90)	ALL: 0.76* (0.73–0.80)	ALL: 0.86* (0.84–0.88)	
	TIP: 0.35* (0.28–0.42)	TIP: 0.93* (0.92–0.94)	TIP: 0.82* (0.80–0.85)	TIP: 0.80* (0.77–0.83)	TIP: 0.86* (0.83–0.88)	
	OTIP: 0.41* (0.34–0.47)	OTIP: 0.96* (0.95–0.96)	OTIP: 0.88* (0.86–0.90)	OTIP: 0.71* (0.67–0.75)	OTIP: 0.88* (0.86–0.89)	
	BOP: 0.39* (0.32–0.45)	BOP: 0.98* (0.97–0.98)	BOP: 0.90* (0.88–0.91)	BOP: 0.76* (0.72–0.79)	BOP: 0.86* (0.83–0.88)	
Distance > 85% PS	ALL: 0.03 (-0.05–0.10)	ALL: 0.42* (0.36–0.49)	ALL: 0.19* (0.11–0.26)	ALL: 0.70* (0.67–0.74)	ALL: 0.30* (0.23–0.37)	ALL: 0.46* (0.40–0.52)
	TIP: 0.10* (0.02–0.18)	TIP: 0.47* (0.41–0.53)	TIP: 0.26* (0.19–0.33)	TIP: 0.68* (0.64–0.72)	TIP: 0.39* (0.32–0.45)	TIP: 0.54* (0.48–0.60)
	OTIP: 0.08 (-0.00–0.16)	OTIP: 0.38* (0.31–0.44)	OTIP: 0.18* (0.10–0.25)	OTIP: 0.68* (0.63–0.72)	OTIP: 0.29* (0.21–0.36)	OTIP: 0.42* (0.36–0.49)
	BOP: 0.16* (0.08–0.23)	BOP: 0.46* (0.39–0.52)	BOP: 0.27* (0.19–0.34)	BOP: 0.70* (0.66–0.74)	BOP: 0.35* (0.28–0.42)	BOP: 0.49* (0.43–0.55)

ALL = Whole Match; * = $p < 0.05$

TABLE 4. Mean ± *SD* values for the examined distance metrics standardized by time on pitch.

Variables	Positions	Whole match	TIP	OTIP	BOP
Total distance (m/min)	Defenders	103.2 ± 5.7	124.8 ± 10.7	145.5 ± 8.3	62.8 ± 4.8
	Midfielders	120.3* ± 6.9	158.5* ± 9.9	165.8* ± 12.0	68.4* ± 4.6
	Forwards	111.7°# ± 7.1	160.7# ± 8.8	140.6° ± 10.5	65.9 ± 5.9
	Overall	111.0 ± 10.1	142.9 ± 19.9	152.7 ± 14.7	65.4 ± 5.5
High-speed running distance (> 5.5 m/s) (m/min)	Defenders	7.2 ± 2.9	8.2 ± 6.9	15.8 ± 5.4	0.8 ± 0.7
	Midfielders	10.3* ± 2.1	15.1 ± 6.5	20.7* ± 5.3	0.8 ± 0.7
	Forwards	9.9 ± 2.0	24.7°# ± 7.1	12.2° ± 4.3	1.0 ± 0.7
	Overall	8.8 ± 2.9	13.2 ± 8.8	17.2 ± 6.0	0.8 ± 0.7
High-intensity running distance (5.5–7 m/s) (m/min)	Defenders	5.7 ± 2.0	6.1 ± 4.5	12.5 ± 4.2	0.7 ± 0.6
	Midfielders	8.7* ± 1.7	12.5* ± 4.8	17.3* ± 4.3	0.7 ± 0.6
	Forwards	7.8# ± 1.5	18.6°# ± 4.7	10.2° ± 3.6	0.8 ± 0.5
	Overall	7.1 ± 2.3	10.3 ± 6.4	14.1 ± 5.0	0.7 ± 0.6
Sprint (> 7 m/s) distance (m/min)	Defenders	1.6 ± 1.0	2.1 ± 2.8	3.2 ± 1.8	0.1 ± 0.3
	Midfielders	1.7 ± 0.8	2.5 ± 2.4	3.4 ± 1.8	0.1 ± 0.2
	Forwards	2.1 ± 0.9	6.1°# ± 3.2	2.0 ± 1.4	0.2 ± 0.3
	Overall	1.7 ± 0.9	2.9 ± 3.0	3.1 ± 1.8	0.1 ± 0.3
Distance > MAS (m/min)	Defenders	14.6 ± 4.3	19.2 ± 10.7	29.5 ± 8.9	2.2 ± 1.2
	Midfielders	19.4* ± 3.1	31.3* ± 8.7	36.2* ± 8.2	1.8 ± 1.1
	Forwards	20.9# ± 2.8	50.6°# ± 10.9	26.1° ± 6.3	2.5° ± 1.2
	Overall	17.4 ± 4.5	28.3 ± 14.6	31.6 ± 9.2	2.1 ± 1.2
Distance > 30% ASR (m/min)	Defenders	6.1 ± 2.3	7.6 ± 6.0	12.9 ± 4.9	0.7 ± 0.6
	Midfielders	7.8* ± 1.8	11.5 ± 5.3	15.0 ± 4.8	0.5 ± 0.6
	Forwards	7.9 ± 1.6	20.9°# ± 6.6	9.0°# ± 3.3	0.8° ± 0.6
	Overall	6.9 ± 2.1	11.0 ± 7.3	13.2 ± 5.0	0.6 ± 0.6
Distance > 85% PS (m/min)	Defenders	0.2 ± 0.2	0.3 ± 0.6	0.5 ± 0.7	0.0 ± 0.1
	Midfielders	0.3 ± 0.3	0.5 ± 0.8	0.7 ± 0.7	0.0 ± 0.1
	Forwards	0.2° ± 0.2	0.7 ± 0.8	0.1°# ± 0.2	0.0 ± 0.1
	Overall	0.3 ± 0.3	0.4 ± 0.7	0.5 ± 0.7	0.0 ± 0.1

* denotes a significant difference for midfielders vs. defenders; ° denotes a significant difference for forwards vs. midfielders; # denotes a significant difference for forwards vs. defenders

showed slightly higher between-player variability than > 30% ASR (both CV = 4.1%). A possible explanation for this may be the distances based on relative thresholds reporting not perfect correlations, yet still very large to almost perfect, correlations with the respective distances calculated using generic thresholds (rmcorr = 0.91 for distance > MAS vs. HSRD; and rmcorr = 0.70 for distance > 85% PS vs. sprint distance). In the process of load monitoring during training and competition in team sports, it is normally desirable for practitioners to monitor a smaller set of load metrics after reducing the number of available data and select only a few among several correlated variables [49, 50]. From a practical perspective, the present results would seem to suggest that distance covered at > 30% ASR would be unnecessary to assess in elite soccer players during match-play as long as HSRD is examined, whereas it may still be useful and informative to assess the distance covered > MAS and especially > 85% PS, as these distances, based on relative thresholds, are not perfectly correlated with any generic distance metric. Indeed distance covered > 85% PS may be necessary for practitioners to prepare players for match-play and avoid de-training for non-starters [16]. However, it cannot be excluded that in soccer players of different levels or age categories, or in elite players playing in different elite national leagues, the individual values of > 30% ASR are more variable than in the present metrics, leading to lower relationships with HIRD. In such case, considering distance at speed > 30% ASR may be required to gain detailed information on the actual physical effort of each individual player during match-play.

A further purpose of this study was to compare the physical load across playing positions and possession phases of match-play, such

as, TIP, OTIP, and BOP. Indeed, while differences between playing positions for generic distances covered during the entire match have been widely documented in male soccer players at all ages and playing levels [24, 51], only limited knowledge is available regarding positional differences of distances based on MAS, PS, and ASR, or during specific phases related to the ball in/out of play and ball possession. For example, Di Salvo, et al. [46] showed that, in a sample of EPL players competing in the 2003–2004 to 2005–2006 seasons, mean total (whole-match) HSRD (> 5.5 m/s) ranged from 681 m (central defenders) to 1049 m (wide midfielders). Although, the position-specific HSRD covered ranged from 179 m (central defenders) to 566 m (forwards) when in the ball possession phase, and from 331 m (forwards) to 498 m (wide defenders) in the out-of-possession phase. These ranges reflect the HIRD shown by our sample of players. Furthermore, in the TIP phase, attackers covered the greatest distances among all playing positions, followed by wide midfielders, central midfielders, wide defenders and central defenders. Conversely, in the OTIP phase, the authors showed that almost similar HIRD in all defenders and midfielders, while attackers had a much lower distance covered when compared to other positions. Although the current study classified players into three position categories (defenders, midfielders, forwards) due to examining only one team and thus not having a large enough sample to consider a greater number of categories, our overall results confirm those of Di Salvo, et al. [46] concerning HSRD and extend to other relevant generic and relative distance variables in EPL players.

Indeed, the present study also reported that in the TIP phase, forwards covered greater distances than both defenders and midfielders for most of the examined high-intensity variables, including sprint distance and distance > 85% PS. Whereas for other variables forwards cover lower distances than both midfielders and forwards in the OTIP phase. These findings are likely related to the specific tactical behavior and assigned tasks of players in the TIP and OTIP phases and thus might be slightly different according to a team's playing formation, to the specific characteristics of individual players (that is, irrespective of their position), and to the specific team defensive and offensive strategies. Instead, our results are only partially consistent with the study of Mendez-Villanueva, et al. [10] where the authors assessed, among other variables, distances > MAS and > 30% ASR during international youth (U13–U19) matches. These authors showed that, especially in the first half of the match, wide midfielders covered greater distances > MAS than full-backs, central backs and central midfielders. Furthermore, central midfielders covered lower distances > 30% ASR than all other positions, and forwards covered a greater distance at such intensity compared to all other positions. The differences between those results and the present findings may be related to the diverse positional definitions utilized and the varying match-play characteristics between youth and elite senior soccer.

Interestingly, in the TIP phase, a significantly greater sprint distance, with large effects in forwards vs. both defenders and midfielders was observed, although these differences were no more evident when considering the distance > 85% PS (Table 3). Similarly, during the OTIP phase, forwards covered significantly less distance > 85% PS than defenders and midfielders, while differences were not significant when considering sprint distance. These discrepancies may be due to the varying individual PS from different playing positions in the present sample, and the > 85% PS (defenders: 8.19 ± 0.30 m/s; midfielders: 7.96 ± 0.36 m/s; forwards: 8.36 ± 0.27 m/s). Thus, considering a relative rather than a generic speed threshold for sprint speed may provide different, and arguably more accurate, information on the actual external load of players due to inter-player and inter-position PS variability.

The distances covered in the BOP phase showed little differences between positions (Table 3). From a practical perspective, distances covered during the BOP phase may not elicit as much information regarding the players' load and physical performance as TIP and OTIP distances, although still represent a non-negligible quantity of total distance at different intensities and may be interesting from a certain perspective. In agreement with the findings of Mernagh, et al. [52], the current study showed that forwards covered greater distances > MAS and > 30% ASR than midfielders, arguably linked to actions such as re-gaining defensive shape following an attacking phase, to prevent an opponent's counter-attack concluding with a shot on goal, or, conversely, to occupy an advantageous position prior to the start of a new possession phase.

Despite the previous findings, some limitations of the study should be acknowledge: a) the study was conducted using only one team and thus a limited sample of players were examined, which consequently may restrict a generalization of the results; b) the playing position classification adopted did not allow for the differentiation within each unit; c) the speed distance chosen for this study did not account for the transition between the different speed and intensity zones, usually expressed by accelerometry based variables; d) internal load was not collected which would have strengthened the results of the present study; and e) contextual factors such match location, opponent ranking or match outcome was not considered for analysis that should be encouraged for future studies. Therefore, further research is warranted to assess the distances covered during match-play at relative speed thresholds in players of different levels and of a wider range of MAS, PS and ASR values and examine the nature and practical implications of high-intensity distances covered during ball-out-of-play phases in elite soccer matches. If possible, a greater sample size, acceleration and deceleration data as well as internal load variables should also be included in future studies.

CONCLUSIONS

In conclusion, the present study showed that, in EPL players, high-intensity distances covered during match-play are partially different when calculated using relative, individualized speeds rather than absolute, generic thresholds. This is particularly evident for speed > 85% PS, that showed some relevant differences when

compared to speed > 7 m/s. A significant novel finding of this study is that high-intensity distances covered above specific speeds based on individual thresholds have been assessed during official EPL matches, and, in general, in elite soccer players. This provides valuable information for practitioners and researchers on the individual demands of match-play. Although the generic and relative speed thresholds show almost perfect correlation, the differences between HSRD, HIRD and distance > MAS indicate that players may be exposed to more high-intensity distance when using relative thresholds. This knowledge of individualized match demands can aid practitioners in prescribing training loads to athletes. In addition , using thresholds underpinned by scientific rationale may help practitioners reduce injury risk [40] and improve aerobic performance [14] by simply monitoring and adapting to these demands. Future research should aim to examine high-intensity periods as this may highlight greater differences between positions.

Conflict of Interest

The authors declared no conclict of interest.

REFERENCES

1. Drust B, Atkinson G, Reilly T. Future perspectives in the evaluation of the physiological demands of soccer. Sports Med. 2007; 37(9):783–805.
2. Ravé G, Granacher U, Boullosa D, Hackney AC, Zouhal H. How to Use Global Positioning Systems (GPS) Data to Monitor Training Load in the "Real World" of Elite Soccer. Front Physiol. 2020; 11:944.
3. Morgans R, Rhodes D, Teixeira J, Modric T, Versic S, Oliveira R. Quantification of training load across two competitive seasons in elite senior and youth male soccer players from an English Premiership club. Biol Sport. 2023; 40(4):1197–1205.
4. Akenhead R, Hayes PR, Thompson KG, French D. Diminutions of acceleration and deceleration output during professional football match play. J Sci Med Sport. 2013 Nov; 16(6):556–61. doi: 10.1016/j.jsams.2012.12.005.
5. Hunter F, Bray J, Towlson C, et al. Individualisation of time-motion analysis: a method comparison and case report series. *Int J Sports Med*. 2015; 36(1):41–48. doi:10.1055/s-0034 -1384547.
6. Miguel M, Oliveira R, Loureiro N, García-Rubio J, Ibáñez SJ. Load measures in training/match monitoring in soccer: A systematic review. Int J Environ Res Public Health. 2021; 18(5):2721.
7. Rico-González M, Oliveira R, Vieira LHP, Pino-Ortega J, Clemente F. Players' performance during worst-case scenarios in professional soccer matches: a systematic review. Biol Sport. 2022; 39(3):695–713.
8. Abbott W, Brickley G, Smeeton NJ. An individual approach to monitoring locomotive training load in English Premier League academy soccer players. Int J Sports Sci Coach. 2018; 13(3):421–428. doi: 10.1177/1747 954118771181.
9. Abt G, Lovell R. The use of individualized speed and intensity thresholds for determining the distance run at high-intensity in professional soccer. J Sports Sci. 2009 Jul; 27(9):893–8. doi: 10.1080/02640410902998239.
10. Mendez-Villanueva A, Buchheit M, Simpson B, Bourdon PC. Match play intensity distribution in youth soccer. Int J Sports Med. 2013 Feb; 34(2):101–10. doi: 10.1055/s-0032-1306323.
11. Sonderegger K, Tschopp M, Taube W. The challenge of evaluating the intensity of short actions in soccer: a new methodological approach using percentage acceleration. PloS One. 2016; 11(11):e0166534.
12. Baker D, Heaney N. Review of the literature normative data for maximal aerobic speed for field sport athletes: a brief review. J Aust Strength Cond. 2015; 23(7):60–67.
13. Gabbett TJ. Use of Relative Speed Zones Increases the High-Speed Running Performed in Team Sport Match Play. J Strength Cond Res. 2015 Dec; 29(12):3353–9. doi: 10.1519/JSC .0000000000001016.
14. Fitzpatrick JF, Hicks KM, Hayes PR. Dose-Response Relationship Between Training Load and Changes in Aerobic Fitness in Professional Youth Soccer Players. Int J Sports Physiol Perform. 2018 Nov 19; 1–6. doi: 10.1123 /ijspp.2017-0843.
15. Kavanagh R, Carling C, Malone S, Di Michele R, Morgans R, Rhodes D. 'Bridging the gap': Differences in training and match physical load in 1st team and U23 players from the English Premier League. 2023.
16. Gualtieri A, Rampinini E, Sassi R, Beato M. Workload monitoring in top-level soccer players during congested fixture periods. Int J Sports Med. 2020; 41(10):677–681.
17. Padrón-Cabo A, Solleiro-Duran D, Lorenzo-Martínez M, Nakamura FY, Campos-Vázquez M, Rey E. Application of arbitrary and individualized load quantification strategies over the weekly microcycle in professional soccer players. Biol Sport. 2023; 41(1):153–161.
18. Clemente FM, Ramirez-Campillo R, Beato M, Moran J, Kawczynski A, Makar P, Sarmento H, Afonso J. Arbitrary absolute vs. individualized running speed thresholds in team sports: A scoping review with evidence gap map. Biol Sport. 2023; 40(3):919–943. doi: 10.5114/biolsport.2023.122480.
19. Akenhead R, Nassis GP. Training Load and Player Monitoring in High-Level Football: Current Practice and Perceptions. Int J Sports Physiol Perform. 2016 Jul; 11(5):587–93. doi: 10.1123 /ijspp.2015-0331.
20. Morgans R, Orme P, Bezuglov E, Di Michele R. Technical and physical performance across five consecutive seasons in elite European Soccer. Int J Sports Sci Coach. 2022.
21. Abbott W, Brickley G, Smeeton NJ. Physical demands of playing position within English Premier League academy soccer. J Hum Sport Exerc. 2018; 13(2).
22. Bloomfield J, Polman R, O'Donoghue P. Physical demands of different positions in FA Premier League soccer. J Sports Sci Med. 2007; 6(1):63.
23. Bradley PS, Lago-Peñas C, Rey E, Gomez Diaz A. The effect of high and low percentage ball possession on physical and technical profiles in English FA Premier League soccer matches. J Sports Sci. 2013; 31(12):1261–1270.
24. Lorenzo-Martinez M, Kalen A, Rey E, Lopez-Del Campo R, Resta R, Lago-Penas C. Do elite soccer players cover less distance when their team spent more time in possession of the ball? Sci Med Footb. 2021 Nov; 5(4):310–316. doi: 10.1080/24733938.2020.1853211.
25. Morgans R, Kweon D, Ryan B, et al. Playing position and match location affect the number of high-intensity efforts more than the quality of the opposition in elite football players. Biol Sport. 2024; 41(3):29–37. doi:10.5114/biolsport .2024.133669.
26. Chmura P, Konefał M, Chmura J, Kowalczuk E, Zając T, Rokita A, Andrzejewski M. Match outcome and running performance in different intensity ranges among elite soccer players. Biol Sport. 2018; 35(2):197–203. doi: 10.5114/biolsport.2018.74196.

27. Faude O, Koch T, Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. J Sports Sci. 2012; 30(7):625–631.
28. Modric T, Versic S, Morgans R, Sekulic D. Match running performance characterizing the most elite soccer match-play. Biol Sport. 2023; 40(4):949–958.
29. Aalbers B, Van Haaren J. Distinguishing between roles of football players in play-by-play match event data. In: Machine Learning and Data Mining for Sports Analytics: 5th International Workshop, MLSA 2018, Co-located with ECML/PKDD 2018, Dublin, Ireland, September 10, 2018, Proceedings 5. Springer; 2019:31–41.
30. Trewin J, Meylan C, Varley MC, Cronin J. The influence of situational and environmental factors on match-running in soccer: a systematic review. Sci Med Football. 2017; 1(2):183–194.
31. Oliveira R, Brito J, Martins A, Mendes B, Calvete F, Carriço S, Ferraz R, Marques MC. In-season training load quantification of one-, two- and three-game week schedules in a top European professional soccer team. Physiol Behav. 2019 Mar 15; 201:146–156. doi: 10.1016/j.physbeh.2018.11.036.
32. Nobari H, Brito JP, Pérez-Gómez J, Oliveira R. Variability of external intensity comparisons between official and friendly soccer matches in professional male players. Healthcare. 2021; 9(12):1708.
33. Nobari H, Khalili SM, Oliveira R, Castillo-Rodríguez A, Pérez-Gómez J, Ardigò LP. Comparison of official and friendly matches through acceleration, deceleration and metabolic power measures: a full-season study in professional soccer players. Int J Environ Res Public Health. 2021; 18(11):5980.
34. Ingebrigtsen J, Dalen T, Hjelde GH, Drust B, Wisløff U. Acceleration and sprint profiles of a professional elite football team in match play. Eur J Sport Sci. 2015; 15(2):101–110.
35. Bradley PS, Sheldon W, Wooster B, Olsen P, Boanas P, Krustrup P. High-intensity running in English FA Premier League soccer matches. J Sports Sci. 2009; 27(2):159–168.
36. Kavanagh R, McDaid K, Rhodes D, McDonnell J, Oliveira R, Morgans R. An Analysis of Positional Generic and Individualized Speed Thresholds Within the Most Demanding Phases of Match Play in the English Premier League. Int J Sports Physiol Perform. 2023; 1–11.
37. Winter EM, Maughan RJ. Requirements for ethics approvals. 2009.
38. Bezuglov E, Talibov O, Khaitin V, Pirmakhanov B, Waśkiewicz Z, Butovskiy M, Morgans R. Running Performance during the Holy Month of Ramadan in Elite Professional Adult Soccer Players in Russia. Int J Environ Res Public Health. 2021 Nov 8; 18(21):11731. doi: 10.3390/ijerph182111731. PMID: 34770245; PMCID: PMC8583445.
39. FIFA. Test Report. 17-11-2022 2021. [Online]. Available: https://www.fifa.com/technical/football-technology/resource-hub?id=440b5a4c9b08464898bf51a08c0b8a5e.
40. Colby MJ, et al. Improvement of Prediction of Noncontact Injury in Elite Australian Footballers With Repeated Exposure to Established High-Risk Workload Scenarios. Int J Sports Physiol Perform. 2018 Oct 1; 13(9):1130–1135. doi: 10.1123/ijspp.2017-0696.
41. Kelly V, Wood A. The correlation between the 30–15 intermittent fitness test and a novel test of running performance. J Aust Strength Cond. 2013; 21(S1):91–94.
42. Berthon P, Fellmann N, Bedu M, Beaune B, Dabonneville M, Coudert J, Chamoux A. A 5-min running field test as a measurement of maximal aerobic velocity. Eur J Appl Physiol Occup Physiol. 1997; 75(3):233–8. doi: 10.1007/s004210050153. PMID: 9088842.
43. Knicker AJ, Renshaw I, Oldham AR, Cairns SP. Interactive processes link the multiple symptoms of fatigue in sport competition. Sports med. 2011; 41(4):307–328.
44. Bakdash JZ, Marusich LR. Repeated measures correlation. Front Psychol. 2017; 8:456.
45. Hopkins W, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1):3.
46. Di Salvo V, Gregson W, Atkinson G, Tordoff P, Drust B. Analysis of high intensity activity in Premier League soccer. Int J Sports Med. 2009; 30(03):205–212.
47. Barnes C, Archer D, Hogg B, Bush M, Bradley P. The evolution of physical and technical performance parameters in the English Premier League. Int J Sports Med. 2014; 35(13):1095–1100.
48. Bush M, Barnes C, Archer DT, Hogg B, Bradley PS. Evolution of match performance parameters for various playing positions in the English Premier League. Hum Mov Sci. 2015; 39:1–11.
49. Pexa B, Ryan ED, Blackburn JT, Padua DA, Garrison JC, Myers JB. Influence of baseball training load on clinical reach tests and grip strength in collegiate baseball players. J Athl Train. 2020; 55(9):984–993.
50. Williams S, Trewartha G, Cross MJ, Kemp S, Stokes KA. Monitoring What Matters: A Systematic Process for Selecting Training-Load Measures. Int J Sports Physiol Perform. 2017; 12.
51. da Mota GR, Thiengo CR, Gimenes SV, Bradley PS. The effects of ball possession status on physical and technical indicators during the 2014 FIFA World Cup Finals. J Sports Sci. 2016; 34(6):493–500.
52. Mernagh D, Weldon A, Wass J, et al. A Comparison of Match Demands Using Ball-in-Play versus Whole Match Data in Professional Soccer Players of the English Championship. Sports (Basel). 2021; 9(6):76. Published 2021 May 26. doi:10.3390/sports9060076.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.132992
© Institute of Sport – National Research Institute

Characterizing microcycles' workload when combining two days structure within single training sessions during congested fixtures in an elite male soccer team

AUTHORS: Antonio Gómez-Díaz[1], Fábio Yuzo Nakamura[2,3], Pedro Menezes[4], João Barreira[2], Pedro Figueiredo[5,3,6], Diogo Coutinho[2,3]

[1] Spanish Football Federation (RFEF), Madrid, Spain
[2] Department of Sports Sciences and Physical Education, University of Maia, Maia, Portugal
[3] Research Center in Sports Sciences, Health Sciences and Human Development, CIDESD, 5000-801 Vila Real, Portugal
[4] Clube Regatas do Flamengo, Rio de Janeiro, Brazil
[5] Physical Education Department, College of Education, United Arab Emirates University, Al Ain, United Arab Emirates
[6] Portugal Football School, Portuguese Football Federation, Oeiras, Portugal

Corresponding author:
Diogo Coutinho
Research Center in Sports Sciences, Health Sciences and Human Development, CIDESD, University of Maia, Av. Carlos Oliveira Campos – Castelo da Maia, 4475-690 Maia, Portugal
E-mail:
diogoamcoutinho@gmail.com

ORCID:
Diogo Coutinho
0000-0001-6605-9505

Fábio Yuzo Nakamura
0000-0002-5336-3652

João Barreira
0000-0002-2652-8685

Pedro Figueiredo
0000-0001-5515-3694

ABSTRACT: This study aimed to describe and compare specific matchdays sessions and playing positions external load during congested fixtures in elite football when combining the objectives from two different training days in one session. Data was collected from 27 players from the 1st Brazilian division (28.7 ± 18.61 years) that participated in the following training days during congested fixtures (n = 16 weeks): a) Match day+1 (MD+1^{MD-2}, session 1 day after the game with tasks from MD+1 and MD-2 sessions, n = 9); b) Matchday-2 (MD-2^{MD+2}, session 2 days prior to subsequent match with tasks from MD-2 and MD+2 sessions, n = 11); c) Matchday-1 (MD-1^{MD+2}, session 1 day prior to subsequent match with tasks from MD-1 and MD+2 sessions, n = 12); and d) Matchday-1 (MD-1^{MD+3}, session 1 day prior to subsequent match with tasks from MD-1 and MD+3 sessions, n = 11). External load was collected with global positioning systems, while internal load with the rating of perceived exertion (RPE). The MD+1^{MD-2} showed higher total distance covered ($F = 116.92$, $p < 0.001$) and player load ($F = 56.67$, $p < 0.001$) values than the other three training days, while both the MD+1^{MD-2} and MD-2^{MD+2} revealed higher distance covered at high-speed running ($F = 22.43$, $p < 0.001$) and high metabolic load distance covered ($F = 75.98$, $p < 0.001$) than both MD-1 sessions. Fullbacks covered higher high-speed running distance ($F = 3.6$, $p = 0.033$) than center backs, while midfielders reported higher RPE ($F = 5.29$, $p = 0.003$) values than defensive midfielders and fullbacks. Coaches may use the MD+1^{MD-2} to emphasize total distance covered, while both MD+1^{MD-2} and MD-2^{MD+2} to promote HSR and HML distance compared to MD-1 sessions. In addition, combining training sessions allows to normalize external load across playing positions with the exception of fullbacks that are exposed to higher stimulus.

CITATION: Gómez-Díaz A, Nakamura FY, Menezes P et al. Characterizing microcycles' workload when combining two days structure within single training sessions during congested fixtures in an elite male soccer team. Biol Sport. 2024;41(4):87–100.

Received: 2023-05-08; Reviewed: 2023-09-10; Re-submitted: 2023-10-23; Accepted: 2023-10-27; Published: 2024-03-18

Key words:
Training Sessions
Team Sports
External Load
Playing Positions
Football

INTRODUCTION

A major aim during an association football training week (i.e., microcycle) is to enhance the team tactical coordination [1] while simultaneously maintaining high levels of physical fitness to face the increasing demands of the competition [2]. The design of a microcycle must entail daily training load fluctuations while decreasing the likelihood of inducing injuries and excessive fatigue [3]. These fluctuations are often identified throughout the microcycle. Accordingly, the first session of the week, often referred to as match day +1/+2 (MD, minus or plus; MD+1, i.e., training session held on the day after the competition) entails a double aim: i) recover the players that perform more than 60-min during the last match; ii) compensate load for those players' that did not attain sufficient stimulus [4]. The MD-4 aims to develop the team intra-sectorial coordination by adopting intermittent small-sided games (SSG) in small spaces to emphasize acceleration and deceleration [5]. In contrast, training tasks involving a higher number of players and pitch space is used to promote team collective coordination while emphasizing total distance covered and distance covered at high-intensity [6, 7]. The MD-2 is focused on match strategical preparation by developing specific movement patterns and inter-sectorial coordination using

training tasks in numerical superiority (e.g., 7 vs 4), while intending to emphasize sprinting distance [4, 6, 8]. Lastly, the MD-1 is often dedicated to promote the team offensive and defensive set pieces movement patterns during a low-intensity session [4].

Consequently, each MD emphasizes a specific team tactical aim, while adjusting the training tasks to induce appropriate stimulus. From a physical perspective, there is a trend towards increasing the training intensity from the first session of the week, often referred to as match day +1/+2 (MD, minus or plus; MD+1, i.e., training session held on the day after the competition) towards the MD-3 (i.e., training session held three days prior to the match) [2]. Meanwhile, a taper has been reported from MD-2 to MD-1 (i.e., training days held two and one days prior to the next match) to allow optimal performance in the match [5]. Considering a regular training microcycle (i.e., cycle composed by 5 training days: MD+1, MD-4, MD-3, MD-2 and MD-1 and one game per week), several studies have explored its external load distribution [9]. For example, Akenhead et al. [5] found that MD-4 presented higher mean load values for all variables than the remaining days, especially in terms of the number of accelerations and decelerations. Consequently, players have been observed to execute anywhere from approximately 110 to 150 accelerations (counted at > 3 m/s^{-2}) and approximately 100 to 130 decelerations (counted at > 3 m/s^{-2}), with midfielders reporting the highest numbers and strikers recording the lowest [4]. MD-3 also stands out as a session with a substantial load, often emphasizing total distance covered and distance covered at high-speed running (HSR) levels (> 21 km/h-1). In these sessions, players typically cover distances ranging from about 5100 m to 6500 m, with approximately 340 m of it categorized as HSR [4, 8]. Interestingly, during MD-3 in regular microcycles, fullbacks have been observed to cover more high-intensity distance than players in other positions, while midfielders tend to cover less high-intensity distance [4]. Furthermore, the majority of research has identified a tapering strategy in relation to MD-2 and MD-1. This tapering is evident in the reduced distance covered with high metabolic load (i.e., distance covered when metabolic power exceeds 25.5 W/kg), which averages around 405 m in MD-2 and approximately 580 m in MD-1, respectively [8].

Additionally, MD-2 places a strong emphasis on sprinting distance (> 25.2 km/h-1), often interspersed with periods of low-intensity activities. This reduction in load becomes even more pronounced in MD-1, where lower values are reported for most of the previously mentioned variables [4, 5, 8]. Despite these findings, differences in the load distribution have been found when analyzing teams from different cultures [10]. Thus, further research is required to provide additional information regarding general load values for each training day and its variability across teams in different continents.

Despite the increasing literature comparing different training days and playing positions' external load during regular microcycles, the growing competitive demands in modern elite football [9] has promoted a change in the weekly periodization paradigm [8, 11]. In contemporary soccer, there is notable variability in the duration of microcycles, which can extend beyond 7 days (e.g., during breaks for FIFA National teams' matches) or fewer than 3 days when teams engage in European competitions (e.g., the Champions League) or national cup fixtures. Consequently, microcycles can be categorized as 'long' when there is an interval of more than 8 days between matches within a week's schedule, 'regular' when the gap between matches spans at least 7 days, or 'short' when teams contend with a mere 5 to 6 days between matches [8, 12]. When contrasting microcycle lengths (i.e., long, regular, and short), research findings have been inconsistent. For instance, some studies have reported higher external loads during longer microcycles compared to regular and short ones [13]. Conversely, when examining the number of games within a microcycle, Oliveira et al. [11] found no significant primary distinctions among weekly schedules featuring 3, 2, or 1 match, albeit they identified a noticeable trend towards reduced external load by the time of the last training session before a match (MD-1). Similarly, Anderson et al. [14] reported similar training load values when comparing regular with short microcycles. More recently, Lozano et al. [8] observed greater training volume and intensity, with the exception of accelerations, decelerations (measured at > 3 m/s^{-2}), and HMLD, during longer microcycles in comparison to shorter and regular schedules [8]. These disparities among studies may arise from variations in training methodologies, coaching philosophies, and strategic preparations for upcoming matches [15].Furthermore, it is worth noting that while many studies investigating short-term schedules have considered a 5 to 6-day gap between matches, professional teams often face more demanding scenarios with as little as 2 to 3 days between competitive fixtures.

Short (i.e., three training days between matches) and very short (i.e., two training days between matches) cycles are now more prevalent, requiring different planning structures. For example, despite the adjustment in the total weekly training volume [11], coaches seem to maintain similar load prescriptions for the MD 2 and MD-1 sessions in congested fixtures (e.g., two matches in the same week) compared to regular weeks (i.e., only one weekly match) [16]. In fact, Swallow et al. [16] reported similar HSR (measured in distances higher than 19.8 km/h^{-1}) distance in both MD-2 and MD-1 covered by semi-professional players during the two matches microcycles, despite identifying higher total distance and player load in the microcycles with 2 matches compared to the microcycles with 1 match. However, it is important to note that during the calendar with 3 games per week, professional teams trained 2 days between games without any day off. Therefore, in this case, the MD+1 also corresponded to the MD-2 by being 2 days before the subsequent match. These types of scenarios are emerging more often in the elite level, and thus further research is required to better support the technical staff on how to manage the players' training loads properly. Advancing knowledge in this topic is urgent, as ~40% of players exposed to two to three matches within the same week have to complete

all matches [17], increasing the injury risk [18]. To effectively address the fluctuating duration of training days within the microcycle, arising from competitive fixtures, a commonly employed strategy is to integrate objectives from two distinct days [8]. For instance, a training structure akin to MD-2, which prioritizes the refinement of team strategic movement patterns and highlights sprinting distances, can be combined with elements from MD+2 sessions. These MD+2 sessions are designed to facilitate low-intensity activities, aiding in the recovery of players who have exerted themselves for more than 60 minutes during a match, while also offering additional stimuli for players who did not experience such exertion. This amalgamation of training objectives may allow a balanced and effective approach to preparing the team for both physical recovery and match preparation. Despite such a strategy being applied to the acquisition days, less is known regarding its application to the first session after a match or to the last two before the following match. Therefore, the aim of the present study was to compare the external load profile of combining training sessions (MD+1 $^{MD-2}$, MD-2 $^{MD+2}$, MD-1 $^{MD+2}$ and MD-1 $^{MD+3}$) during very-short microcycles. A secondary aim of the study was to explore how these MD combinations affects the training load stimulus from different playing positions.

MATERIALS AND METHODS

Participants

Thirty-seven elite outfield football players from the Brazilian first division (i.e., Brasileirão – Série A) were selected based on a convenience sampling to participate in this study during the 2022 season (January to December). This club played in international competitions during the observation season (e.g., Copa Libertadores da América). This team is often forced to play several games within short periods of time (n = 77 matches during the season within the different competitions), which requires a vast squad to face such demanding contexts. In addition, the team had often to travel long distances to compete and play in very specific environmental conditions [19], that consequently require effective training-time strategies, such as combine two session structure in one session, between matches to maximize the team tactical preparation while avoiding inducing fatigue. This allowed to obtain the internal and external load from different microcycles employing the different MD combinations and playing positions. However, only 30 were retained for analyses (age: 28.7 ± 18.61 years; height: 180.75 ± 6.31 cm; body mass: 74.96 ± 6.98 kg; playing experience at a high level: 8.33 ± 5.66 years) on the basis that they attended the full training days for the selected weeks [5]. In turn, seven players were excluded as result of: (i) had fewer training days than required (less than 80% of the training days within the study duration) [6]; (ii) missing any session within the microcycle considered for analysis [12]; (iv) being in rehabilitation process both one-month before or during data collection [20]; (v) becoming injured or sick during more than two weeks during data collection; and (vi) did not complete at least 60-min of a competitive match [11]. Also, the goalkeepers (n = 5) were excluded from the present sample due to their specific and restrictive positioning, contributing to a distinct workload profile [16, 21]. The participating players comprised nine center backs, seven fullbacks, four defensive midfielders, four midfielders and six strikers (see table 1). The study protocol followed the recommendations of the Declaration of Helsinki; however, following previous guidelines regarding data collection in elite sports [22], ethics committee clearance was not required.

Procedures

From a total of 45 recorded training weeks, only 16 were retained for analyses (see table 2). These 16 training microcycles were selected based on: i) belonging to a congested period (i.e., a maximum of three days between competitive matches); ii) there was a competitive match between training days without any day off between matches [14]; iii) being training days that combined two different objectives inside the training session. Hence, these 16 microcycles were thoughtfully chosen as they met several essential prerequisites, and all 30 participating players were available for these selected microcycles [14]. t's worth noting that the training period also encompassed sessions structured with only a single-day design (e.g., MD-4); however, these sessions were intentionally excluded from our analysis. This decision was made to maintain a sharp focus on

TABLE 1. Players' characterization according to their playing positions.

Variables	Center Backs n = 9 Mean ± SD	Fullbacks n = 7 Mean ± SD	Defensive Midfielders n = 4 Mean ± SD	Midfielders n = 4 Mean ± SD	Strikers n = 6 Mean ± SD
Age (years)	25.8 ± 6.0	24.7 ± 6.2	25.5 ± 3.7	26.8 ± 9.7	25.0 ± 6.7
Height (cm)	188.3 ± 4.5	176.8 ± 2.6	178.5 ± 2.1	175.3 ± 3.2	179.2 ± 5.9
Weight (kg)	83.4 ± 6.4	70.4 ± 1.8	72.8 ± 2.2	70.0 ± 5.3	72.3 ± 4.0
Playing Experience (years)	9.1 ± 5.8	8.1 ± 5.2	8.5 ± 3.8	8.8 ± 9.7	7.0 ± 5.6

Note: cm = centimeters; kg = kilograms; n = number.

elucidating the effects of integrating two distinct day structures within a single training session. Our analyses exclusively considered the team's primary training sessions, encompassing warm-up activities, the main training session phase, and the subsequent slowdown activities [11]. As a result, activities such as individual rehabilitation sessions or specialized individual training were not included in our analysis [11, 23, 24]. The training sessions themselves covered a wide spectrum, encompassing physical aspects (including warm-up routines and circuit-based activities), technical components (comprising rondos, ball control, passing exercises, and finishing exercises), and tactical elements (involving positional games, pressing tasks, specific movement patterns, and set pieces). All activities were monitored by the head coach and the technical staff without interference from the research team.

Training sessions during very short microcycles (i.e., three matches within one week) are often interspersed with two to three days, during which coaches typically employ the following strategies [8, 11, 14]: i) One session is dedicated to recovery, specifically designed for players who have participated for more than 60 minutes in the previous match. This session involves activities such as practicing passing patterns and employing team positioning in a slower manner to review specific errors made in the past match. Simultaneously, it includes moderate-intensity tasks for players who were not exposed to such stimulus, often involving SSG and positional games.; ii) the second session is focused on match strategic preparation, emphasizing defensive and offensive strategies. Coaches employ tasks that create a high superiority situation or incorporate passive opposition to reduce external load (this session is present when there are three training days between matches); iii) A set pieces session is conducted to refine specific movements for the upcoming match. These approaches leave limited time to develop the team's tactical performance, which has been observed to be compromised during congested fixtures [25]. In response to these challenges, coaches have begun to adopt a mixed approach. This approach involves dedicating half of the session to recovery or tapering strategies to ensure that players are fresh for the upcoming match. In the remaining session time, coaches increase the intensity by incorporating the training structure of other training days to emphasize team movements and tactical preparation [8]. Considering the frequent exposure of the team to very short microcycles within the demanding competitive calendar, our study explores a combination of training sessions to address these challenges effectively (please refer to table 2 for a detailed understanding of the training structure for each day): MD+1 $^{MD-2}$ (session that was performed 1 day after the last match and with a distance of two days to the following match), MD-2 $^{MD+2}$ (2 days prior to the following match, and 2 days after the last one), MD-1 $^{MD+2}$ (1 day prior to the match and 2 days after the last one) and MD-1 $^{MD+3}$ (1 day prior to the match and 3 days after the last one) [5].

TABLE 2. Characteristics of training days.

Training Day	Typology	Number	Duration (min)	Description
MD+1 $^{MD-2}$	MD+1 / MD-2	9	50.3 ± 10.6	Session focused on low to moderate impact activities, composed by the players' that performed less than 60-min of the match. The session MD+1 structure of the session consisted in high-intensity circuits, rondos, small-sided games. The MD-2 part of the session consisted in positional games and specific ball set plays as tapering exercises.
MD-2 $^{MD+2}$	MD+2 / MD-2	11	54.4 ± 11.3	Higher focus on technical-tactical preparation, such as match strategic plan. The MD+2 structure of the session consisted in specific rondos (e.g., 3+3+1 vs 3) and finishing drills under high speed and accelerations demands (e.g., 1 vs 1, 2 vs 1, 3 vs 2). The MD-2 profile of session was composed by offensive set movements, positional games with floaters and tactical exercises in numerical superiority.
MD-1 $^{MD+2}$	MD+2 / MD-1	12	49.5 ± 11.3	Higher focus on tactical preparation, such as working on set pieces. The MD+2 structure of the session consisted in ball control and passing tasks. The MD-1 structure of the session consisted in teambuilding activities and set pieces.
MD-1 $^{MD+3}$	MD+3 / MD-1	11	57.7 ± 10.3	Higher focus on tactical preparation, such as working on set pieces. The MD+3 structure of the session consisted in conditioning activation, followed by in rondos and pressing tasks. The MD-1 structure of the session consisted in teambuilding activities and set pieces.

Note: MD: match day; MD+1: 1 day after the match; MD+2: 2 days after the match; MD+3: 3 days after the match; MD-2: 2 days prior to the match; MD-1: 1 day prior to the match.

Data Collection

Players' external load during each training session was monitored using portable 10 Hz Global Positioning Systems (GPS, WIMU Pro™ tracking systems, RealTrack Systems, Almeria, Spain). These units have been found to increase bias when capturing movements at high intensity (from ~1.6% bias during walking to ~3.5% bias during sprinting) and the type of movement (~1% for linear movements and ~1.6% for circular movements). Still, these systems have been found to be valid and reliable in capturing football players' movement patterns and workload [26]. The GPS devices were activated 15 to 20-min before utilization, following the manufacturer's recommendations. The number of satellites connected to devices was 10.6 0.3, with a horizontal dilution of precision of 0.9 ± 0.2. The players also wore the same unit to eliminate the inter-unit variability [27].

The players' total distance covered in meters (m), high-speed running distance (HSR, above 21 km/h), player load ($AU \cdot min^{-1}$), and high-metabolic load distance (i.e., distance covered when the metabolic power higher than 25.5 W/kg) were used to characterize training days and playing positions' external load. These variables have been used to compare different training days within the same or different microcycles [6, 8, 10, 16, 20, 28], and to compare different playing positions' profiles over the training week [24].

The rating of perceived exertion (RPE) was collected 30 minutes after each training session using the CR-10 scale [29]. The individuals responded using a portable tablet, without the presence of other players. This procedure has been successfully reported to decrease pressure and biases related to the presence of peers [30]. Since players were familiar with this scale, no familiarization was required.

Statistical Analysis

Descriptive data were presented as mean (M) ± standard deviation (SD). A linear mixed model was applied to compare the external load (distance covered, HSR, HMLD, Load) and internal load (RPE) according to the training days (MD+1 $^{MD-2}$, MD-2 $^{MD+2}$, MD-1 $^{MD+2}$, MD-1 $^{MD+3}$), playing positions (fullback, center back, midfielder, striker) and the interaction between training days and playing positions. This statistical approach have been used to explore differences between training days within the microcycle [24], mainly from repeated measures data from players' that possess different number of training days participation [31], while also taking into consideration fixed and random effects. Accordingly, the training day and playing positions were defined as categorical fixed effects, while the individual players' and training session were considered as random effects. Additionally, the Bonferroni post-hoc was used for pairwise comparisons. Complementarily to the null hypothesis testing, Cohen's d effect sizes (ES, 95% confidence intervals) were calculated for all comparisons using the following thresholds: < 0.2, trivial; 0.2 – 0.6, small; 0.6 – 1.2, moderate; 1.2 – 2.0, large; > 2.0 very large [32].

TABLE 3. Descriptive statistics (M ± SD) from the external and internal load according to the training days in relation to the match day (MD).

Variables	MD+1 $^{MD-2}$	MD-2 $^{MD+2}$	MD-1 $^{MD+2}$	MD-1 $^{MD+3}$	Difference in means (raw ± 95% CI)					
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	MD+1 $^{MD-2}$ vs MD-2 $^{MD+2}$	MD+1 $^{MD-2}$ Vs MD-1 $^{MD+2}$	MD+1 $^{MD-2}$ vs MD-1 $^{MD+3}$	MD-2 $^{MD+2}$ Vs MD-1 $^{MD+2}$	MD-2 $^{MD+2}$ Vs MD-1 $^{MD+3}$	MD-1 $^{MD+2}$ Vs MD-1 $^{MD+3}$
External Loal										
Total Distance Covered (m)	3907.2 ± 781.8	3763.2 ± 885.6	2828.7 ± 705.4	2927.5 ± 768.9	-159.4; ± 156.9	-1092.5; ± 143.0	-1010.4; ± 146.4	-933.2; ± 133.8	-851.1; ± 137.5	100.0; ± 124.2
Distance HSR (m)	160.3 ± 149.4	138.4 ± 133.4	68.1 ± 94.8	78.5 ± 80.4	-22.6; ± 27.8	-92.9; ± 25.5	-82.8; ± 24.9	-70.3; ± 19.3	-60.3; ± 18.6	10.1; ± 14.7
Distance HMLD (m)	593.5 ± 228.9	535.6 ± 254.6	322.3 ± 147.5	329.7 ± 152.4	-60.7; ± 45.9	-274.4; ± 38.8	-266.4; ± 39.2	-213.7; ± 34.8	-205.7; ± 35.4	8.0; ± 25.2
Player Load (a.u)	60.4 ± 24.2	55.6 ± 20.8	40.3 ± 13.5	40.3 ± 13.5	-4.8; ± 4.5	-20.0; ± 4.0	-20.1; ± 4.1	-15.2; ± 2.9	-15.3; ± 3.0	-0.1; ± 2.3
Internal Loal										
Rating of Perceived Exertion (a.u.)	4.5 ± 1.6	4.1 ± 1.4	3.0 ± 1.3	2.8 ± 1.1	-0.5; ± 0.3	-1.5; ± 0.3	-1.7; ± 0.3	-1.0; ± 0.2	-1.3; ± 0.2	-0.2; ± 0.2

Note: m = meters; HSR = High-sprint running; HMLD = High-Metabolic Load Distance; CI = Confidence Limits.

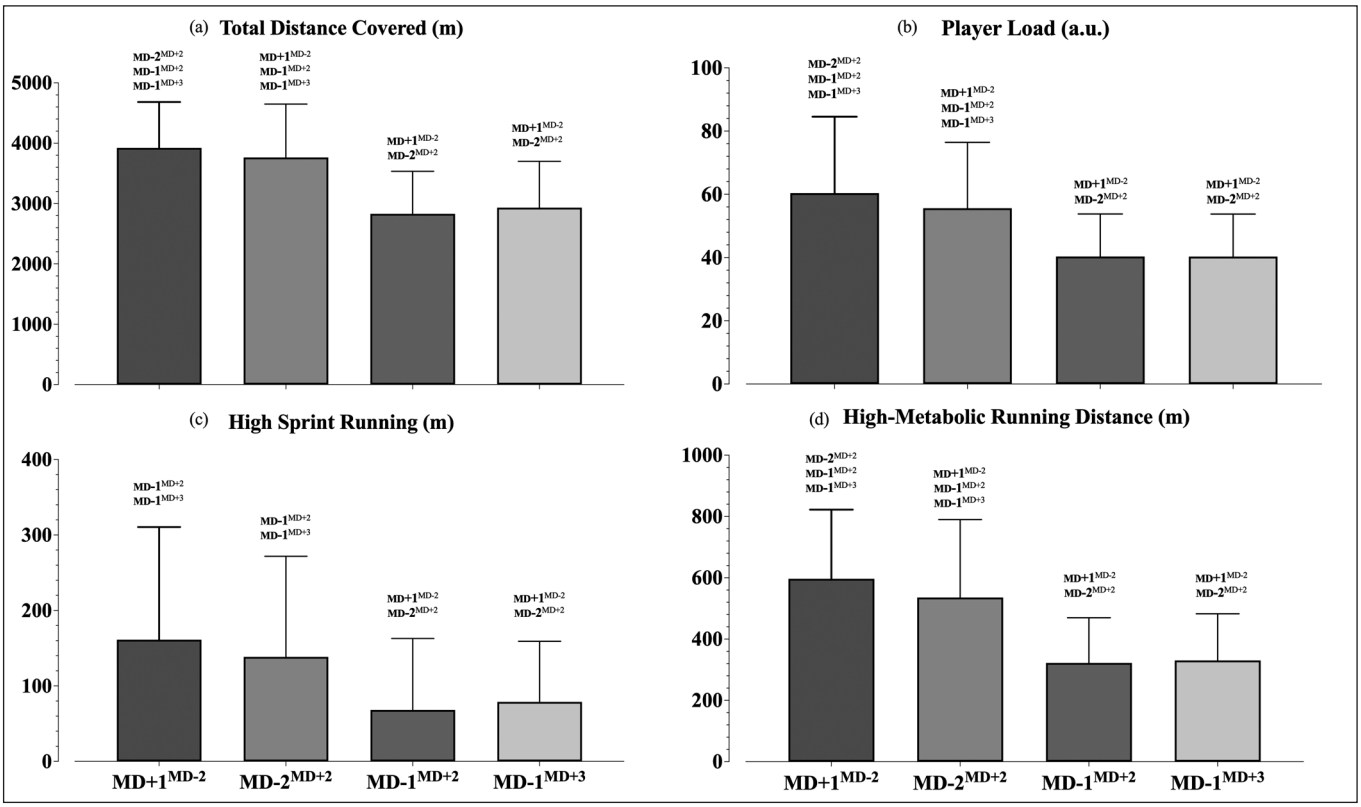


FIG. 1. Descriptive (M ± SD) and inferential statistics from the training load data represented across four training days (MD+1^{MD-2}, MD-2^{MD+2}, MD-1^{MD+2} and MD-1^{MD+3}). Note: having the training day above the bar means statistically significant difference between that day with that / those presented above.

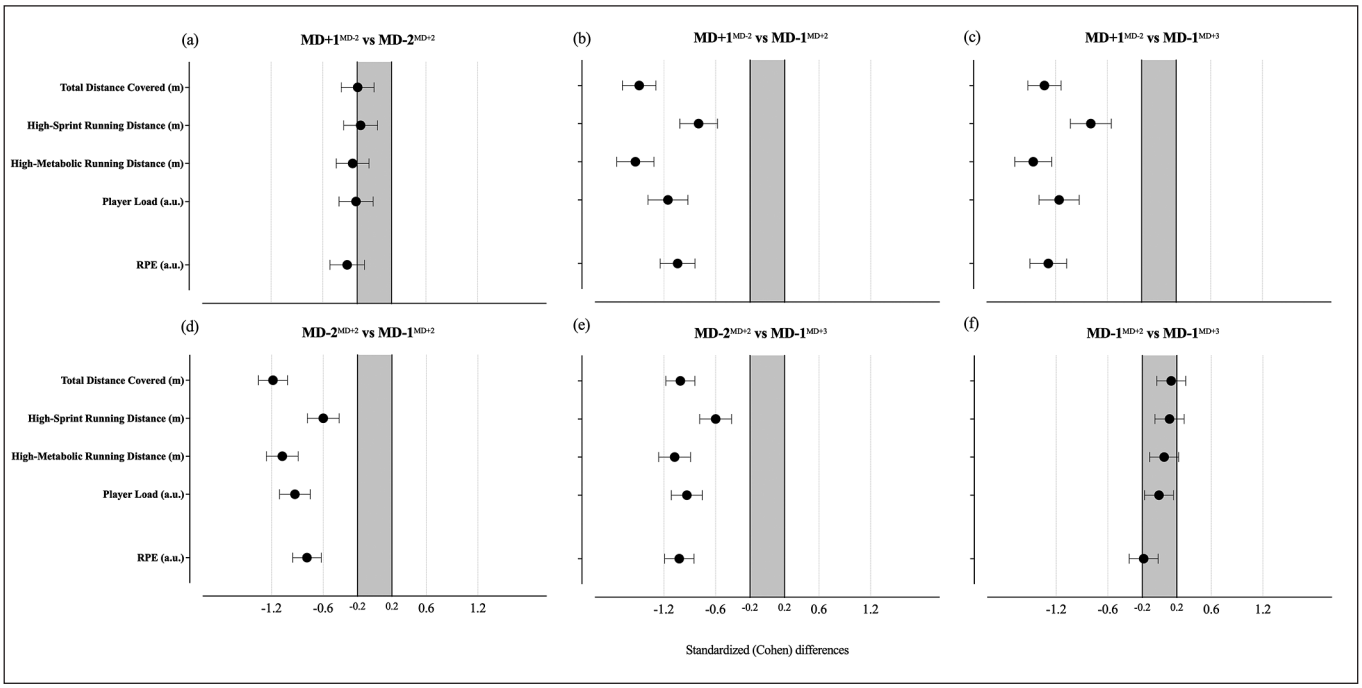


FIG. 2. Standardized (Cohen) differences for the external and internal load according to the training. Errors bars indicate uncertainty in the true mean chances with 95% confidence intervals.

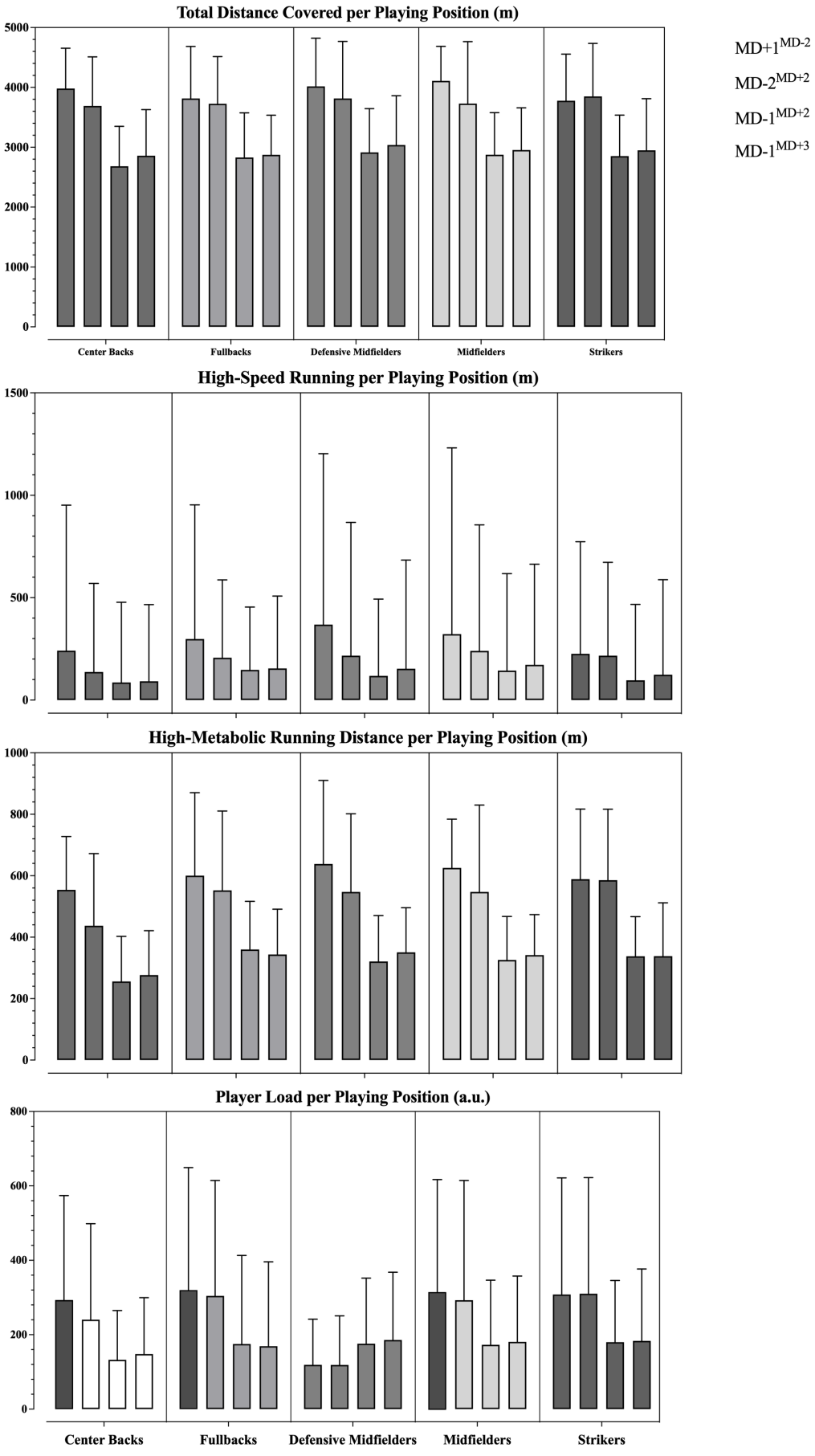


FIG. 3. Descriptive statistics (M ± SD) from the training load data represented across four training days (MD+1^{MD-2}, MD-2^{MD+2}, MD-1^{MD+2} and MD-1^{MD+3}) according to the playing positions.

TABLE 4. Descriptive statistics (M ± SD) from the external and internal load according to playing positions in each training session.

Variables	Difference in means (raw ± 95% CI)									
	Centre Back vs				Fullbacks vs			Defensive Mid.vs		Midfielders vs.
	Fullbacks	Def. Mid.	Midfielders	Strikers	Def. Mid.	Midfielders	Strikers	Midfielders	Strikers	Strikers
MD+1^{MD-2}										
Total Distance Covered (m)	-167.1; ± 361.8	35.2; ± 403.3	127.4; ± 328.5	-205.0; ± 330.0	202.3; ± 435.2	294.5; ± 368.0	-37.9; ± 369.7	92.2; ± 408.7	-332.4; ± 337.1	-240.2; ± 410.3
Distance HSR (m)	73.7; ± 70.0	82.4; ± 89.1	17.6; ± 59.6	22.1; ± 50.9	8.6; ± 100.8	-56.1; ± 76.8	-51.6; ± 70.7	-64.8; ± 94.2	-60.2; ± 89.7	4.5; ± 60.3
Distance HMLD (m)	46.4; ± 105.3	84.4; ± 127.4	71.4; ± 88.2	34.9; ± 90.0	294.5; ± 120.1	281.6; ± 76.6	-11.4; ± 111.0	-12.9; ± 130.5	-49.4; ± 131.9	-36.5; ± 94.9
Load (a.u)	12.3; ± 15.1	2.9; ± 6.9	0.7; ± 5.4	-2.8; ± 4.8	-9.5; ± 15.8	-11.6; ± 15.3	-15.2; ± 15.1	-2.1; ± 7.2	-5.7; ± 6.8	-3.6; ± 5.3
Rating of Perceived Exertion (a.u.)	-0.7; ± 0.8	-0.8; ± 0.9	0.6; ± 0.8	-0.0; ± 0.8	-0.1; ± 0.8	1.3; ± 0.6	0.7; ± 0.7	1.4; ± 0.8	0.7; ± 0.8	-0.7; ± 0.7
MD-2^{MD+2}										
Total Distance Covered (m)	35.6; ± 293.5	124.8; ± 352.6	39.1; ± 377.6	158.8; ± 308.6	89.2; ± 338.7	3.4; ± 364.8	123.2; ± 292.3	-85.7; ± 412.7	34.0; ± 351.7	119.8; ± 376.8
Distance HSR (m)	82.3; ± 49.3	42.4; ± 42.8	70.4; ± 50.4	81.6; ± 43.7	-39.9; ± 49.3	-11.9; ± 56.0	-0.6; ± 50.0	28.0; ± 50.5	39.3; ± 43.7	11.2; ± 51.2
Distance HMLD (m)	115.3; ± 89.6	110.1; ± 96.9	110.2; ± 104.9	148.6; ± 84.6	-5.2; ± 97.6	-5.2; ± 105.5	33.2; ± 85.4	0.0; ± 111.6	38.4; ± 93.1	38.4; ± 101.4
Load (a.u)	11.3; ± 9.3	4.9; ± 5.0	1.7; ± 4.9	2.01; ± 4.3	-6.4; ± 9.8	-9.6; ± 9.7	-9.3; ± 9.4	-3.2; ± 5.8	-2.9; ± 5.2	0.3; ± 5.2
Rating of Perceived Exertion (a.u.)	-0.4; ± 0.5	-0.6; ± 0.5	0.3; ± 0.6	0.2; ± 0.5	-0.1; ± 0.4	0.7; ± 0.5	0.6; ± 0.4	0.9; ± 0.6	0.7; ± 0.4	-0.1; ± 0.6
MD-1^{MD+2}										
Total Distance Covered (m)	146.2; ± 259.9	231.4; ± 274.4	192.4; ± 279.2	169.1; ± 239.0	85.2; ± 279.7	46.2; ± 284.3	22.9; ± 245.0	-39.0; ± 297.5	-62.3; ± 260.6	-23.2; ± 265.6
Distance HSR (m)	77.9; ± 39.1	32.9; ± 33.7	40.4; ± 32.1	20.0; ± 26.8	-45.4; ± 41.1	-38.8; ± 40.1	-57.9; ± 35.9	6.7; ± 34.9	-12.5; ± 29.8	-19.2; ± 28.4
Distance HMLD (m)	104.2; ± 55.9	65.4; ± 58.0	70.1; ± 58.5	82.3; ± 49.5	-38.7; ± 49.7	-34.1; ± 58.3	-22.0; ± 49.3	4.8; ± 60.3	16.9; ± 51.7	12.2; ± 52.3
Load (a.u)	8.1; ± 5.9	5.4; ± 4.3	2.5; ± 3.6	2.6; ± 3.1	-2.7; ± 6.5	-5.7; ± 6.0	-5.5; ± 5.8	-2.9; ± 4.5	-2.8; ± 4.1	0.2; ± 3.4
Rating of Perceived Exertion (a.u.)	-0.3; ± 0.5	-0.5; ± 0.5	-0.1; ± 0.6	0.1; ± 0.5	-0.2; ± 0.5	0.2; ± 0.5	0.4; ± 0.4	0.4; ± 0.6	0.6; ± 0.5	0.2; ± 0.5
MD-1^{MD+3}										
Total Distance Covered (m)	-7.8; ± 257.8	178.5; ± 317.2	95.4; ± 302.7	90.5; ± 298.2	164.1; ± 291.0	81.1; ± 275.0	76.1; ± 269.9	-83.1; ± 320.1	-88.0; ± 316.0	-4.9; ± 301.4
Distance HSR (m)	69.7; ± 29.3	36.7; ± 26.0	57.4; ± 34.0	26.6; ± 20.8	-33.0; ± 32.3	-12.3; ± 39.0	-43.2; ± 28.4	20.8; ± 36.6	-10.1; ± 25.1	-30.9; ± 33.4
Distance HMLD (m)	67.0; ± 54.8	73. 9; ± 57.5	65.1; ± 56.7	61.6; ± 58.0	6.9; ± 56.1	-1.9; ± 55.2	-5.4; ± 56.6	-7.7; ± 57.4	-11.2; ± 58.7	-3.5; ± 58.4
Load (a.u)	4.9; ± 5.5	3.3; ± 4.7	0.1; ± 4.1	1.0; ± 4.1	-1.6; ± 6.1	-4.9; ± 5.6	-3.9; ± 5.6	-3.3; ± 4.8	-2.4; ± 4.8	0.9; ± 4.2
Rating of Perceived Exertion (a.u.)	0.1; ± 0.4	-0.3; ± 0.5	0.4; ± 0.5	0.3; ± 0.4	-0.4; ± 0.4	0.3; ± 0.4	0.2; ± 0.4	0.7; ± 0.5	0.6; ± 0.4	-0.2; ± 0.4

Note: m = meters; HSR = High-sprint running; HMLD = High-Metabolic Load Distance; CI = Confidence Limits.

RESULTS

No significant effects or interactions were identified for the interaction between training days and playing positions (F = 0.93, p = 0.539). However, the linear mixed model identified several effects, mainly between training days.

The differences between training days in relation to the MD are presented in Figure 1, Figure 2 and Table 3. The analysis revealed differences between the training days in all variables (total distance covered, F = 116.92, $p < 0.001$; high-sprint running, F = 22.43, $p < 0.001$; high-metabolic load distance covered F = 75.98, $p < 0.001$; load, F = 56.67, $p < 0.001$; and RPE, F = 40.49, $p < 0.001$).

Accordingly, the MD+1^{MD-2} showed small to large higher distance covered compared with the remaining three conditions ($p < 0.01$, vs MD-2^{MD+2}: ES with 95% CI: ES = -0.20 [-0.39; -0.00]; vs MD-1^{MD+2}: ES = -1.49 [-1.68; -1.29]; vs MD-1^{MD+3}: ES = -1.33 [-1.52; -1.14]), followed by the MD-2^{MD+2} that presented moderate higher values than both the MD-1^{MD+2} ($p < 0.01$, ES = -1.18 [-1.35; -1.01]) and MD-1^{MD+3} ($p < 0.01$, ES = -1.01 [-1.18; -0.84]). As regards to the HSR, moderate higher values were found in the MD+1^{MD-2} when compared to both MD-1^{MD+2} ($p < 0.01$, ES = -0.8 [-1.02; -0.58]) and MD-1^{MD+3} ($p < 0.01$, ES = -0.79 [-1.03; -0.55]), as well as between MD-2^{MD+2} and both the MD-1^{MD+2} ($p < 0.01$, ES = -0.63 [-0.81; -0.46]) and MD-1^{MD+3} ($p < 0.01$, ES = -0.6 [-0.78; -0.41]). For the HMLD, results showed small higher values in MD+1^{MD-2} than in MD-2^{MD+2} ($p = 0.027$, ES = -0.25 [-0.44; -0.06]) and large higher than both MD-1^{MD+2} ($p < 0.01$, ES = -1.53 [-1.75; -1.31]) and MD-1^{MD+3} ($p < 0.01$, ES = -1.46 [-1.67; -1.24]), while the MD-2^{MD+2} also revealed moderate higher values than both MD-1 days ($p < 0.01$, vs MD-1^{MD+2}, ES = -1.14 [-1.32; -0.95]; vs MD-1^{MD+3}, ES = -1.07 [-1.26; -0.89]). A small higher load was identified in MD+1^{MD-2} when compared to MD-2^{MD+2} ($p = 0.04$, ES = -0.21 [-0.41; -0.01]), while also a moderate higher than both the MD-1^{MD+2} ($p < 0.01$, ES = --1.15 [-1.39; -0.92]) and MD-1^{MD+3} ($p < 0.01$, ES = -1.16 [-1.39; -0.92]). In addition, the MD-2^{MD+2} also revealed moderate higher load values than the MD+1^{MD+2} ($p < 0.01$, ES = -0.93 [-1.11; -0.75]) and MD-1^{MD+3} ($p < 0.01$, ES = -0.93 [-1.11; -0.75]).

Lastly, the RPE values showed small to large higher values for MD-1^{MD+2} than the other training days (vs MD-2^{MD+2}, $p < 0.001$, ES = -0.32 [-0.52; -0.11]; vs MD-1$^{MD+2,}$ $p < 0.01$, ES = -1.04 [-1.24; -0.84]; and MD-1^{MD+3}, $p < 0.01$, ES = -1.28 [-1.5; -1.07]), while also moderate higher in MD-2^{MD+2} than in MD-1 sessions ($p < 0.001$, vs MD-1^{MD+2}, ES = -0.79 [-0.95; -0.62]; vs MD-1^{MD+3}, ES = -1.02 [-1.19; -0.85]).

The differences between training days in relation to the MD are presented on Figure 3 and Table 4. In general, no effects were identified between playing positions for the studied variables. Differences were only identified for the high-speed running distance (F = 3.6, p = 0.033) and the RPE (F = 5.29, p = 0.003). In this respect, the fullbacks covered more high-speed running distance compared to the center backs (p = 0.002). The midfielders reported higher RPE values than both the defensive midfielders (p = 0.019) and fullbacks (p = 0.007).

DISCUSSION

This study aimed to describe the external load during congested fixtures in elite football when combining the objectives from two different training days in one session. Overall, the results highlight that: 1) combining MD+1 and MD-2 training content resulted in higher total distance covered, compared to the other conditions, 2) HSR and HMLD distance were higher in MD+1^{MD-2} and MD-2^{MD+2}, compared to both MD-1 sessions, and 3) training loads were generally evenly distributed between playing positions, with the exceptions of the fullbacks, that covered more HSR distance compared to the center-backs, and the midfield players, that reported higher RPE values than the defensive midfielders and fullbacks.

The fact is that the increasing competitive trends in modern elite football will likely make these shorter microcycles the most common standard since top teams are constantly playing 2–3 games in a single week [9], which results in short and very short microcycles (3 and 2 days between 2 matches, respectively) [8, 11]. Planning this type of short period is often a challenge for the technical staff since there might not be enough time for players to fully recover from the previous match, while coaches must prepare the team for the next one. Furthermore, previous investigations [25] have unequivocally showcased the unwavering physical prowess displayed by athletes in the crucible of congested fixtures. However, a conspicuous deviation from this norm comes to light as we observe a discernible decline in players' movement synchronization [25]. This decline raises the tantalizing possibility of a correlation with the constrained temporal window for formulating essential tactical and strategic frameworks crucial in countering the imminent opposition. Consequently, it seems tenable to propose that coaches may progressively place a heightened emphasis on fortifying team tactical preparation during periods characterized by fixture congestion [33]. To face such competitive requirements, coaches may combine the training structure of two different training days aiming to promote enough stimulus to enhance the team's tactical behavior while adjusting the load to avoid the accumulation of fatigue [8]. While this strategy may sound appropriate to prepare the teams, scientific evidence is scarce in providing descriptive results on the effect of combining two different days' structures within the same training session. Nonetheless, the repercussions of these strategies on players' external load remain uncharted territory.

Depending on the number of sessions between games, the first and/or the second session are often the most physically demanding, while a clear taper has been identified in the MD-1 [11]. In fact, Oliveira et al. [11] compared training days from weeks with 1, 2 or 3 matches and identified the MD+1 as the most physically demanding session, with statistically significant effects compared to the MD-2 and MD-1. The results from this study seem to support this trend, as

players covered more total distance, HSR, HMLD distance and also presented higher Player Load in the first two training days, i.e., MD+1^{MD-2} and MD-2 $^{MD+2}$, than in the session that preceded the match (MD-1^{MD+2} or MD-1^{MD+3}), independently of the structure adopted. In contrast to these findings, Swallow et al. [16] found higher total distance and player load in the MD-1 when having 2 games per week than when having just 1 game. However, these differences may rely on the differences between the playing levels (i.e., Swallow's study explored the training loads in semi-professional players that had only a maximum of 3 training days per week, while in this study the participants were professional players) or GPS units used (i.e., PlayerTek vs Wimu). Therefore, during congested fixtures, and independently of combining the training structure of two training days within the same session or following just one day structure, coaches seem to design training tasks that are more physically demanding in the first two sessions of the week and then decrease it in the last one.

The MD+1^{MD-2} group also exhibited notable distinctions, displaying greater metrics in terms of total distance covered, high metabolic load distance (HMLD), and overall player load when compared to the MD-2 MD+2 group. The MD+1 phase typically focuses on the recuperation of players who have participated for more than 60 minutes in a match, involving specialized recovery-oriented sessions. In contrast, those players not exposed to such extended match periods confront sessions that rank among the most demanding within the microcycle [4]. However, it is important to note that in the present study, data from the MD+1^{MD-2} group excluded players who had undergone the recovery session, a deliberate exclusion designed to reduce data variability [11]. The training sessions for players receiving physical stimulus in the MD+1 phase encompassed a blend of high-intensity circuits, rondos, and small-sided games (SSG), as well as positional games and passing patterns. Such training methodologies appear to accentuate players' capacity for acceleration and deceleration, notably observed during SSG, circuits, and rondos, while the emphasis on distance covered becomes evident during positional games and passing patterns [6, 12]. Given that the primary objective is to replicate the intensity experienced during 60 minutes of a match, it is reasonable to anticipate that the MD+1^{MD-2} group would exhibit higher performance values in comparison to the MD-2 group, where a tapering strategy is employed [2, 11, 14]. While it is expected that a decrease in training load in days closer to the match, it is also expected that during short length cycles, coaches decrease the load in the MD-2, which often refers to the second training session in a congested period. It is known that depending on the markers considered (i.e., creatine kinase, jumping ability, blood sample), most of them return to baseline values only between 48 h to 72 h after the match [34]. Therefore, under congested fixtures, coaches seem to decrease the training load in the MD-2 as a result of the proximity to subsequent match [9, 11], but also taking into consideration the recovery process of line-up players, as well as the load that substitutes and non-used players were exposed on the previous training (i.e., MD-1). The lack of effects for the HSR distance would be somehow expected. That is, the MD+1 focus on providing load to the substitute and non-used players, who often are in a lower number than the remaining sessions. In this respect, it is well known that a lower number of players on a game-based task combined with a lower pitch size leads to lower distance covered at high-intensity [35], while the MD-2 session has the participation of the lineup players that are not fully recovered and thus, coaches often avoid creating very high-intensity stimulus [3].

Following the MD+1^{MD-2} session, it was evident that the MD-2^{MD+2} session imposed a more substantial training load than the cumulative MD-1 days. In conventional training microcycles, coaches frequently employ this session to cultivate strategic movement patterns based on an analysis of the opposition. For instance, they may simulate specific scenarios, such as goal kick build-ups, based on video analysis of the opposition's pressure. This session also incorporates training tasks designed to enhance sprinting abilities, such as analytical drills and finishing drills based on long-distance passes. It culminates in a match simulation (typically involving a Gk+10v10+Gk). In this simulation, the defensive team is often confined to specific areas to reduce physical load while allowing for a review of team tactical coordination. Research has revealed that such sessions generally lead to players covering distances ranging from approximately 3490 to 5780 meters [4, 5], with high-speed running (HSR) segments varying from around 23 (measured above 21 km/h^{-1}) [5] to 284 m (measured above > 19.8 km/h^{-1}) [16]. Additionally, players tend to accumulate a player load of approximately 543 a.u. [5].

In shorter-term microcycles, studies have shown that players cover distances ranging from about 4780 [8] to 6700 m [11], with HSR segments (measured above 19 km/h) ranging from approximately (measured above > 21 km/h^{-1}) [8] to 280 meters (measured above > 19 km/h^{-1}) [11]. These sessions also typically result in players covering approximately 760 meters of HMLD and reporting player load values of approximately 70 a.u. [8].

While prior research has suggested similar training load values in MD-2 sessions across regular and short microcycles [8], a combined approach seems to elicit a distinct training stimulus profile. In the combined MD-2^{MD+2} session, players covered approximately 3760 meters in total distance, with approximately 140 meters at high-intensity (measured above 21 km/h), around 535 meters of HMLD, and a player load of about 55 a.u. It's worth noting that these values are lower than the upper limits observed in typical microcycles, particularly in terms of total distance covered, despite comparable HSR figures. These differences may be attributed to session variations, as the study by Oliveira [11] categorized the first session as MD-2 rather than MD+1 when only two sessions were considered. Additionally, disparities in data collection technology (WIMU vs. DatatraX®) and variations in metric parameters, such as HSR thresholds (above 19 km/h, above 19.8 km/h, and above 21 km/h), could contribute to these differences. Furthermore, the microcycle length differs between studies, with a 3-day gap between matches in the

present study and a 5-day gap in the Oliva-Lozano study [8], which can limit direct comparisons.

In general, adopting a combined session structure like MD-2^{MD+2} appears to induce lower total distance covered values compared to the majority of typical and short microcycles, despite similar HSR figures. Consequently, this combined approach may be advantageous for enhancing player recovery from the preceding match, aiding in the removal of blood lactate and pH recovery [3] while still addressing the speed development essential for this training session [6]. Additionally, this approach seems to alleviate the mechanical load on players, as indicated by lower HMLD and player load figures, which could enhance player readiness for upcoming matches.

The final training session preceding a match, often referred to as MD-1, is typically dedicated to refining team set pieces and reviewing strategic movements, such as strategies for pressing the opposition during their build-up. Given its proximity to the match, this session is usually shorter in duration and consists of two to three key exercises. These exercises often include activities like rondos for specific player activation, interspersed with reaction speed drills, a 10 vs 10 simulation of passive strategic movements, and concludes with offensive and defensive set piece drills. Available data has generally shown consistent external load characteristics during MD-1, regardless of the length of the microcycle [8]. For instance, in the study by Oliva-Lozano et al. [8]., similar metrics were reported for distance covered (approximately 4091 m vs. 3950 m), high-speed running (measured above 21 km/h, approximately 130 m vs. 127 m), high metabolic load distance (approximately 611 m vs. 581 m), and player load (approximately 58 a.u. vs. 56 a.u.) when comparing short microcycles (5 days between matches) with regular microcycles (6 days between matches). When considering the number of matches within a week, higher total distance covered was found during the microcycle with two matches (with two sessions between matches, approximately 5100 m) compared to one match (with three sessions between matches, approximately 4423 m), along with higher player load (approximately 250 a.u. vs. 220 a.u.) [16]. Additionally, Oliveira et al. [11] reported total distance covered values ranging from approximately 3620 m to 4420 m and RPE values of around 3 a.u. when facing three matches within the same week with two training sessions in between.

In the present study, MD-1 sessions (both MD-1^{MD+2} and MD-1^{MD+3}) reported lower values for total distance covered (approximately 2830 to 2930 m), high-speed running (approximately 68 to 79 m), high metabolic load distance (approximately 322 to 330 m), and player load (approximately 40 a.u.) compared to previous research. However, it's important to note significant methodological differences, as distance between matches varied from 5 days [8] to 2 days with [16] or without day off [11], while the present study considered 3 sessions between matches. These discrepancies make direct comparisons challenging, despite the clear indication of lower external load when employing a two-session structure. Interestingly, no significant differences were observed when comparing the two MD-1 structures (MD-1^{MD+2} and MD-1^{MD+3}). This lack of distinction could be attributed to the similar activity profiles demanded by the tasks in these different structures. For instance, in MD-1^{MD+2}, players engaged in ball control and passing drills, while in MD-1^{MD+3}, they participated in rondos and passive pressing tasks against opposition. Ball control and passing drills are typically of low-intensity effort and were applied for a short duration, contributing to a similar physical demand when compared to rondos and passive pressing tasks. Moreover, this MD-1 session is known for its lower volume [4], so it's plausible that the limited exposure time to various tasks, coupled with consistent exposure to set pieces, resulted in the lack of discernible differences. Nevertheless, coaches may intentionally introduce variability into the training structure during MD-1 to prevent monotony and align the training content with the analysis of the upcoming opposition. For example, MD-1^{MD+2} could be used to refine offensive passing patterns when the team is expected to dominate possession, while MD-1^{MD+3} might be more appropriate when facing higher-quality opponents and expecting to spend more time on defensive tasks. This adaptability allows coaches to tailor their training to the specific demands of the upcoming match and optimize player preparation.

At last, minimal differences were found in the training load exposure between playing positions. It is known that the match demands vary depending on the positional role that players have on the field. For instance, center backs usually cover lower total distance and HSR than fullbacks, central-midfielders, wide-midfielders and forwards [36]. Wide midfielders and forwards cover greater total distances, while wide-midfielders and second attackers present higher peak match speeds and frequency of high-intensity activities [36]. Since soccer training is very game based, i.e., exercises usually try to replicate the match demands and the different phases of the match (i.e., defensive organization, offensive transition, offensive organization), these between playing position differences are also observed in training. Akenhead et al. [5] found that center midfielders covered higher total distance when compared to center backs during the microcycles'. Other authors also found that fullbacks covered a higher total distance than the remaining positions, specifically on the MD-4 and MD-3 [4]. These small differences were somewhat expected and can be attributed to the overall characteristics of the sessions explored in our study (i.e., rondos, circuits, set pieces, positioning exercises, and overall smaller spaces), common in lower loads training days [4, 6, 8]. Between positions differences are more commonly observed in training days with higher loads, such as MD-4 and MD-3, which are characterized by larger playing areas that try to replicate the match demands [4, 5]. When looking into the days characterized by lower training loads (MD+1, MD-2, and MD-1), the results of other studies [5, 6] generally align with ours. The tactical role of a player is known to be a powerful determinant of their match physical performance, so it is necessary that the conditioning stimulus of training has a positional element to it [37]. However, the focus of the first and last sessions of the microcycle is not on the conditioning side, but more on the match compensation (in case of

substitutes) or recovery, technical-tactical elements, activations and set pieces, respectively [4, 5, 8].

In summary, the integration of training structures from various days offers a valuable means to reduce external load when compared to the more conventional microcycles or shorter-term microcycles that typically feature only one training structure. Given that the primary disparities in player performance during congested fixture periods are closely linked to tactical behaviors, coaches can strategically employ these combined training structures to emphasize and refine these tactical aspects while concurrently mitigating the overall external load. This approach allows for a more balanced and position-specific normalization of the training stimulus across the team, ultimately contributing to enhanced player preparation and performance in congested fixture scenarios.

Limitations and future directions

The study has some general limitations. Firstly, it's important to note that our study focused exclusively on one elite football team. Thus, it inherently limits the generalizability of our findings to a broader spectrum of elite football teams. Given the inherent diversity in coaching philosophies, player characteristics, and playing styles across different teams, it's crucial to recognize that training load strategies may vary significantly. Furthermore, we employed convenience sampling in this study for practical reasons. However, it's crucial to acknowledge that convenience sampling introduces potential bias into the sample selection process, as participants are chosen based on their accessibility and availability. Consequently, it is imperative to interpret the findings of this study within the context of this non-random sampling method. Caution should be exercised when attempting to generalize our results to broader populations of elite football players. To address these limitations, future research endeavors should consider employing more extensive and diverse participant recruitment methods. This approach would likely provide a more comprehensive understanding of the topic, ensuring a broader representation of elite football players. Additionally, the data presented in our study is primarily descriptive in nature. Consequently, it would be important that further studies compare training sessions with only one structure with those presenting structures from two different training days. Such comparative analyses would help uncover the potential advantages of combining different training structures within a single session, offering deeper insights into the underlying mechanisms and causality behind our findings.

CONCLUSIONS

Overall, the results from this study highlighted that combining two different training days in the same session contributed to a higher training load in the MD+1^{MD-2}, followed by MD-2^{MD+2} and then by both MD-1^{MD+2} and MD-1^{MD+3}. As regard to players positioning, adopting combined sessions led to a similar profile between players, apart from fullbacks that covered more HSR distance than the center backs. In this respect, combining sessions that may stress the players' physical performance more with sessions that are more focused on taper (e.g., MD-1 with MD+2; MD-2 with MD+2; MD-1 with MD+2; or MD-1 with MD+3) seems to level the training load across positions. Thus, combining two different training structures within the same session may help coaches best tailor the training loads according to the tactical preparation requirements and regulate playing positioning stimulus. However, to properly understand the potential of this strategy, further studies may compare the composed by the structure of 2 different training days to sessions based only on one training day.

Funding

CIDESD, supported by national funds through the Portuguese Foundation for Science and Technology, I.P., under the project UID04045/2020. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Disclosure of interest

The authors report no conflict of interest.

REFERENCES

1. Folgado H, Duarte R, Fernandes O, Sampaio J. Competing with lower level opponents decreases intra-team movement synchronization and time-motion demands during pre-season soccer matches. Plos One. 2014; 9(5):e97145. doi: 10.1371/journal.pone.0097145. PubMed PMID: 24817186; PubMed Central PMCID: PMC4016249.
2. Silva H, Nakamura FY, Castellano J, Marcelino R. Training Load Within a Soccer Microcycle Week—A Systematic Review. Strength Cond J. 2023.
3. Ramos-Cano J, Martín-García A, Rico-González M. Training intensity management during microcycles, mesocycles, and macrocycles in soccer: A systematic review. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology.0(0):17543371221101227. doi: 10.1177/17543371221101227.
4. Martin-Garcia A, Gomez Diaz A, Bradley PS, Morera F, Casamichana D. Quantification of a Professional Football Team's External Load Using a Microcycle Structure. J Strength Cond Res. 2018; 32(12):3511–8. doi: 10.1519/JSC.0000000000002816. PubMed PMID: 30199452.
5. Akenhead R, Harley JA, Tweddle SP. Examining the External Training Load of an English Premier League Football Team With Special Reference to Acceleration. J Strength Cond Res. 2016; 30(9):2424–32. Epub 2016/01/29. doi: 10.1519/jsc.0000000000001343. PubMed PMID: 26817740.
6. Castillo D, Raya-González J, Weston M, Yanci J. Distribution of External Load During Acquisition Training Sessions and Match Play of a Professional Soccer Team. J Strength Cond Res. 2021; 35(12):3453–8. doi: 10.1519/jsc.0000000000003363. PubMed PMID: 31469765.
7. Buchheit M, Lacome M, Cholley Y, Simpson BM. Neuromuscular Responses to Conditioned Soccer Sessions Assessed via GPS-Embedded Accelerometers: Insights Into Tactical Periodization. Int J Sports Physiol Perform. 2018; 13(5):577–83. Epub 20180522. doi: 10.1123/ijspp.2017-0045.

Oliva-Lozano JM, Gómez-Carmona CD, Fortes V, Pino-Ortega J. Effect of training day, match, and length of the microcycle on workload periodization in professional soccer players: a full-season study. Biol Sport. 2022; 39(2):397–406. Epub 20210601. doi: 10.5114/biolsport .2022.106148. PubMed PMID: 35309541; PubMed Central PMCID: PMC8919886.
8. Anderson L, Orme P, Di Michele R, Close GL, Morgans R, Drust B, Morton JP. Quantification of training load during one-, two- and three-game week schedules in professional soccer players from the English Premier League: implications for carbohydrate periodisation. J Sports Sci. 2016; 34(13):1250–9. Epub 20151104. doi: 10.1080/02640414.2015.110 6574. PubMed PMID: 26536538.
9. Clemente FM, Owen A, Serra-Olivares J, Nikolaidis PT, van der Linden CMI, Mendes B. Characterization of the Weekly External Load Profile of Professional Soccer Teams from Portugal and the Netherlands. J Hum Kinet. 2019; 66:155–64. doi: 10.2478/hukin -2018-0054. PubMed PMID: 30988849.
10. Oliveira R, Brito J, Martins A, Mendes B, Calvete F, Carriço S, et al. In-season training load quantification of one-, two- and three-game week schedules in a top European professional soccer team. Physiol Behav. 2019; 201:146–56. Epub 20181206. doi: 10.1016 /j.physbeh.2018.11.036. PubMed PMID: 30529511.
11. Vardakis L, Michailidis Y, Topalidis P, Zelenitsas C, Mandroukas A, Gissis I, et al. Application of a Structured Training Plan on Different-Length Microcycles in Soccer— Internal and External Load Analysis between Training Weeks and Games. Appl. Sci. 2023; 13(12):6935. PubMed PMID: doi: 10 .3390/app13126935.
12. Clemente FM, Rabbani A, Conte D, Castillo D, Afonso J, Truman Clark CC, et al. Training/Match External Load Ratios in Professional Soccer Players: A Full-Season Study. Int J Environ Res Public Health. 2019; 16(17):3057. PubMed PMID: doi:10.3390/ijerph 16173057.
13. Anderson L, Orme P, Di Michele R, Close GL, Morgans R, Drust B, Morton JP. Quantification of training load during one-, two- and three-game week schedules in professional soccer players from the English Premier League: implications for carbohydrate periodisation. J Sports Sci. 2016; 34(13):1250–59. doi: 10.1080/0264 0414.2015.1106574.
14. Turner A, Stewart P. Strength and Conditioning for Soccer Players. Strength Cond J. 2014; 36:1–13. doi: 10.1519/ SSC.0000000000000054.
15. Swallow WE, Skidmore N, Page RM, Malone JJ. An examination of in-season external training load in semi-professional soccer players: considerations of one and two match weekly microcycles. Int J Sports Sci Coach. 2021; 16(1):192–9. doi: 10.1177/1747954120951762.
16. Carling C, McCall A, Le Gall F, Dupont G. What is the extent of exposure to periods of match congestion in professional soccer players? J Sports Sci. 2015; 33(20):2116–24. Epub 20151013. doi: 10.1080/0264 0414.2015.1091492. PubMed PMID: 26460635.
17. Dupont G, Nedelec M, McCall A, McCormack D, Berthoin S, Wisløff U. Effect of 2 soccer matches in a week on physical performance and injury rate. Am J Sports Med. 2010; 38(9):1752–8. Epub 20100416. doi: 10.1177/0363 546510361236. PubMed PMID: 20400751.
18. Augusto D, de-Oliveira LA, Aquino R, Fernandes I, Bezerra Almeida M, Vasconcellos F. Within-subject variation of technical performance in elite Brazilian professional soccer players: the environmental stress, match location, and opposition's ranking influences. Int J Perform Anal Sport. 2022; 22(4):583–93. doi: 10.1080/2474 8668.2022.2097835.
19. Oliva-Lozano JM, Barbier X, Fortes V, Muyor JM. Key load indicators and load variability in professional soccer players: a full season study. Res Sports Med. 2021:1–13. Epub 20210714. doi: 10.1080/15438627.2021.1954517 . PubMed PMID: 34259100.
20. White A, Hills SP, Cooke CB, Batten T, Kilduff LP, Cook CJ, et al. Match-Play and Performance Test Responses of Soccer Goalkeepers: A Review of Current Literature. Sports Med. 2018; 48(11):2497–516. doi: 10.1007 /s40279-018-0977-2. PubMed PMID: 30144021.
21. Winter EM, Maughan RJ. Requirements for ethics approvals. J Sports Sci. 2009; 27(10):985. doi: 10.1080 /02640410903178344.
22. Los Arcos A, Mendez-Villanueva A, Martínez-Santos R. In-season training periodization of professional soccer players. Biol Sport. 2017; 34(2):149–55. Epub 20170101. doi: 10.5114/biolsport.2017.64588. PubMed PMID: 28566808; PubMed Central PMCID: PMC5424454.
23. Malone JJ, Di Michele R, Morgans R, Burgess D, Morton JP, Drust B. Seasonal training-load quantification in elite English premier league soccer players. Int J Sports Physiol Perform. 2015; 10(4):489–97. Epub 2014/11/14. doi: 10.1123/ijspp.2014-0352. PubMed PMID: 25393111.
24. Folgado H, Duarte R, Marques P, Sampaio J. The effects of congested fixtures period on tactical and physical performance in elite football. J Sports Sci. 2015; 33(12):1238–47. doi: 10.1080/02640414.2015.1022576. PubMed PMID: 25765524.
25. Bastida Castillo A, Gómez Carmona CD, De la Cruz Sánchez E, Pino Ortega J. Accuracy, intra- and inter-unit reliability, and comparison between GPS and UWB-based position-tracking systems used for time-motion analyses in soccer. Eur J Sport Sci. 2018; 18(4):450–7. Epub 20180131. doi: 10.1080 /17461391.2018.1427796. PubMed PMID: 29385963.
26. Castellano J, Casamichana D, Calleja-González J, Román JS, Ostojic SM. Reliability and Accuracy of 10 Hz GPS Devices for Short-Distance Exercise. J Sports Sci Med. 2011; 10(1):233–4. Epub 20110301. PubMed PMID: 24137056; PubMed Central PMCID: PMC3737891.
27. Rey E, Corredoira FJ, Costa PB, Pérez-Ferreirós A, Fernández-Villarino MA. Acute effects of training load on contractile properties during a competitive microcycle in elite soccer players. Biol Sport. 2020; 37(2):157–63. Epub 20200330. doi: 10.5114/biolsport.2020.93041. PubMed PMID: 32508383; PubMed Central PMCID: PMC7249794.
28. Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, et al. A new approach to monitoring exercise training. J Strength Cond Res. 2001; 15(1):109–15. PubMed PMID: 11708692.
29. Burgess D, Drust B. Developing a physiology-based sports science support strategy in the professional game. In: Williams M, editor. Science and Soccer: Developing Elite Performers. Oxon, UK: Routledge; 2012. p. 372–89.
30. Di Salvo V, Gregson W, Atkinson G, Tordoff P, Drust B. Analysis of high intensity activity in Premier League soccer. Int J Sports Med. 2009; 30(3):205–12. Epub 2009/02/14. doi: 10.1055/s-0028-1105950. PubMed PMID: 19214939.
31. Cumming G. Understanding the New Statistics: Effect Sizes, Confidence Intervals, and Meta-Analysis. New York: Routledge, Taylor & Francis Group; 2012.
32. Julian R, Page RM, Harper LD. The Effect of Fixture Congestion on Performance During Professional Male Soccer Match-Play: A Systematic Critical Review with Meta-Analysis. Sports Med. 2021; 51(2):255–73. doi: 10.1007/s40279 -020-01359-9. PubMed PMID:

33068272; PubMed Central PMCID: PMC7846542.
33. Nédélec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in Soccer. Sports Med. 2012; 42(12):997–1015. doi: 10.1007/BF03262308.
34. Hill-Haas SV, Dawson B, Impellizzeri FM, Coutts AJ. Physiology of small-sided games training in football: a systematic review. Sports Med. 2011; 41(3):199–220. doi: 10.2165/11539740-000000000 -00000. PubMed PMID: 21395363.
35. Buchheit M, Mendez-Villanueva A, Simpson BM, Bourdon PC. Match running performance and fitness in youth soccer. Int J Sports Med. 2010; 31(11):818–25. doi: 10.1055 /s-0030-1262838.
Di Salvo V, Baron R, Tschan H, Calderon Montero FJ, Bachl N, Pigozzi F. Performance characteristics according to playing position in elite soccer. Int J Sports Med. 2007; 28(3):222–7. Epub 20061006. doi: 10.1055/s-2006 -924294. PubMed PMID: 17024626.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.133667
© Institute of Sport – National Research Institute

Effect of the phase of the season and contextual variables on match running performance in Spanish *LaLiga* football teams

AUTHORS: Joaquín González-Rodenas[1], Jordi Ferrandis[1], Víctor Moreno-Pérez[2], Roberto López-Del Campo[3], Ricardo Resta[3], Juan Del Coso[1]

[1] Sport Sciences Research Centre, Rey Juan Carlos University, Fuenlabrada, Spain
[2] Sports Research Center, Miguel Hernandez University of Elche, Alicante, Spain
[3] Department of competitions and Mediacoach, LaLiga, Madrid, Spain

ABSTRACT: This study aimed to examine the intra-season variation and the effects of contextual variables on total distance (TD), high-intensity running distance (HIRD) and high-speed distance (HSD) covered by Spanish football teams. The sample included 20 professional teams that competed in the Spanish *LaLiga* during the 2021–2022 season. Data were recorded using the TRACAB (ChyronHego, New York, USA) multicamera computerized optical tracking system. Multilevel linear mixed models were used to examine the effects of five contextual variables (1: phase of the season in six periods, 2: match location, 3: opponent ranking, 4: team ranking and 5: congested schedule) on TD, HIRD and HSD. Teams increased the running performance from period 1 to 5 of the season in TD (+2.2%; $P < 0.05$) and from period 1 to 4 in HIRD (+7.2%; $P < 0.05$), while a declining effect was found in period 6 for both TD (-1.2%; $P < 0.05$) and HIRD (-5.8%; $P < 0.05$). More HIRD (+1.5) and HSD (+5.3) were covered at home ($P < 0.05$), and more TD and HIRD were covered when playing against opponents ranked in the first (+2.4% and +5.3%, respectively; $P < 0.05$) and second quartile (+1.2% and +5.0%, respectively; $P < 0.05$), compared to teams from the fourth quartile. Football coaches and fitness specialists should note that running performance of Spanish teams increased throughout the season, but it declined during the last matches of the competition. Additionally, home matches and high-ranked opponents elicited higher running demands.

CITATION: González-Rodenas J, Ferrandis J, Moreno-Pérez V et al. Effect of the phase of the season and contextual variables on match running performance in Spanish *LaLiga* football teams. Biol Sport. 2024;41(4):101–108.

Received: 2023-07-27; Reviewed: 2023-09-27; Re-submitted: 2023-10-03; Accepted: 2023-11-23; Published: 2024-04-08.

Corresponding author:
Joaquín González-Rodenas
Sport Sciences Research Centre
Rey Juan Carlos University
Camino del Molino, s/n, 28943
Fuenlabrada, Madrid, Spain
E-mail: joaquin.gonzalez@urjc.es

ORCID:
Joaquín González-Rodenas
0000-0002-3583-7375

Víctor Moreno-Pérez
0000-0003-3357-0045

Roberto López-Del Campo
0000-0002-9286-6113

Juan Del Coso
0000-0002-5785-984X

Key words:
Soccer
Match demands
Team sports
Motion analysis
Physical performance

INTRODUCTION

Professional football (soccer) is a physically demanding team sport characterized by the repetition of high-intensity activities such as accelerations, decelerations, changes of directions, sprinting, jumping, and dribbling over 90 min [1, 2]. As a consequence of these high physical demands during football match play, football players incur several signs of acute fatigue such as declining muscle strength [3], reductions in the sprinting and jumping capacities [4] and biochemical alterations (muscle damage, inflammatory and immunological markers, etc.) [5]. The acute signs of fatigue induced by a football match can persist for up to 72 hours or even longer after the match [6]. Moreover, the physical demands of professional football have considerably increased over the last decades in the main European competitions, especially in relation to the distance covered at high intensity and sprint [7, 8].

This heightened physicality of modern football makes it necessary for professional players to be highly trained to cope with the physical demands of the game, as well as to recover as quickly as possible between matches. In recent decades, professional football has experienced a progressive increase in the density of matches [9] and elite football teams can play between 50 and 60 matches per year in national and international competitions. To be successful, professional football squads require an optimal physical condition that must be preserved through the whole season [10]. However, with a competitive season lasting 9–10 months and teams frequently playing more than one match per week, chronic fatigue can be experienced across the season, ultimately affecting the distance covered per match during specific periods of the season [11]. Interestingly, scientific evidence has not consistently demonstrated a significant decrease in running performance during congested competitive periods [12, 13]. Nonetheless, recent studies have reported significant variations in physical performance throughout different phases of the season [14–16], suggesting a link between the chronic fatigue developed across the whole season and reduced match performance.

In early studies [17, 18] conducted in the Italian Serie A, variables such as total distance (TD) and high-intensity running distance (HIRD) increased towards the end of the season. In contrast, recent studies conducted in the Spanish [11] and German national leagues [14] found that TD and HIRD peaked at around two-thirds

of the season but declined in the final matchdays of the season. Meanwhile, Springham et al. [16] observed large reductions in sprint performance, HIRD and TD across the season in an English Championship team. Surprisingly, Li et al. [15] observed a completely different trend in the Chinese Super League, where teams showed a 'U'-shaped pattern with running performance reaching its highest level early in the season, gradually declining to its lowest point at two-thirds of the season, and progressively rebounding towards the end. So, it seems that there is no consensus to ascertain whether there is an effect of the accumulation of matches through the season on match running metrics. Perhaps the characteristics (team's level, number of matchdays, congestion) of each national football league [19] and the introduction of the five-substitution option [20] are responsible in part for the lack of agreement among investigations. In any case, the study of the intra-season variation in different match running metrics with the actual conditions of professional performance deserves further investigation.

Additionally, in the analysis of match running performance across the season it is imperative to include the combined effects of contextual variables, as it has been empirically demonstrated that factors such as the venue of the match, the ranking of the opponent, and the ranking of the team itself exert considerable influence on match running performance [21]. In this regard, existing studies in different competitions have consistently revealed that home teams exhibited superior levels of running performance in comparison to the teams playing away [22–24]. Furthermore, playing against stronger opponents appears to elevate the physical demands of the teams [17, 25]. Conversely, the association between a team's ranking and physical performance remains a subject of contention, as unrelated findings have been reported across different competitions [26–28], which suggests that match running performance does not guarantee greater success in professional football.

Therefore, the aim of this study was to examine the intra-season variation and the effects of contextual variables such as match location, own team's level, opponent's level and match schedule on total distance (TD) high-intensity running distance (HIRD) and high-speed distance (HSD) in teams competing in the Spanish *LaLiga* across the season. We hypothesized that football teams would experience a decline in all running metrics in the last matchdays of the season, while they would run more when playing at home and against high-ranked opponents.

MATERIALS AND METHODS

Sample

The sample included 20 professional male football teams that competed in the first division of Spanish football (*LaLiga*) during the season 2021–2022, including the analysis of 760 team observations during 380 official matches. The collective and total running performance of each team during each match was registered. The competition started on 13 August, 2021 and finished on 22 May, 2022, lasting a total of 9 months and 9 days. The dataset utilized in this investigation was provided by *LaLiga*, which granted authorization for the analysis of pertinent variables and the dissemination of results for scientific purposes. In strict adherence to the ethical guidelines outlined by *LaLiga*, the present investigation does not contain any information that could lead to the identification of individual football players. Furthermore, all procedures and protocols employed in this study were conducted in accordance with the principles set forth in the Declaration of Helsinki and the Institutional Review Board of the Rey Juan Carlos University approved this study.

Procedure

The design of this current descriptive and comparative investigation is based on suggestions made by Mackenzie and Cushion [29]. In this regard, this study takes multiple factors into consideration, including the sample (i.e., 20 elite football teams), competitive nature of football (i.e., official matches played over one season of a national football league), and the operational definitions of the investigated variables (i.e., match running metrics and contextual variables). Running data during the matches were captured using the TRACAB (ChyronHego, New York, USA) multicamera computerized optical tracking system, which has a sampling frequency of 25 Hz, and processed using the Mediacoach software (*LaLiga*, Madrid, Spain), which is a valid and reliable system to analyse football performance [30]. Specifically, for evaluating the match running performance of teams on each matchday, three independent variables based on total distance and high-speed distance [1] were analysed:

1. Total distance (TD): the number of metres that the team covered during the match.
2. High-intensity running distance (HIRD): the number of metres that the team covered during the match between 21 $km \cdot h^{-1}$ and 24 $km \cdot h^{-1}$
3. High-speed distance (HSD): the number of metres that the team covered during the match at > 24 $km \cdot h^{-1}$.

The data of this tracking system have been used in recent prestigious investigations that included the analysis of running performance in professional football teams [31, 32].

The independent variables of this study included five contextual variables:

1. Phase of the season: The season was divided into six different periods (Period 1: matchday 1–7; Period 2: matchday 8–13; Period 3: matchday 14–19; Period 4: matchday 20–25; Period 5: matchday 26–31; Period 6: matchday 32–38), based on a previous study with a similar objective [14].
2. Mach location: Home matches versus away matches.
3. Opponent's ranking: The ranking of the opponent at the end of the season divided into four quartiles (First quartile: first to fifth position; Second quartile: sixth to tenth position; Third quartile: eleventh to fifteenth position; Fourth quartile: sixteenth to twentieth position).

4. Own team's ranking: The ranking of the team at the end of the season divided into four quartiles (First quartile: first to fifth position; Second quartile: sixth to tenth position; Third quartile: eleventh to fifteenth position; Fourth quartile: sixteenth to twentieth position).
5. Congested schedule: Number of matches played in the same week [12, 13, 33] (1: non-congested matches: The team plays one match in the same week; 2: The team plays two matches in the same week).

Statistical analysis

The data were transferred from Mediacoach to a .csv database which was organized in Microsoft Excel. All statistical analyses were carried out using the software IBM SPSS Statistics Version 27.0. Due to the hierarchical structure of teams' performance in football (each team has its own tactical style), a multilevel mixed model [34] was performed to cluster the collective performance (level 2) into teams (level 1). With this organization of the data, a generalized mixed linear model was carried out to explore the effects of the contextual variables (fixed effects) on the running performance, considering the effect of the team (random effects). Thus, the "team effects" represented unobserved team characteristics that influence the running performance and account for the non-independence of the data [32]. Graphic charts with the predicted means and confidence intervals were displayed to show running performance of teams according to the contextual variables evaluated. Pairwise comparisons of the estimated means were performed through Fisher's least significant difference test. The significance level was set to $P < 0.050$.

RESULTS

Table 1 shows the coefficients and statistical differences concerning the effects of the phase of the season and other contextual variables on the match running demands. Regarding the effect of the phase of the season, a significant effect was found for TD, HIRD and HSD. Specifically, the TD covered showed an increasing effect as the season was progressing, reaching its largest increase in the fifth period of the season (Coeff = 2441.22; SE = 469.97; $P < 0.001$), in comparison with the first period of the season. For HIRD, an increasing effect was observed in comparison with the first period of the season, reaching its largest increase in the fourth period (Coeff = 267.28; ES = 55.86; $P < 0.001$). After this period, both TD and HIRD showed a decrease in the sixth period. For HSD, there was an increasing trend from the

TABLE 1. Comparative analyses of match running demands according to the phase of the season and other contextual variables.

	TD (m)		HIRD (m)		HSD (m)	
	Coeff (SE)	P	Coeff (SE)	P	Coeff (SE)	P
Intercept	114991 (991.75)	< 0.001	3806.31 (110.16)	< 0.001	2988.05 (99.02)	< 0.001
Season phase						
1: 1–7 matches						
2: 8–13 matches	930.10 (451.40)	**0.049**	70.17 (49.63)	0.158	15.41 (56.00)	0.783
3: 14–19 matches	1862.37 (468.67)	**< 0.001**	234.04 (49.23)	**< 0.001**	73.58 (55.54)	0.186
4: 20–25 matches	2412.88 (471.36)	**< 0.001**	267.28 (49.51)	**< 0.001**	134.49 (55.86)	**0.016**
5: 26–31 matches	2441.22 (469.97)	**< 0.001**	231.42 (49.36)	**< 0.001**	90.41 (55.69)	0.105
6: 32–38 matches	983.22 (451.40)	**0.030**	34.97 (47.41)	0.461	56.04 (53.49)	0.295
Match location						
Home						
Away	-215.03 (273.46)	0.432	-57.79 (28.72)	**0.045**	-156.18 (32.40)	**< 0.001**
Opponent ranking						
First quartile						
Second quartile	-1343.03 (387.44)	**0.001**	-11.99 (40.70)	0.768	112.71 (45.91)	**0.014**
Third quartile	-1825.11 (385.97)	**< 0.001**	-151.05 (40.54)	**< 0.001**	-46.48 (45.74)	0.310
Fourth quartile	-2663.63 (386.06)	**< 0.001**	-197.57 (40.55)	**< 0.001**	-10.19 (45.75)	0.824
Team ranking						
First quartile						
Second quartile	540.08 (1266.42)	0.670	193.46 (142.34)	0.175	207.77 (120.46)	0.085
Third quartile	-86.727 (1268.23)	0.945	116.08 (142.52)	0.416	111.89 (120.73)	0.354
Fourth quartile	-1613.10 (1268.56)	0.204	-181.08 (142.55)	0.204	-118.553 (120.78)	0.327
Congested match						
Congested						
Not congested	-517.32 (296.07)	0.081	-46.38 (31.10)	0.136	-39.238 (35.06)	0.264

first to fourth period of the season, with a statistically significant difference between the first and the fourth period, when the HSD was higher (Coeff = 134.49; SE =55.86; P = 0.016).

Concerning match location, significant decreases of HIRD (P < 0.001) and HSD (P < 0.001) were observed in away matches with regard to home matches, while no differences were found in TD (Table 2). As for the ranking of the opponent team, significant effects were observed for TD, HIRD and HSD (all P < 0.050). Particularly, a decreasing effect was observed in TD and HIRD as the ranking of the opponent was lower (Figure 1). For HSD, a significant difference was found between the first and second quartile (Coeff = 112.71; SE = 32.40; P = 0.014). Finally, no differences in match running performance variables were found for own's team ranking or match schedule (Table 1).

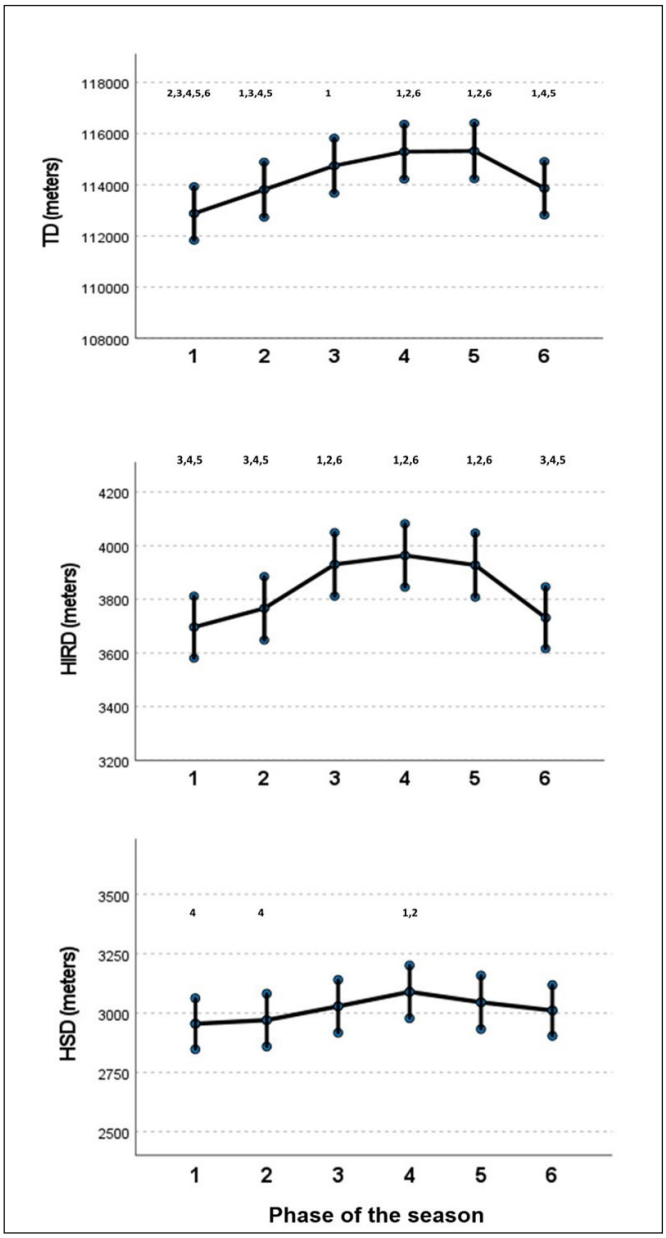


FIG. 1. Estimated means and confidence intervals of TD, HIRD and HSD according to the phase of the season. Data correspond to the team's running performance, including data of 11 players per team.
1 = different from 1; 2 = different from 2; 3 = different from 3; 4 = different from 4; 5 = different from 5; 6 = different from 6. Statistical differences = P < 0.05.

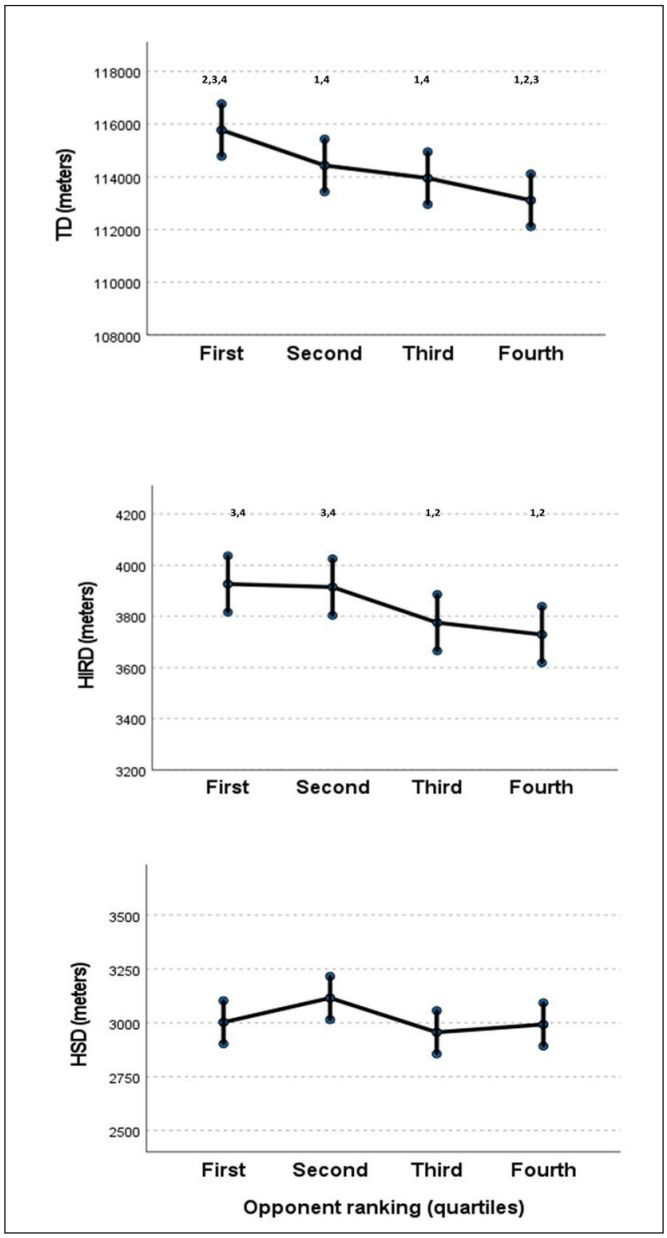


FIG. 2. Estimated means and confidence intervals of TD, HIRD and HSD according to the opponent ranking in quartiles. Data correspond to the team's running performance, including data of 11 players per team.
1 = different from 1; 2 = different from 2; 3 = different from 3; 4 = different from 4; 5 = different from 5; 6 = different from 6. Statistical differences = P < 0.05.

Figure 1 shows the longitudinal evolution of TD, HIRD and HSD through the different periods of the season. For TD, an increasing effect was found from the first period (112877 m; 95% CI: 111829.75–113925-05) to the fifth period (+2.2%), while a decline of 1.2% was observed between the fifth and the sixth period of the season. As regards HIRD, an increasing effect was also found from the first period (3696.18 m; 95% CI: 3580.65–3811.71) to the fourth period (+7.2%) ($P < 0.05$) and a descending effect was observed between the fourth and the sixth period (-5.8%) ($P < 0.05$). Finally, a significant increasing difference was observed between the first and the fourth period regarding HSD (+4.5%) ($P < 0.05$), while no differences were found between the rest of the periods.

Figure 2 depicts the effects of the opponent ranking on TD, HIRD and HSD. For TD, the higher the ranking of the opponent was, the greater was the TD was covered by football teams. Specifically, playing against an opponent ranked in the first quartile demanded 2.3% more of TD, in comparison with the fourth quartile ($P < 0.05$). As regards HIRD, playing against teams ranked in the first or second quartile demanded more HIRD than playing against teams ranked in the third (+4.0%; +3.7%) and fourth quartile (+5.3%; 5.0%), respectively ($P < 0.05$). Finally, the opponents ranked in the second quartile were the teams that demanded more HSD, in comparison with the first (+3.8%), third (+5.4%) and fourth (+4.1%) ($P < 0.05$).

DISCUSSION

The aim of this study was to examine the intra-season variation and the influence of several contextual variables on TD, HIRD and HSD in teams participating in the Spanish *LaLiga* in the 2021–2022 season. The analyses employed in this study included the assessment of a generalized linear mixed model, revealing significant effects of variables such as the phase of the season, opponent's ranking and match location on all match running performance variables. Conversely, variables such as team ranking and congested match schedules did not exhibit any discernible impact on the running output of the teams. Collectively, the outcomes of this study are innovative because they describe how the running metrics during official matches of a national league vary across the season with peak values between match days 20–30 of a 38-matchday competition. Additionally, this analysis confirms that professional football teams adapt to the characteristics of each game, running more when they play at home and against top-tier rivals.

The findings of the current study demonstrated that match running performance (especially TD and HIRD) presented an inverted U-shaped trajectory. Teams displayed lower running performance during the initial phases of the season (periods 1 and 2) but exhibited a significant improvement in subsequent phases, maintaining their performance until the latter stages of the season (period 6), when values declined. Similar trends have been observed in previous investigations conducted in Spain [11, 35] and Germany [14], emphasizing the lower running performance observed at the beginning and end of the competitive season, compared to the middle periods. It is interesting to note that teams covered less TD, HIRD and HSD during the first period of the season, following the preseason period. Although previous studies have observed a fitness improvement of players after the preseason period [36–38], our research suggested that teams did not reach their peak match running performance until the middle phases of the season, when at least 12 matches had been played. This delay may be attributed to the players and teams adapting to the demands of real competition, which require higher physical capabilities than those encountered during friendly matches and the progressive training and playing load during preseason. Additionally, some studies have reported a decline in sprint time and repeated sprint ability following the preseason period [37, 39], possibly due to the high density of physical load experienced within this specific training period of the season. In practical terms, the inverted U-shaped trajectory for all running metrics presented in this investigation might be useful for strength and physical conditioning coaches as it reflects that the current activities performed in the transition period do not fully prepare players to attain maximal performance on the first matchdays of the season as they need more than 20 matchdays to obtain peak running performance. These outcomes also encourage professional teams to achieve high running performance from the first match after resuming the competition as it may be a competitive advantage with respect to the remaining teams. This has especial relevance for national leagues, in which the benefits (i.e., points earned) are the same in all matches of the season, but should not be applied for other football competitions such as knockout competitions (e.g., UEFA Champions League or World Cups), where a progressive tapering in running metrics towards the end of the competition may be beneficial.

On the other hand, a decline in match running performance was observed in the last period of the season, especially for TD and HIRD. Existing literature suggests that players experience increased high stress, fatigue [40], elevated levels of muscle damage biomarkers [41] and a higher incidence of injuries [42] towards the end of the season. These findings highlight the complex nature of the last phases of the season of professional football, wherein teams engage in crucial matches to achieve their competitive objectives while attempting to maintain their technical and tactical success without compromising their running performance. In modern football, which entails 50–60 matches per year in a combination of national and international competitions, successful professional football squads may need to enhance their physical conditioning to preserve a more stable running performance during the last matchdays of the season.

It is worth noting that other studies have observed different patterns of match running performance over the season in different competitions and specific teams. For instance, a recent investigation of Li et al. [15] found that Chinese teams showed U-shaped variation through the season, where the lowest match running performance was observed in the middle phases of the season, while the first and last parts of the season showed the highest performance.

Differently, Springham et al. [16] evaluated a team competing in the English Championship and reported a decreasing trend in match physical performance throughout the season, while Smpokos et al. [43] observed lower physical performance during the second quarter of the season (November) and higher average levels during the fourth quarter of the season (February-March) in a Greek professional team. These divergent findings emphasize that while our study in Spanish football identified a specific trend in match running performance over the season, such trends can vary significantly depending on the context and the specific teams under investigation. So, until further investigations are available to understand how the characteristics of each national league influence the match running performance across the season, the current findings should be applied to football teams competing in *LaLiga* or national competitions with similar duration in matchdays and playing level.

Regarding the influence of the remaining contextual variables on running performance variables, our study revealed that Spanish teams demonstrated higher HIRD and HSD in home matches than when they played away. In line with this finding, a wide quantity of previous studies also observed higher physical demands in home matches [22–24, 44], although variations can be observed when examining specific teams [45, 46]. In this regard, home teams typically have greater winning expectations and a more offensive strategy than away teams [47], as well as displaying faster attacks [48, 49], and achieve greater offensive production [50]. Moreover, additional factors such as crowd effects, familiarity with the field, travel effects or psychological factors can also contribute to higher physical output during home games [51].

Playing against a higher-ranked opponent was also found to elicit greater physical demands, irrespective of the team's own ranking, which had no effect on match running performance. Specifically, Spanish football teams ran greater distances when they played against top-five ranked teams, suggesting that these rivals posed higher demands on the football teams, probably because they have better technical and tactical characteristics that require the opponent team to run more to compensate potential deficiencies [52]. This finding aligns with previous studies conducted in diverse contexts [17, 22, 25]. In this regard, playing against high-ranked opponents seems to make it more difficult to sustain long attacks [48], which also entails spending more time without having the ball, as well as trying to be more vertical offensively [49]. This tactical context induced by the higher-ranked teams requires greater physical effort to neutralize the offensive production of the opposing team, which can explain the higher values in TD, HIRD and HSD. In fact, the study of Folgado et al. [25] reported that playing against stronger opponents implied that teams spent more time in synchronized behaviour and performing faster movements. In contrast, our study did not observe significant differences in running performance based on the team's own ranking, which aligns with the conclusions drawn by Asian Clemente et al. [28] in their investigation of the Spanish *LaLiga*. This fact indicates that the final success of teams is not directly associated with higher match running performance, so other tactical and technical variables seem to be more important. Nevertheless, noteworthy observations from recent studies conducted on the Spanish *LaLiga* [53]and the German *Bundesliga* [26, 27] observed that high-ranked teams covered greater distances with ball possession and performed higher numbers of maximal velocity runs. This suggests the necessity of incorporating additional context-specific physical variables to explore potential discrepancies among teams occupying distinct ranking positions. Additionally, it seems that the best football teams cover the same running distance as lower-ranked teams, but they may differ in the distance running with the ball.

Lastly, no significant effects were observed on match running performance when teams played in congested schedules. Previous studies have indicated that players experience muscle damage up to 72 hours after a match [6] and face a higher risk of injuries during congested periods [33]. However, consistent with our results, scientific evidence has not demonstrated significant declines in running performance when competing in congested periods in professional football [13]. This suggests that despite the potential physiological and mental fatigue suffered by players during congested periods [54], their match running performance generally remains unaffected. In this regard, it is worth exploring new physical metrics to fully understand the real impact of these intensified competitive periods within the season [12]. For instance, a recent study by Djaoui et al. [55] revealed a decline in acceleration and deceleration performance during congested periods compared to non-congested ones. Therefore, analysing match running performance alone may not capture the true extent of congested periods' impact on teams' and players' physical performance.

It is important to acknowledge the limitations of this study. Firstly, this investigation evaluated the match running performance of teams without considering the individual characteristics of players or specific playing positions. Secondly, the study evaluated one single season, which may reflect the specific conditions and team's performance in that period. Thirdly, the current investigation was conducted exclusively with data from a national professional male football league in Spain, and caution should be exercised when generalizing the result to other competitions, categories, or women's football.

CONCLUSIONS

In conclusion, our study revealed an inverted U-shaped pattern in the match running performance of Spanish professional teams through the season. Specifically, running values such as TD, HIRD and HSD were lower at the outset of the season, showed a gradual increase leading to sustained performance, and subsequently declined in the final matches of the season. Additionally, match running performance was found to be higher when playing at home and when facing high-ranked opponents, whereas no significant effects were observed for variables such as team ranking and congested matches.

Regard to practical applications, our study holds considerable relevance for fitness coaches and performance directors of football clubs

in comprehending seasonal variations and the influence of contextual variables on the match running performance of teams. Based on our findings, fitness coaches should design a suitable yearly training and recovery periodization with the objective of sustaining the match running performance of teams until the culmination of the competitive season and avoiding a decline in the last third of the season. Furthermore, fitness coaches should incorporate considerations of playing at home and facing high-ranked opponents into their training periodization and match analysis, as these circumstances may elicit greater running demands compared to playing away or against lower-ranked opponents.

Conflict of interest declaration

The authors declare no conflict of interest

REFERENCES

1. Gualtieri A, Rampinini E, Dello Iacono A, Beato M. High-speed running and sprinting in professional adult soccer: Current thresholds definition, match demands and training strategies. A systematic review. Front Sports Act Living. 2023 Feb 13; 5:1116293.
2. Stølen T, Chamari K, Castagna C, Wisløff U. Physiology of soccer: an update. Sport Med. 2005; 35(6):501–36.
3. Reilly T, Drust B, Clarke N. Muscle fatigue during football match-play. Sport Med. 2008; 38(5):357–67.
4. Marqués-Jiménez D, Calleja-González J, Arratibel-Imaz I, Terrados N. Match loads may predict neuromuscular fatigue and intermittent-running endurance capacity decrement after a soccer match. Int J Environ Res Public Health. 2022; 19(22):15390.
5. Hader K, Rumpf MC, Hertzog M, Kilduff LP, Girard O, Silva JR. Monitoring the athlete match reponse: can external load variables predict post-match acute and residual fatigue in soccer? A systematic review with meta-analysis. Sports Med Open. 2019; 5(48).
6. Silva J, Ascensao A, Marques F, Seabra A, Rebelo A, Magalhaes J. Neuromuscular function, hormonal and redox status and muscle damage of professional soccer players after a high-level competitive match. Eur J Appl Physiol. 2013; 113:2193–201.
7. Lago-Peñas C, Lorenzo-Martinez M, López-Del Campo R, Resta R, Rey E. Evolution of physical and technical parameters in the Spanish LaLiga 2012–2019. Sci Med Footb. 2023; 7(1):41–6.
8. Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The evolution of physical and technical performance parameters in the english premier league. Int J Sports Med. 2014 Jul 10; 35(13):1095–100.
9. Nassis GP, Massey A, Jacobsen P, Brito J, Randers MB, Castagna C, et al. Elite football of 2030 will not be the same as that of 2020: Preparing players, coaches, and support staff for the evolution. Scand J Med Sci Sports. 2020; 30(6):962–4.
10. Ekstrand J. Keeping your top players on the pitch: the key to football medicine at a professional level. Br J Sports Med. 2013; 47(12):723–4.
11. Brito de Souza D, González-Garcia J, López-Del Campo R, Resta R, Buldú J, Wilk M, et al. Players´physical performance in LaLiga across the season: insights for competition continuation after Covid-19. Biol Sport. 2021; 38(1):3–7.
12. Carling C, Gregson W, McCall A, Moreira A, Wong DP, Bradley PS. Match Running Performance During Fixture Congestion in Elite Soccer: Research Issues and Future Directions. Sports Med. 2015; 45(5):605–13.
13. Julian R, Page RM, Harper LD. The Effect of Fixture Congestion on Performance During Professional Male Soccer Match-Play: A Systematic Critical Review with Meta-Analysis. Sports Med. 2021; 51(2):255–73.
14. Chmura P, Konefał M, Wong DP, Figueiredo AJ, Kowalczuk E, Rokita A, et al. Players' physical performance decreased after two-thirds of the season: Results of 3 consecutive seasons in the German first bundesliga. Int J Environ Res Public Health. 2019; 1; 16(11).
15. Li P, Zhong S, Chmura P, Liu H. Match performance of football teams in different competition phases: Analysis on the data of eight consecutive seasons in the Chinese Super League. Front Psychol. 2023; 11; 13:1069082.
16. Springham M, Williams S, Waldron M, Burgess D, Newton RU. Large Reductions in Match Play Physical Performance Variables Across a Professional Football Season With Control for Situational and Contextual Variables. Front Sports Act Living. 2020; 15; 2.
17. Rampinini E, Coutts A, Castagna C, Sassi R, Impellizzeri F. Variation in top level soccer match performance. Int J Sports Med. 2007; 28(12):1018–24.
18. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sports Sci. 2003 Jul 1; 21(7):519–28.
19. Poli R, Ravenel L, Besson R. Analysis of the distances covered in professional football competitions. CIES Football Observatory Monthly Report. 2021; 68.
20. López-Valenciano A, Moreno-Perez V, López-Del Campo R, Resta R, Del Coso J. The Five-substitution option enhances Teams´running peroformance at high speed in football. Int J Sports Med. 2023; 44(5):1982–9808.
21. Paul DJ, Bradley PS, Nassis GP. Factors affecting match running performance of elite soccer players: shedding some light on the complexity. Int J Sports Physiol Perform. 2015; 10(4):516–9.
22. Castellano J, Blanco-Villaseñor A, Alvarez D. Contextual variables and time-motion analysis in soccer. Int J Sports Med. 2011; 32(6):415–21.
23. Oliva-Lozano J, Rojas-Valverde D, Gómez-Carmona C, Fortes V, Pino-Ortega J. Impact of contextual variables on the representative external load profile of Spanish professional soccer match-play: a full season study. Eur J Sport Sci. 2021; 21(4):497–506.
24. Aziz R, Jones M, Jagim A, Feit M, Kuhlman N, Crabil T, et al. In-season match demands of men´s collegiate: A comparison by half position, match outcome, match location, and competition phase. Int J Strength Cond. 2023; 3(1).
25. Folgado H, Duarte R, Fernandes O, Sampaio J. Competing with lower level opponents decreases intra-team movement synchronization and time-motion demands during pre-season soccer matches. PLoS One. 2014; 9(5):e97145.
26. Andrzejewski M, Oliva-Lozano J, Chmura P, Chmura J, Czarniecki S, Kowalczuk E, et al. Analysis of team success based on match technical and running performance in a professional soccer league. BMC Sports Sci Med Rehabil. 2022; 14:82.
27. Chmura P, Oliva-Lozano J, Muyor J, Andrzejewski M, Chmura J, Czarniecki S, et al. Physical performance indicators and team success in the german soccer league. J Hum Kinet. 2022; 83:257–65.
28. Asian Clemente J, Requena B, Jukic I, Nayler J, Santalla Hernández A, Christopher C. Is physical performance a differentiation element between more or less successful football teams? Sports. 2019; 7(10):216.

29. Mackenzie R, Cushion C. Performance analysis in football: a critical review and implications for future research. J Sports Sci. 2013; 31(6):639–76.
30. Felipe JL, Garcia-Unanue J, Viejo-Romero D, Navandar A, Sánchez-Sánchez J. Validation of a video-based performance analysis system (Mediacoach) to analyze the physical demands during matches in LaLiga. Sensors. 2019; 19(19):4113.
31. Lago-Peñas C, Lorenzo-Martinez M, López-Del Campo R, Resta R, Rey E. Evolution of physical and technical parameters in the Spanish LaLiga 2012–2019. Sci Med Footb. 2022; 1–6.
32. García-Calvo T, Fernandez-Navarro J, Díaz-García J, López-Del Campo R, Martínez Fernández F, Memmert D. The impact of COVID-19 lockdown on soccer positional and physical demands in the Spanish La Liga. Sci Med Footb. 2022; 1–7.
33. Page R, Field A, Langley B, Harper L, Julian R. The effects of fixture congestion on injury in professional male soccer: A systematic review. Sports Medicine. 2022; 53:667–85.
34. Sommet N, Morselli D. Keep Calm and Learn Multilevel Logistic Modeling: A Simplified Three-Step Procedure Using Stata, R, Mplus, and SPSS. Int Rev Soc Psychol. 2017; 30(1):229–30.
35. Ponce-Borbón J, García-Calvo T, Candela-Guardiola J, Serpiello F, López-Del Campo R, Resta R, et al. The relationship between running distance and coaches´perception of team performance in professional soccer player during multiple seasons. Sci Rep. 2022; 12:1454.
36. Fessi M, Zarrouk N, Filetti C, Rebai H, Elloumi M, Moalla W. Physical and anthropometric changes during pre-and in-season in professional soccer players. J Sports Med Phys Fitness. 2015; 56(10):1163–70.
37. Meckel Y, Doron O, Eliakim E, Eliakim A. Seasonal variations in physical fitness and performance indices of elite soccer players. Sports. 2018; 6(1):14.
38. Kalapotharakos VI, Ziogas G, Tokmakidis SP. Seasonal aerobic performance aerobic variations in elite soccer players. J Strength Cond Res. 2011; 25(6):1502–7.
39. Eliakim E, Doron O, Meckel Y, Nemet D, Eliakim A. Pre-season fitness level and injury rate in professional soccer-a prospective study. Sports Med Int Open. 2018; 2(3):E84–90.
40. Nobadi H, Fani M, Clemente FM, Carlos-Vivas J, Pérez-Gómez J, Paolo Ardigo L. Intra- and Inter-week Variations of Well-Being Across a Season: A Cohort Study in Elite Youth Male Soccer Players. Front Psychol. 2021; 12.
41. Silva J, Rebelo A, Marques F, Pereira L, Seabra A, Ascensao A, et al. Biochemical impact of soccer: an analysis of hormonal, muscle damage and redox markers during the season. Appl Physiol, Nutri Metab. 2014; 39(4):432–8.
42. Leventer L, Eek F, Lames M. Intra-seasonal variation of injury patterns among German Bundesliga soccer players. J Sci Med Sport. 2019; 22(6):661–6.
43. Smpokos E, Mourikis C, Linardakis M. Seasonal changes of physical (motor) activities in professional Greek football players. Trends Sport Sci. 2018; 2(25):99.
44. Lago C, Casais L, Dominguez E, Sampaio J. The effects of situation variables on distance covered at various speeds in elite soccer. Eur J Sport Sci. 2010; 10(2):103–9.
45. Augusto D, Brito J, Aquino R, Figuereido P, Eiras F, Tannure M, et al. Contextual variables affect running performance in professional soccer players: A brief report. Front Sports Act Living. 2021; 3:350.
46. Oliva-Lozano J, Rojas-Valverde D, Gómez-Carmona C, Fortes V, Pino-Ortega J. Worst case scenario match analysis and contextual variables in professional soccer players: a longitudinal study. Biol Sport. 2020; 37(4):429–36.
47. Staufenbiel K, Lobinger B, Strauss B. Home advantage in soccer – a matter of expectations, goal setting and tactical decisions of coaches? J Sports Sci. 2015; 33(18):1932–41.
48. González-Rodenas J, Aranda R, Aranda-Malavés R. The effect of contextual variables on the attacking style of play in professional soccer. J Hum Sport Exerc. 2020; 16(2):399–410.
49. Fernandez-Navarro J, Fradua L, Zubillaga A, McRobert A. Influence of contextual variables on styles of play in soccer. Int J Perform Anal Sport. 2018; 18(3):423–36.
50. Almeida C, Volossovitch A. Home advantage in Portuguese football: effects of level of competition and mid-terms trends. Int J Perform Anal Sport. 2017; 17(3):244–55.
51. Lago-Peñas C. The Role of Situational Variables in Analysing Physical Performance in Soccer . J Hum Kinet. 2012; 35:89–95.
52. Brito de Souza D, López-Del Campo R, Blanco-Pita H, Resta R, Del Coso J. An extensive comparative analysis of successful and unsuccesful football teams in LaLiga. Front Psychol. 2019; 8(10):2566.
53. Brito Souza D, López-Del Campo R, Blanco-Pita H, Resta R, Del Coso J. Association of match running performance with and without ball possession to football performance. Int J Perform Anal Sport. 2020; 20(3):483–94.
54. Garcia-Romero-Perez A, Ordoñez F, Reyes-Gil F, Rodriguez-Lopez E, Oliva-Pascual-Vaca. Muscle damage biomarkers in congestion weeks in english premier league soccer players: a prospective study for two consecutive seasons. Int J Environ Res Public Health. 2021; 18(15):7960.
55. Djaoui L, Owen A, Newton M, Nikolaidis P, Dellal A, Chamari K. Effects of congested match periods on acceleration and deceleration profiles in professional soccer. Biol Sport. 2022; 39(2):307–17.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.136086
© Institute of Sport – National Research Institute

Possession or position games: What is the key in soccer?

AUTHORS: Jose A. Asian-Clemente[1,2], Borja Muñoz[1], Jose Vicente Beltran-Garrido[3], Bernardo Requena[2]

[1] Department of Sport sciences, Universidad Pablo de Olavide, Seville, Spain
[2] Football Science Institute, Granada, Spain
[3] Department of Education Science, School of Humanities and Communication Sciences, Universidad Cardenal Herrera-CEU, CEU Universities. Castellon de la Plana, Spain

Corresponding author:
Jose Antonio Asian-Clemente
Universidad Pablo de Olavide
ctra Utrera km 1, 41500 Seville
Spain
Tel.: +34 954977601
E-mail: jasicle@upo.es

ORCID:
Jose Antonio Asian-Clemente
0000-0002-5540-5676

Jose Vicente Beltran-Garrido
0000-0001-9286-8453

Bernardo Requena
0000-0002-2398-5370

ABSTRACT: The aims of this study were to compare the running performance of possession and position games and to describe the external load of the same position game played on pitches of different dimensions. Using a GPS system (WIMU Pro, RealTrack Systems, Almería, Spain), the running demands of 25 professional soccer players were monitored during 18 possession (without a standardized role position) and 18 positional (with a specific role position) games of 9 vs. 9 + 2 floaters. Each format was developed in small (< 60 m^2 per payer), medium (60–90 m^2 per player) and large (> 90 m^2 per player) sizes. Position games obtained significantly lower distance covered, peak speed and player load values than possession games (all $p < 0.05$). However, position games obtained significantly higher values of maximal acceleration, maximal deceleration, accelerations higher than 3 m·s^{-2} and decelerations lower than -3 m·s^{-2} than possession games (all $p < 0.05$). Likewise, large position games obtained significantly higher values of distance covered, distance covered > 21 km·h^{-1}, peak speed and player load than small and medium sizes. Large size also showed significantly higher values of maximal acceleration and deceleration than small size, significantly fewer accelerations and decelerations, and fewer accelerations lower than 3 m·s^{-2} and decelerations higher than -3 m·s^{-2} compared to medium and small size (all $p < 0.05$). Practitioners should keep in mind the use of these games and their size to modify the external load of the players during their training.

CITATION: Asian-Clemente JA, Muñoz B, Beltran-Garrido JV, Requena B. Possession or position games: What is the key in soccer? Biol Sport. 2024;41(4):109–117.

Received: 2023-07-08; Reviewed: 2023-11-23; Re-submitted: 2023-12-20; Accepted: 2024-02-27; Published: 2024-04-08.

Key words:
Small-sided games
Time-motion
Football
Area per player

INTRODUCTION

Soccer is the sport with the largest number of participants worldwide, and it has become in the most studied sport in the world [1]. Research has been developed to analyse different factors that affect soccer performance: technical, tactical, mental and physical/physiological areas. Of them all, physical and physiological aspects have received the most attention [2–4]. Previous literature has reported that soccer players run, on average, 9–13 km, with 8–9% covered at speeds above 20 km·h^{-1}, and 2–3% at speeds above 25 km·h^{-1} [5]. Likewise, it has been established that during the game, soccer players face significant demands in terms of accelerations and decelerations, contributing to 7–10% and 5–7% of the total player load, respectively [6]. Currently, it is well established that players' requirements are influenced by their positional roles [5, 7, 8]. For example, a recent study on the last FIFA World Cup Qatar 2022 demonstrated that defensive and central midfielders covered more total distance than players in other positions, while wide midfielders and wide forwards achieved greater distances covered at higher intensities [8]. Similarly, previous studies [6, 9] have shown that acceleration and deceleration demands also vary according to player positions, highlighting that wide midfielders and fullbacks cover more distance while accelerating and decelerating, achieving a greater amount of high-intensity acceleration and deceleration. Meanwhile, midfielders perform a greater number of low-intensity accelerations and decelerations. For this reason, some authors consider it necessary to contextualize the running demands of soccer players to avoid underestimating and overestimating overall physical performance metrics [7].

Physical and physiological improvements are achieved when there is greater similarity between soccer training and actual competition [10]. It follows that the best way to achieve these improvements is to incorporate game-related drills and exercises into soccer training sessions. By simulating the intensity, speed, and decision-making aspects of a real game, players can develop the specific skills and fitness required for match situations. In soccer, small-sided games (SSGs) are considered one of the better resources for this purpose [11]. SSGs are modified games played on reduced pitch areas using adapted rules and involving smaller numbers of players compared to the official match play [3, 12, 13]. Pitch size, player number, inclusion of goalkeepers, duration of bouts, coach encouragement, number of touches allowed and the method of defending are

some of the studied variables in SSGs [3, 14–16]. Despite the fact that SSGs have been widely studied and reported in the specialist literature [3, 13, 16–19], most of the studies have been carried out in a possession format where the players had to maintain ball possession or obtain one goal with a specific position according to the game system. Taking into account that SSGs are among the exercises most frequently used by soccer coaches [11, 12, 20], they have received many modifications. One of the most novel modifications is the creation of position games. These drills are SSGs where the soccer players have to perform according to a specific role position, trying to reproduce similar situations as in the competition. Although they are daily used in the practice of professional soccer teams, their running requirements are unknown. For this reason, the aims of this study were (1) to compare the running performance of possession and position games and (2) to describe the external load of the same position game played in different dimensions.

MATERIALS AND METHODS

Experimental approach to the problem

A descriptive design was adopted to compare running demands of two kinds of sided games. Possession and position games were developed through different formats to maintain ball possession. In possession games the players could move without a standardized role position while in the position games they had to follow their specific role position assigned in the official games. Taking into account that these drills were frequently used during the sessions of the teams, it was not necessary to perform familiarization sessions. The training load of both sided games was monitored to characterize these drills.

Subjects

Twenty-five young soccer players of the second team of a professional Spanish first division team participated in this study (age: 21.9 ± 1.9 years; height: 177.9 ± 5.2 cm; weight: 75.5 ± 4.8 kg; % body fat (Faulkner): 11.1 ± 1.4%). A total of 656 individual data of outfield players (goalkeepers excluded) were included in the analysis. Players were categorised into five individual playing positions: central defenders (CD), fullbacks (FB), defensive midfielders (DM), offensive midfielders (OM), wide midfielders (WM) and strikers (S). All players were informed about the purpose of the study and each player provided written informed consent. All procedures were approved by the ethical committee of the local university according to the principles of the Declaration of Helsinki for studies involving human subjects.

Procedures

A descriptive design of 36 training sessions to compare the external load of two types of sided games (possession and position game) was adopted during the 2021–2022 season. Soccer players were divided by the coach into two teams of 9 according to their playing position and a subjective skill assessment of them to allocate players to balanced SSG teams. Moreover, two more players occupied a floater role, always playing with the team in possession of the ball. All sessions started with a 20-min standardized warm-up based on

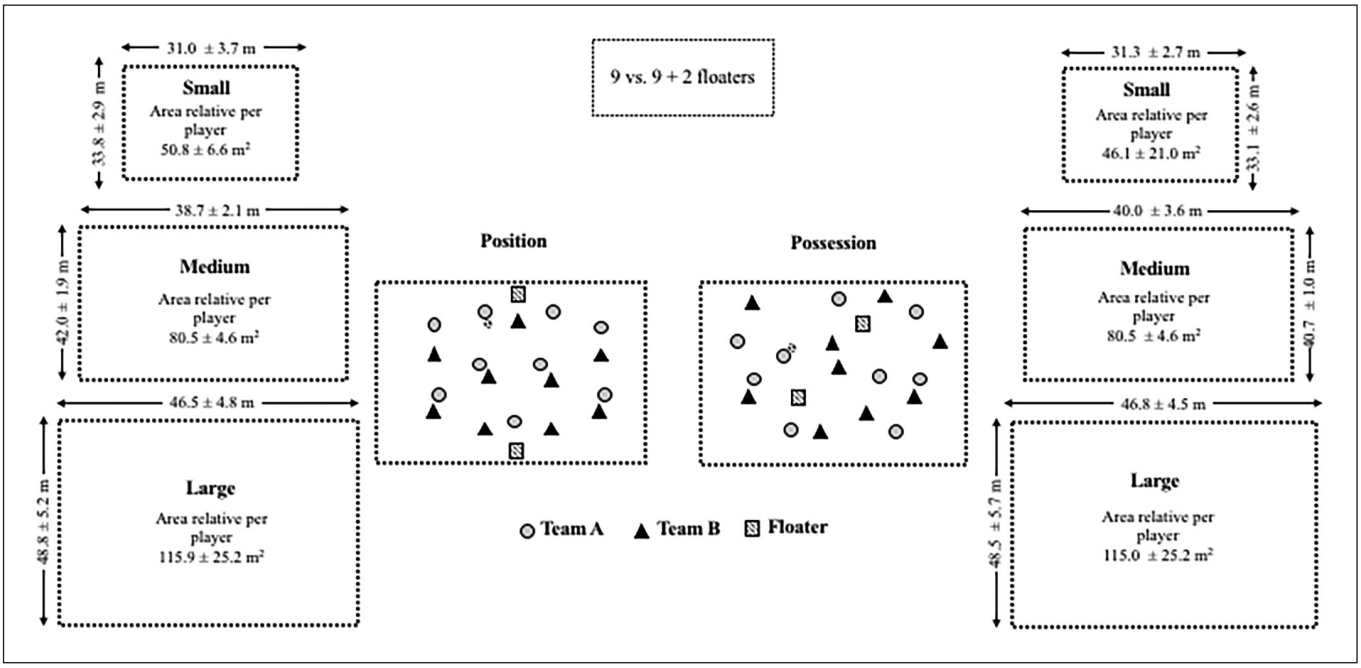


FIG. 1. Graphical representation of possession and position games.

running, ball possession, and dynamic stretching exercises, after which the studied drills were developed. The tasks were performed using a continuous format of 8 min and played with a maximum of two touches per player. These games were presented in a randomized sequence on different days of the week over a period of 36 weeks, according to the tactical and physical requirements of the microcycle. Coaches were required to give verbal encouragement and constructive feedback and to introduce balls immediately when the ball left the playing field.

Possession games and position games

The small-sided games implemented in this study are represented in Figure 1. Players were grouped in two teams of 9 with 2 offensive floater players and they performed two formats: possession and position game. The main difference between the formats was that during the possession games (n = 18) the players were moved without a standardized role position, while in the position games (n = 18) they had to follow their specific role position assigned in a 1-4-2-3 system of play (a variant of the 1-4-3-3 development with 9 players in the team and 1 goalkeeper) and according to the previous explained role position. Independently of format, all tasks were developed to maintain the ball possession. Each format of these games was developed in three sizes, classified according to their relative area per player (ApP) as: small (< 60 m^2 per payer), medium (60–90 m^2 per player) and large (> 90 m^2 per player) with six measures made for each size and format (see Figure 1).

Running activity

Running activity was monitored using a GPS system (WIMU Pro, RealTrack Systems, Almería, Spain) with a sampling rate of 10 Hz. The validity and reliability of this device have been analysed for the collection of time-motion variables, and it is considered a suitable instrument for this purpose in football [21, 22]. Total distance covered (DC), distance covered above 21 $km \cdot h^{-1}$ (DC > 21 $km \cdot h^{-1}$), peak speed, maximal accelerations and decelerations, number of accelerations (Acc_{COUNT}) and decelerations (Dec_{COUNT}), accelerations lower and higher than 3 $m \cdot s^{-2}$ ($Acc_{<3}$; $Acc_{>3}$, respectively) and decelerations lower and higher than -3 $m \cdot s^{-2}$ ($Dec_{<3}$; $Dec_{>3}$, respectively), and player load were recorded. These variables have been used in the previous literature [19, 23–25].

Statistical analyses

A descriptive design was adopted to compare running demands of two kinds of small-sided games. To confirm the data normality of each dataset, the Kolmogorov-Smirnov test, the Q-Q plot of residuals and the random coefficients histogram were used. Data not following a normal distribution were transformed before further analysis [26]. General linear model analyses were used to compare the effects of space size (i.e., large, medium, small) of the position and possession tasks on the dependent parameters. The model used for each dependent parameter had size and type of task as independents fixed factors. The ANOVA omnibus test was used to assess the goodness of fit of the models. When a significant main effect was obtained,

TABLE 1. Running demands of possession and position games.

Variable	Possession	Position
DC (m)	857.53 ± 7.01	792.49 ± 6.89*
DC > 21 $km \cdot h^{-1}$ (m)	12.43 ± 0.87	11.51 ± 0.95
Peak Speed ($Km \cdot h^{-1}$)	20.67 ± 0.13	20.07 ± 0.13*
Player Load (AU)	11.85 ± 0.15	10.84 ± 0.15*
Acc_{COUNT} (counts)	215.15 ± 1.03	217.06 ± 1.03
Dec_{COUNT} (counts)	214.66 ± 1.04	217.17 ± 1.05
Maximal accelerations ($m \cdot s^2$)	4.00 ± 0.03	4.09 ± 0.03*
Maximal decelerations ($m \cdot s^2$)	-4.65 ± 0.04	-4.81 ± 0.04*
$Acc_{<3}$ (counts)	211.18 ± 1.08	208.52 ± 1.09
$Acc_{>3}$ (counts)	5.60 ± 0.16	6.23 ± 0.16*
$Dec_{<3}$ (counts)	208.80 ± 1.15	206.54 ± 1.16
$Dec_{>3}$ (counts)	7.78 ± 0.21	8.44 ± 0.21*

DC = distance covered; DC > 21 $km \cdot h^{-1}$ = distance covered above 21 $km \cdot h^{-1}$; Peak Speed = highest speed reached; Player load = vector magnitude representing the sum of accelerations recorded in the anterior-posterior, mediolateral and vertical planes of movement; Acc_{COUNT} = amount of accelerations; Dec_{COUNT} = amount of decelerations; Maximal accelerations = Maximal accelerations reached; Maximal decelerations = Maximal decelerations reached; $Acc_{<3}$ = Accelerations lower than 3 $m \cdot s^{-2}$; $Acc_{>3}$ = Accelerations higher than 3 $m \cdot s^{-2}$; $Dec_{<3}$ = Decelerations lower than -3 $m \cdot s^{-2}$; $Dec_{>3}$ = Decelerations higher than -3 $m \cdot s^{-2}$. * = $p \leq 0.05$ statistically significant different from possession task.

Bonferroni's correction was used for multiple comparison analysis. To assess between-task differences for each space size, simple effects were calculated with type of task as the simple effects variable and space size as the moderator variable. Statistical significance was set at $\alpha < 0.05$. Unless otherwise stated, all values are presented as the estimated marginal mean (SE) or estimated marginal mean and 95% confidence interval (CI). The data analysis was performed using JAMOVI for Mac [27] (version 2.3.16) and the jamovi module GAMLj: General Analyses for the Linear Model in Jamovi [28].

RESULTS

Descriptive statistics of the possession and position games are presented in Table 1 and Figures 2 and 3. When comparing the type of task, position games obtained significantly lower values than possession games in DC (mean difference [MD] = -65.04 ± 9.83 m, $p < 0.001$), peak speed (MD = -0.59 ± 0.18 km·h^{-1}, $p < 0.001$) and player load (MD = -1.01 ± 0.21 AU, $p < 0.001$) variables. However, position games obtained significantly higher values than Possession games in maximal acceleration (MD = 0.09 ± 0.04 m·s^{-2}, $p = 0.016$), maximal deceleration (MD = 0.16 ± 0.06 m·s^{-2}, $p = 0.011$), $Acc_{>3}$ (MD = 0.63 ± 0.23 counts, $p = 0.006$) and $Dec_{>3}$ (MD = 0.66 ± 0.30 counts, $p = 0.029$) variables. See Table 1 and Figures 2 and 3.

Running demands of the position games at the three different sizes studied are shown in Table 2 and Figures 4 and 5. When comparing the size of the task space, a significant main effect was found in all variables ($p \leq 0.05$) except in $Acc_{>3}$ ($p = 0.118$). See Table 2 and Figures 4 and 5.

Small size was associated with significantly lower values than medium size in DC (MD = -117.77 ± 18.89 m, $p < 0.001$), peak speed (MD = -2.69 ± 0.31 km·h^{-1}, $p < 0.001$) and player load (MD = -1.23 ± 0.41 AU, $p = 0.010$) variables. However, small size was associated with significantly higher values than medium size in the maximal decelerations variable (MD = 0.33 ± 0.11 m·s^{-2}, $p = 0.005$)

Small size was associated with significantly lower values than large size in DC (MD = -219.40 ± 19.28 m, $p < 0.001$), DC > 21 km·h^{-1} (MD = -10.96 ± 2.53 m, $p < 0.001$), peak speed (MD = -4.02 ± 0.31 km·h^{-1}, $p < 0.001$), maximal accelerations (MD = -0.16 ± 0.06 m·s^{-2}, $p = 0.028$), $Dec_{>3}$ (MD = -1.70 ± 0.53 counts, $p = 0.004$) and player load (MD = -2.53 ± 0.42 AU, $p < 0.001$) variables. However, small size was associated with significantly higher values than large size in ACC_{COUNT} (MD = 23.28 ± 2.52 counts, $p < 0.001$), DEC_{COUNT} (MD = 24.86 ± 2.53 counts, $p < 0.001$), maximal decelerations (MD = 0.66 ± 0.11 m·s^{-2}, $p < 0.001$), $Acc_{<3}$ (MD = 11.29 ± 2.69 counts, $p < 0.001$) and $Dec_{<3}$ (MD = 12.89 ± 2.93 counts, $p < 0.001$) variables.

Medium size was associated with significantly lower values than large size in DC (MD = -101.63 ± 19.07 m, $p < 0.001$), DC 21 km·h^{-1} (MD = -4.79 ± 1.47 m, $p = 0.004$), peak speed (MD = -1.33 ± 0.31 km·h^{-1}, $p < 0.001$) and player load

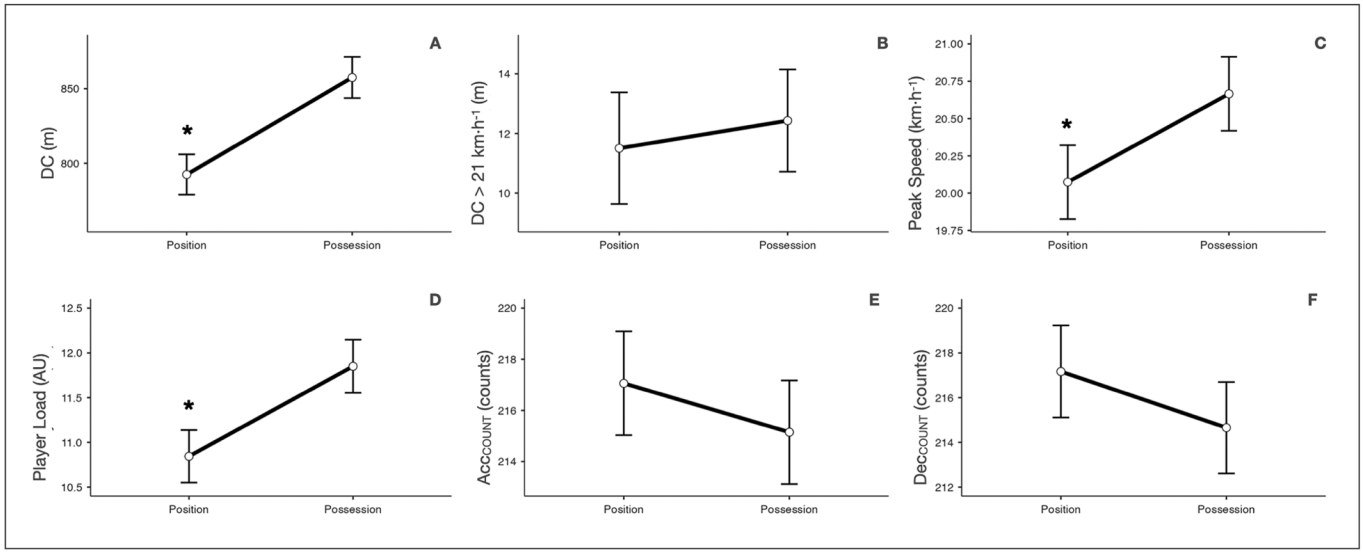


FIG. 2. Comparison of possession and position games in A) DC, B) DC > 21 km·h^{-1}, C) peak speed, D) player load, E) Acc_{COUNT} and F) Dec_{COUNT}. DC = distance covered; DC > 21 km·h^{-1} = distance covered above 21 km·h^{-1}; peak speed = highest speed reached; player load = vector magnitude representing the sum of accelerations recorded in the anterior-posterior, mediolateral and vertical planes of movement; Acc_{COUNT} = number of accelerations; Dec_{COUNT} = number of decelerations; * = p ≤ 0.05 statistically significantly different from possession task.

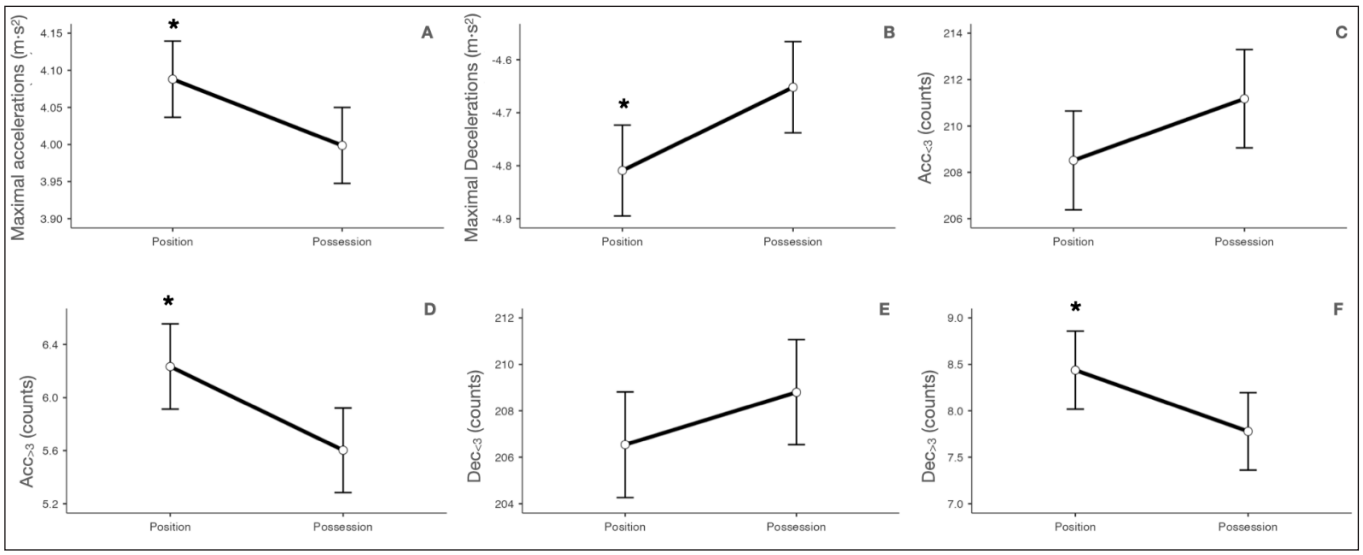


FIG. 3. Comparison of possession and position games in A) maximal accelerations, B) maximal decelerations, C) $Acc_{<3}$, D) $Acc_{>3}$, E) $Dec_{<3}$ and F) $Dec_{>3}$. Maximal accelerations = maximal accelerations reached; maximal decelerations = maximal decelerations reached; $Acc_{<3}$ = accelerations lower than 3 $m \cdot s^{-2}$; $Acc_{>3}$ = accelerations higher than 3 $m \cdot s^{-2}$; $Dec_{<3}$ = decelerations lower than -3 $m \cdot s^{-2}$; $Dec_{>3}$ = decelerations higher than -3 $m \cdot s^{-2}$. * = $p \leq 0.05$ statistically significantly different from possession task.

TABLE 2. Running demands of the different sizes from position games.

Variable	Small	Medium	Large
DC (m)	752.92 ± 13.51* ^	870.68 ± 13.20*	972.31 ± 3.76
DC > 21 $km \cdot h^{-1}$ (m)	7.03 ± 2.32*	13.20 ± 1.07*	17.99 ± 1.01
Peak Speed ($Km \cdot h^{-1}$)	18.43 ± 0.22* ^	21.12 ± 0.22*	22.45 ± 0.22
Player Load (AU)	10.81 ± 0.29* ^	12.04 ± 0.29*	13.34 ± 0.30
Acc_{COUNT} (counts)	224.08 ± 1.75*	220.18 ± 1.75*	200.80 ± 1.81
Dec_{COUNT} (counts)	224.16 ± 1.77*	220.05 ± 1.77*	199.30 ± 1.82
Maximal accelerations ($m \cdot s^2$)	3.93 ± 0.04*	3.97 ± 0.04	4.08 ± 0.04
Maximal decelerations ($m \cdot s^2$)	-4.33 ± 0.08* ^	-4.66 ± 0.07*	-4.99 ± 0.08
$Acc_{<3}$ (counts)	215.44 ± 1.86*	214.79 ± 1.84*	204.15 ± 1.94
$Acc>_3$ (counts)	5.22 ± 0.27	5.40 ± 0.26	5.98 ± 0.27
$Dec_{<3}$ (counts)	213.82 ± 2.04*	212.31 ± 2.03*	200.93 ± 2.10
$Dec_{>3}$ (counts)	6.85 ± 0.37*	7.93 ± 0.36	8.56 ± 0.38

DC = distance covered; DC > 21 $km \cdot h^{-1}$ = distance covered above 21 $km \cdot h^{-1}$; Peak Speed = highest speed reached; Player load = vector magnitude representing the sum of accelerations recorded in the anterior-posterior, mediolateral and vertical planes of movement; Acc_{COUNT} = amount of accelerations; Dec_{COUNT} = amount of decelerations; Maximal accelerations = Maximal accelerations reached; Maximal decelerations = Maximal decelerations reached; $Acc_{<3}$ = Accelerations lower than 3 $m \cdot s^{-2}$; $Acc_{>3}$ = Accelerations higher than 3 $m \cdot s^{-2}$; $Dec_{<3}$ = Decelerations lower than -3 $m \cdot s^{-2}$; $Dec_{>3}$ = Decelerations higher than -3 $m \cdot s^{-2}$. Small: small size of the task's space; Medium: medium size of the task's space; Large: large size of the task's space. *: $p \leq 0.05$ statistically significant different from large size of the task's space; ^: $p \leq 0.05$ statistically significant different from medium size of the task's space.

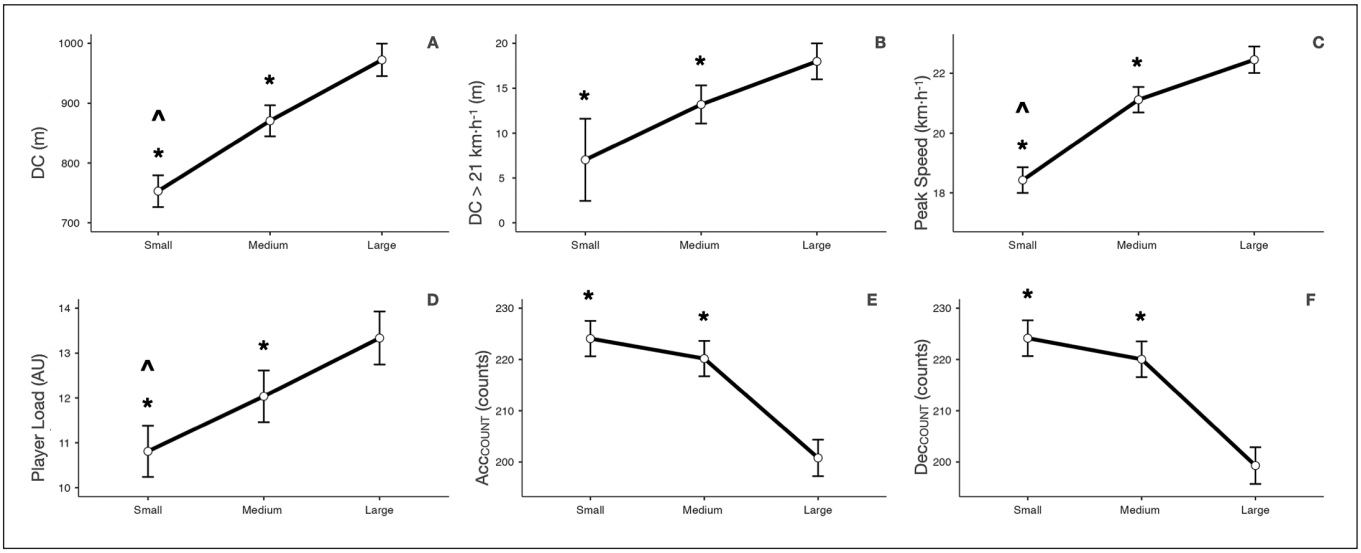


FIG. 4. Comparison between sizes of position games in A) DC, B) DC > 21 km·h^{-1}, C) peak speed, D) player load, E) Acc_{COUNT} and F) Dec_{COUNT}. DC = distance covered; DC > 21 km·h^{-1} = distance covered above 21 km·h^{-1}; peak speed = highest speed reached; player load = vector magnitude representing the sum of accelerations recorded in the anterior-posterior, mediolateral and vertical planes of movement; Acc_{COUNT} = number of accelerations; Dec_{COUNT} = number of decelerations; small: small size of the task's space; medium: medium size of the task's space; large: large size of the task's space. *: $p \leq 0.05$ statistically significantly different from large size of the task's space; ^: $p \leq 0.05$ statistically significantly different from medium size of the task's space.

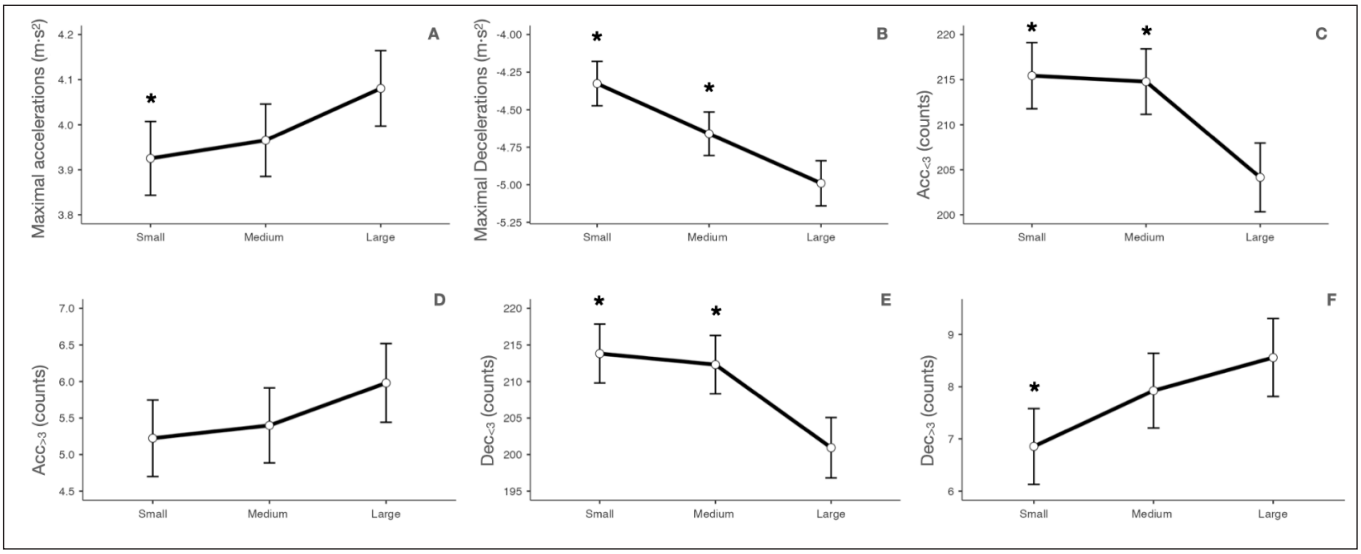


FIG. 5. Comparison between sizes of position games in in A) maximal accelerations, B) Maximal decelerations, C) $Acc_{<3}$, D) $Acc_{>3}$, E) $Dec_{<3}$ and F) $Dec_{>3}$. Maximal accelerations = maximal accelerations reached; maximal decelerations = maximal decelerations reached; $Acc_{<3}$ = accelerations lower than 3 m·s^{-2}; $Acc_{>3}$ = accelerations higher than 3 m·s^{-2}; $Dec_{<3}$ = decelerations lower than -3 m·s^{-2}; $Dec_{>3}$ = decelerations higher than -3 m·s^{-2}. Small: small size of the task's space; medium: medium size of the task's space; large: large size of the task's space. *: $p \leq 0.05$ statistically significantly different from large size of the task's space; ^: $p \leq 0.05$ statistically significantly different from medium size of the task's space.

(MD = -1.30 ± 0.42 AU, $p = 0.006$) variables. However, medium size was associated with significantly higher values than large size in Acc_{COUNT} (MD = 19.39 ± 2.52 counts, $p < 0.001$), Dec_{COUNT} (MD = 20.75 ± 2.53 counts, $p < 0.001$), maximal decelerations (MD = -0.33 ± 0.11 $m \cdot s^{-2}$, $p = 0.006$), $Acc_{<3}$ (MD = 10.64 ± 2.68 counts, $p < 0.001$) and $Dec_{<3}$ (MD = 11.37 ± 2.92 counts/min, $p < 0.001$) variables.

DISCUSSION

The aims of this study were to compare the running performance of possession and position games and to describe the external load of the same position game played in different dimensions. The main findings were that possession and position games had different running demands showing greater acceleration and deceleration requirements in the possession games and higher DC, peak speed and player load during the position games. Larger size of the position games was associated with higher DC, DC > 21 $km \cdot h^{-1}$, player load and more intense accelerations and decelerations while a smaller size resulted in greater demands of accelerations and decelerations of lower intensity.

The drills monitored in this study showed different features of external loads depending on the inclusion of tactical requirements during SSGs. The presence of a tactical role during the position games forced the soccer players to return to their original position continuously after each movement, which could have led to the higher acceleration and deceleration achieved during these tasks. Likewise, the non-structured format of the possession games where players moved freely without tactical information could have provoked their higher DC, peak speed and player load. During these games there are no any rules restricting the players' space exploration, which could explain the obtained results. These findings are in line with previous research suggesting that a specific tactical approach may present different performance of the soccer players during matches and training sessions [29–31]. Previously, it was found that different team formations and associated tactical demands had a significant influence on the external load parameters [29], which would explain the dissimilar response of possession and position games. The inclusion of tactical aspects through position games has been shown to be an effective alternative to modify the external load of the traditional SSGs without changing other constrains. Our results reinforce the idea that tactical instructions regarding team formation is one of the most efficient instruments for coaches to change the players' running behaviour [32]. Furthermore, taking into account that the current knowledge regarding the load experienced by professional soccer players performing SSG-tactical-conditioned training approaches is still scarce [31], these findings could shed some light on this topic, helping coaches in planning training.

In the literature it has been reported that one of the main variables influencing training load during small-sided games is the play area [12, 33]. Different configurations through the pitch size and ApP [34–36] are considered the most important element to manipulate the load of the soccer players in these drills. Although these aspects have been extensively investigated in SSGs [37, 38], to the authors' knowledge the influence of pitch modification in the external load of position games has not yet been studied.

This study found that when the pitch size of the position games was increased, the soccer players experienced greater DC, running demands at higher speed, more intense change of velocity and higher player load; on the other hand, a smaller pitch size was associated with more accelerations and decelerations of lower intensity. These outcomes are in line with the previous literature published on SSGs [12, 13, 33, 39]. Smaller pitches lead to shorter distances between teammates and opponents [40], which could elicit more non-maximal accelerations and decelerations due to the smaller amount of space developed during the small and medium position games. An interesting study [41] conducted with youth players also found that on a small pitch, more transitions were produced, while on a large pitch, longer ball possessions were more frequent. This would stimulate the presence of this mechanical load during the smaller positional games. Similarly, a recent study confirmed that interventions with ApP < 85.17 m^2 are likely not large enough to accumulate running and acceleration/deceleration efforts of high intensity [39]. This aspect could explain the decreased load observed during small and medium position games, where the ApP was around 50 and 80.5 m^2, respectively, compared to 115 m^2 during the large position games. Previous researchers have suggested that on larger pitches, there may be more distance covered in high-speed running and more intense actions [15, 39, 42]. The increased available space in larger position games could potentially allow soccer players to accumulate a higher workload. Taking into account that the ApP influenced the running demands of the position games, soccer coaches should understand that this knowledge could help them to control and plan their training sessions. Besides its contribution to the training process in soccer, the current study has limitations that must be considered. Firstly, a unique format of a positional game with nine players on each team was employed. However, the study did not indicate the number of players designated as starters, substitutes, or bench players within each group. Additionally, two floaters participated in the positional games as goalkeepers, and considering the offside rule, one of them could have received the ball while in an offside position. With these considerations in mind, future studies should explore various formats of positional games, such as reducing the number of players on each team or adopting a competition format of 10 vs. 10. These studies should specify the players' status, exclude floaters, or consider variations in the offside rule.

CONCLUSIONS

In conclusion, practitioners should be mindful that the use of possession and position games, as well as their size, can modify the external load on soccer players during training sessions. Possession and position games exhibit different running requirements, with position games showing greater demands for accelerations and

decelerations, and possession games displaying higher DC, peak speed, and player load. Variations in the size of position games are associated with a specialization of the load, resulting in higher DC, DC > 21 $km \cdot h^{-1}$, player load, and more intense accelerations and decelerations in larger formats, while smaller position games involve greater accelerations and decelerations of lower intensity.

Acknowledgements

No sources of funding were used in the preparation of this article.

Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. Kirkendall DT. Evolution of soccer as a research topic. Prog Cardiovasc Dis. 2020 Nov; 63(6):723–9.
2. Haugen TA, Tønnessen E, Hisdal J, Seiler S. The Role and Development of Sprinting Speed in Soccer. Int J Sports Physiol Perform. 2014 May; 9(3):432–41.
3. Hill-Haas S v., Dawson B, Impellizzeri FM, Coutts AJ. Physiology of Small-Sided Games Training in Football. Sports Medicine. 2011 Mar; 41(3):199–220.
4. Carling C. Interpreting Physical Performance in Professional Soccer Match-Play: Should We be More Pragmatic in Our Approach? Sports Medicine. 2013 Aug 11; 43(8):655–63.
5. Altmann S, Forcher L, Ruf L, Beavan A, Groß T, Lussi P, Woll A, Härtel S. Match-related physical performance in professional soccer: Position or player specific? PLoS One. 2021 Sep 10; 16(9):e0256695.
6. Dalen T, Jørgen I, Gertjan E, Geir Havard H, Ulrik W. Player Load, Acceleration, and Deceleration During Forty-Five Competitive Matches of Elite Soccer. J Strength Cond Res. 2016 Feb; 30(2):351–9.
7. Ju W, Doran D, Hawkins R, Evans M, Laws A, Bradley P. Contextualised high-intensity running profiles of elite football players with reference to general and specialised tactical roles. Biol Sport. 2023; 40(1):291–301.
8. Bradley PS. 'Setting the Benchmark' Part 1: The Contextualised Physical Demands of Positional Roles in the FIFA World Cup Qatar 2022. Biol Sport. 2024;
9. Oliva-Lozano JM, Fortes V, Krustrup P, Muyor JM. Acceleration and sprint profiles of professional male football players in relation to playing position. PLoS One. 2020 Aug 6; 15(8):e0236959.
10. DeWeese BH, Hornsby G, Stone M, Stone MH. The training process: Planning for strength–power training in track and field. Part 1: Theoretical aspects. J Sport Health Sci. 2015 Dec; 4(4):308–17.
11. Halouani J, Chtourou H, Gabbett T, Chaouachi A, Chamari K. Small-Sided Games in Team Sports Training. J Strength Cond Res. 2014 Dec; 28(12):3594–618.
12. Sarmento H, Clemente FM, Harper LD, Costa IT da, Owen A, Figueiredo AJ. Small sided games in soccer – a systematic review. Int J Perform Anal Sport. 2018 Sep 3; 18(5):693–749.
13. Clemente FM, Afonso J, Sarmento H. Small-sided games: An umbrella review of systematic reviews and meta-analyses. PLoS One. 2021 Feb 12; 16(2):e0247067.
14. Castillo D, Rodríguez-Fernández A, Nakamura FY, Sanchez-Sanchez J, Ramirez-Campillo R, Yanci J, Zubillaga A, Raya-González J. Influence of Different Small-Sided Game Formats on Physical and Physiological Demands and Physical Performance in Young Soccer Players. J Strength Cond Res. 2021 Aug; 35(8):2287–93.
15. Casamichana D, Castellano J. Time–motion, heart rate, perceptual and motor behaviour demands in small-sides soccer games: Effects of pitch size. J Sports Sci. 2010 Dec; 28(14):1615–23.
16. Aguiar M, Botelho G, Lago C, Maças V, Sampaio J. A Review on the Effects of Soccer Small-Sided Games. J Hum Kinet. 2012 Jun 1; 33(2012):103–13.
17. Asian-Clemente J, Rabano-Munoz A, Requena B, Suarez-Arrones L. High-speed training in a specific context in soccer: transition games. Int J Sports Med. 2022 Mar 10;
18. Asian-Clemente JA, Rabano-Muñoz A, Núñez FJ, Suarez-Arrones L. External and internal load during small-sided games in soccer: use or not floaters. J Sports Med Phys Fitness. 2022 Mar; 62(3):301–7.
19. Asian-Clemente J, Rabano-Muñoz A, Muñoz B, Franco J, Suarez-Arrones L. Can Small-side Games Provide Adequate High-speed Training in Professional Soccer? Int J Sports Med. 2021 Jun 11; 42(06):523–8.
20. Owen AL, Newton M, Shovlin A, Malone S. The Use of Small-Sided Games as an Aerobic Fitness Assessment Supplement within Elite Level Professional Soccer. J Hum Kinet. 2020 Jan 31; 71(1):243–53.
21. Bastida Castillo A, Gómez Carmona CD, Pino Ortega J, de la Cruz Sánchez E. Validity of an inertial system to measure sprint time and sport task time: a proposal for the integration of photocells in an inertial system. Int J Perform Anal Sport. 2017 Jul 4; 17(4):600–8.
22. Bastida Castillo A, Gómez Carmona CD, de la cruz sánchez E, Pino Ortega J. Accuracy, intra- and inter-unit reliability, and comparison between GPS and UWB-based position-tracking systems used for time–motion analyses in soccer. Eur J Sport Sci. 2018 Apr 21; 18(4):450–7.
23. Akenhead R, Hayes PR, Thompson KG, French D. Diminutions of acceleration and deceleration output during professional football match play. J Sci Med Sport. 2013 Nov; 16(6):556–61.
24. Martin-Garcia A, Castellano J, Diaz AG, Cos F, Casamichana D. Positional demands for various-sided games with goalkeepers according to the most demanding passages of match play in football. Biol Sport. 2019; 36(2):171–80.
25. Oliva-Lozano JM, Conte D, Fortes V, Muyor JM. Exploring the Use of Player Load in Elite Soccer Players. Sports Health: A Multidisciplinary Approach. 2023 Jan 17; 15(1):61–6.
26. Field A. Discovering statistics using IBM SPSS statistics. 5th ed. London, England: SAGE Publications; 2017.
27. jamovi project T. jamovi [Internet]. Sidney, Australia; 2022. Available from: https://www.jamovi.org/
28. Gallucci M. GAMLj: General Analyses for the Linear Model in Jamovi.
29. Asian-Clemente J, Suarez-Arrones L, Requena B, Santalla A. Influence of Tactical Behaviour on Running Performance in the Three Most Successful Soccer Teams During the Competitive Season of the Spanish First Division. J Hum Kinet. 2022 Apr 26; 82(1):135–44.
30. Baptista J, Travassos B, Gonçalves B, Mourão P, Viana JL, Sampaio J. Exploring the Effects of Playing Formations on Tactical Behavior and External Workload During Football Small-Sided Games. J Strength Cond Res. 2020 Jul; 34(7):2024–30.
31. Zanetti V, Aoki MS, Bradley PS, Moreira A. External and Internal Training Loads for Intensive and Extensive Tactical-Conditioning in Soccer Small Sided Games. J Hum Kinet. 2022 Sep 8; 83(1):165–73.
32. Memmert D, Raabe D, Schwab S, Rein R. A tactical comparison of the 4-2-3-1 and 3-5-2 formation in soccer: A theory-oriented, experimental approach based on positional data in an 11 vs. 11 game set-up. PLoS One. 2019 Jan 30; 14(1):e0210191.
33. Bujalance-Moreno P, Latorre-Román PÁ, García-Pinillos F. A systematic review on small-sided games in football players: Acute and chronic adaptations. J Sports Sci. 2019 Apr 18; 37(8):921–49.

34. Riboli A, Coratella G, Rampichini S, Cé E, Esposito F. Area per player in small-sided games to replicate the external load and estimated physiological match demands in elite soccer players. PLoS One. 2020 Sep 23; 15(9):e0229194.
35. Castillo D, Raya-González J, Yanci J, Manuel Clemente F. Influence of Pitch Size on Short-Term High Intensity Actions and Body Impacts in Soccer Sided Games. J Hum Kinet. 2021 Mar 31; 78(1):187–96.
36. Riboli A, Esposito F, Coratella G. Small-Sided Games in Elite Football: Practical Solutions to Replicate the 4-min Match-Derived Maximal Intensities. J Strength Cond Res. 2023 Feb; 37(2):366–74.
37. Praça GM, Chagas MH, Bredt S da GT, Andrade AGP de. Small-Sided Soccer Games with Larger Relative Areas Result in Higher Physical and Physiological Responses: A Systematic and Meta-Analytical Review. J Hum Kinet. 2022 Feb 10; 81(1):163–76.
38. Clemente F, Praça GM, Aquino R, Castillo D, Raya-González J, Rico-González M, Afonso J, Sarmento H, Filipa Silva A, Silva R, Ramirez-Campillo R. Effects of pitch size on soccer players' physiological, physical, technical, and tactical responses during small-sided games: a meta-analytical comparison. Biol Sport. 2023;40(1):111–147.
39. Faga J, Bishop C, Maloney SJ. Does size matter? Effects of small versus large pitch small-sided game training on speed and endurance in collegiate soccer players. Int J Sports Sci Coach. 2022 Oct 11; 174795412211269.
40. Clemente F, Sarmento H. The effects of small-sided soccer games on technical actions and skills: A systematic review. Human Movement. 2020; 21(3):100–19.
41. Olthof SBH, Frencken WGP, Lemmink KAPM. Match-derived relative pitch area changes the physical and team tactical performance of elite soccer players in small-sided soccer games. J Sports Sci. 2018 Jul 18; 36(14):1557–63.
42. Hodgson C, Akenhead R, Thomas K. Time-motion analysis of acceleration demands of 4v4 small-sided soccer games played on different pitch sizes. Hum Mov Sci. 2014 Feb; 33:25–32.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.136088
© Institute of Sport – National Research Institute

Genetic markers and predictive model for individual differences in countermovement jump enhancement after resistance training

AUTHORS: Tao Mei[1], Xiaoxia Li[2], Yanchun Li[1], Xiaolin Yang[1], Liang Li[3], Zihong He[4]

[1] China Institute of Sport and Health Science, Beijing Sport University, Beijing, China
[2] Department of Teaching Affairs, Shandong Sport University, Jinan, China
[3] Sultan Idris Education University, Tanjung Malin, Malaysia
[4] Biological Science Research Center, China Institute of Sport Science, Beijing, China

ABSTRACT: This study aims to utilize Genome-Wide Association Analysis (GWAS) to identify genetic markers associated with enhanced power resulting from resistance training. Additionally, we analyze the potential biological effects of these markers and establish a predictive model for training outcomes. 193 Han Chinese adults (age: 20 ± 1 years) underwent resistance training involving squats and bench presses at 70% 1RM, twice weekly, 5 sets × 10 repetitions, for 12 weeks. Whole-genome genotyping was conducted, and participants' countermovement jump (CMJ) height, lower limb muscle strength, and body muscle mass were assessed. CMJ height change was used to assess changes in power and subjected to Genome-Wide Association Analysis (GWAS) against genotypes. Employing Polygenic Score (PGS) calculations and stepwise linear regression, a predictive model for training effects was constructed. The results revealed a significant increase in CMJ height among participants following the resistance training intervention ($\Delta\% = 16.53\%$, $p < 0.01$), with individual differences ranging from -35.90% to 125.71%. 38 lead SNPs, including PCTP rs9907859 ($p < 1 \times 10^{-8}$), showed significant associations with the percentage change in CMJ height after training ($p < 1 \times 10^{-5}$). The explanatory power of the predictive model for training outcomes, established using PGS and phenotypic indicators, was 62.6%, comprising 13.0% from PGS and 49.6% from phenotypic indicators. SNPs associated with power resistance training were found to participate in the biological processes of musculoskeletal movement and the Striated muscle contraction pathway. These findings indicate that individual differences in the training effect of CMJ exist after resistance training, partially explained by genetic markers and phenotypic indicators (62.6%).

CITATION: Mei T, Li X, Li Y et al. Genetic markers and predictive model for individual differences in countermovement jump enhancement after resistance training. Biol Sport. 2024;41(4):119–130.

Received: 2023-11-02; Reviewed: 2023-12-27; Re-submitted: 2024-02-13; Accepted: 2024-02-14; Published: 2024-04-09.

Corresponding author:
Zihong He
Biological Science Research Center, Sports Science Research China Institute of Sport Science

ORCID:
Tao Mei
0000-0002-3438-7157

Xiaoxia Li
0009-0007-2945-7070

Yanchun Li
0000-0003-0892-2264

Xiaolin Yang
0009-0005-0597-1230

Liang Li
0009-0000-0859-1552

Zihong He
0009-0007-2945-7070

Key words:
Genome-wide association study
Resistance training
Countermovement jump
Personalized exercise
Predictive model

INTRODUCTION

In resistance training effects, researchers often concentrate on the average changes within a group, paying less attention to individual differences. Even with rigorously designed experiments and the use of homogeneous samples, results can still vary significantly due to individual differences. Assessing resistance training effects, studies have discovered significant individual variations in muscle strength improvements during resistance training, ranging from -11% to 30% in muscle size, -8% to 60% in 1RM, and -32% to 149% in isometric muscle strength [1, 2]. When reporting mean values, individual response differences are often masked. Some researchers suggest that sports science should prioritize individual data over average data. Focusing on individual differences is more meaningful for tailoring personalized training and enhancing training efficiency.

Individual differences in training effects are influenced by multiple factors, where genetics might be a key intrinsic factor. For instance, a meta-analysis found diverse responses to aerobic training among carriers of different genotypes [3]. Certain carriers of *PPARGC1A* and *PPARD* genotypes were categorized as non-responders, while others were considered negative or optimal responders to aerobic training [3]. In resistance training, approximately 2.1% of resistance training effects (elbow flexor isometric) can be attributed to the *ACTN3* gene [4]. The *IL15RA* genes rs3136617 and rs2296135 respectively explain 3.5% and 7.1% of the regression model variance in lean body mass training effects [5]. Moreover, an intronic marker of the *GLI3* gene can distinguish muscle fiber hypertrophy caused by resistance training in young males [6]. However, it's crucial to note that these percentages might require further confirmation and replication, as such large variations in a complex trait from individual common variants might need validation through additional research.

Countermovement Jump (CMJ) reflects the power of lower limb muscle groups or neuromuscular status, a pivotal indicator for

lower limb power [7]. Although specific exercises can improve power more effectively [8], conventional resistance training is equally effective in enhancing muscle power [9]. This study focuses on the genetic factors involved in improving CMJ through resistance training. The heritability of power measured by CMJ is approximately 0.55 [10], suggesting that individual differences in vertical jump training effects after resistance training may be genetically influenced. Additionally, phenotypic indicators such as age, gender, and strength levels may also influence the training effects of power. However, there is currently no reported research, especially at the whole-genome level analysis.

Therefore, this study aims to first explore individual differences in CMJ changes after 12 weeks of regular resistance training intervention. Secondly, through Genome-Wide Association Analysis (GWAS), it aims to screen SNPs related to CMJ changes after resistance training. Utilizing multi-gene scoring and predictive model construction, the study intends to analyze the explanatory power of SNPs on training effects. Finally, we will conduct bioinformatics analysis on the lead SNPs selected by GWAS to understand potential mechanisms influencing CMJ changes after resistance training. This endeavor aims to provide operational pathways for developing precise fitness guidance and lay the foundation for further exploration of the biological mechanisms of SNPs.

MATERIALS AND METHODS

Participants

Participants were selected based on the following inclusion criteria: (1) Participants had no prior experience with resistance training and were classified as non-regular exercisers using the Global Physical Activity Questionnaire (GPAQ); (2) Participants showed no risk of resistance training-related injuries as determined by the Physical Activity Readiness Questionnaire (PAR-Q); (3) Participants had no adverse dietary habits and maintained a regular diet during the intervention period, as determined by the Chinese Residents' Nutrition and Health Survey Food Frequency Questionnaire; and (4) were of Han Chinese ethnicity in China. A total of 193 participants (95 males and 98 females, age: 20 ± 1 years, height: 172.5 ± 8.7 cm, body mass: 65.6 ± 13.0 kg) were included in the study. The study was conducted in accordance with the Declaration of Helsinki and approved by the Sports Science Experiment Ethics Committee.

Resistance Training Program

The resistance training protocol employed in this study was based on a traditional resistance training program [11]. After a proper warm-up, the participants initiated resistance training exercises, which consisted of squats and bench presses performed at 70% of their one-repetition maximum (1RM). Each participant completed 5 sets of 10 repetitions, with a 2-minute rest interval between sets. Participants were instructed to perform resistance training using a moderate or slower tempo. The training sessions were held twice a week for a duration of 12 weeks. At the end of every 4-week period, a one-repetition maximum (1RM) test was conducted to adjust the training loads based on the participants' strength improvements. Throughout the intervention, close monitoring of the participants' training loads was maintained, ensuring adherence to the prescribed training volume and standardized movement patterns. In cases where participants were unable to perform the exercises independently, minimal assistance was provided to ensure a consistent training load stimulus and maintain the same training content.

Phenotypic Indicators Test

The tests encompass CMJ, 1RM, body composition, lower limb muscle thickness. The percentage change in CMJ height (Δ%) before and after the intervention is employed to evaluate the enhancement of power following strength training. Additionally, 1RM is utilized to determine training loads, whereas body composition and lower limb muscle thickness are considered as dependent variables when constructing predictive models.

CMJ Testing

The measurement of lower limb power involved conducting the CMJ test. The test procedure was as follows: Participants commenced with warm-up activities to prepare and familiarize themselves with the test movements. Participants positioned themselves with hands on their hips on a force platform (Kistler, Switzerland). They rapidly squatted to a knee flexion angle of 90° and executed a quick jump. To minimize the influence of trunk movement on the test results, participants were instructed to maintain an upright position as much as possible during the airborne phase. Prior to the formal testing, a warm-up consisting of vertical jumps was performed. During the actual test, participants were asked to complete three consecutive CMJ tests, with a 15-second recovery period between each test. Participants remained standing during the recovery interval. The highest jump height recorded among the three tests was utilized for analysis. CMJ data were collected using Bioware software and were quantified using Kistler's Measurement, Analysis, and Reporting Software (MARS).

One Repetition Maximum

Lower limb strength was assessed by determining the one repetition maximum (1RM) weight for the squat exercise. Participants begin with a warm-up activity, which involves performing back squats/bench presses at 40% of their subjective 1RM perception. After warming up, the weight is increased by 15–20 kg on top of the warm-up load, and they complete 3–5 back squats/bench presses. A rest period of 2–4 minutes follows, after which the weight is increased again by 15–20 kg (for back squats) or 5–10 kg (for bench presses), and they complete 2–3 back squats/bench presses. A further rest period of 2–4 minutes is taken, and the previous step is repeated. If the participant successfully completes the lift, continue to increase the load; if they fail, reduce the load by 5–10 kg (for back squats) or 2.5–5 kg (for bench presses) until they can complete 1RM

with proper technique. The determination should be made within 5 attempts for both back squats and bench presses 1RM.

Body Composition

Body composition was assessed using a GE lunar iDXA dual-energy X-ray absorptiometry (DXA) scanner (General Electric, USA). Before the test, participants were ensured to have not undergone a barium meal examination, received radioactive isotope injections, or took contrast agents orally or intravenously for CT and MRI scans within the past 7 days. Participants were needed to fast, remove any clothing that could affect the test results, and lie flat on the scanner table. EnCORE software was used to input participant information and set up the scanning parameters. The scanner performed a sequential scan from head to feet to obtain body composition data.

Lower Limb Muscle Thickness

The GE portable color Doppler ultrasound diagnostic system LOGIQ e (General Electric, USA) was used to measure the rectus femoris and rectus femoris-vastus intermedius thickness. Prior to the measurements, the instrument was calibrated, and subject information was entered. The subjects were positioned in a supine position with their legs relaxed and positioned shoulder-width apart. A 12 MHz linear array probe was used to detect the midpoint between the anterior superior iliac spine and the superior border of the patella, and muscle thickness was obtained. Muscle thickness was measured on both sides, and three measurements were taken on each side to obtain the average value.

Analysis of whole genome genetic polymorphisms

DNA samples that passed the quality control were subjected to whole-genome genotyping using the Infinium chip (Chip Type: CGA-24v1-0, Illumina Inc.). Before genotype imputation, genotypes underwent quality control following previously established methods [12, 13]. Imputation of genotype data was carried out using Eagle/Minimac4 with default parameters (chunk size of 10 Mb and step size of 3 Mb) against the 1000 Genomes project Phase3 v5 reference haplotypes. After imputation, quality control of the chip data was conducted using PLINK 1.9 software, following quality control criteria [14]: SNPs with a minor allele frequency (MAF) less than 5% (MAF < 0.05) were excluded, as well as those not conforming to Hardy-Weinberg equilibrium (HWE) ($p < 1 \times 10^{-5}$), SNPs with more than 10% missing genotypes, and individuals with a genotype missing rate exceeding 10%. After quality control, a total of 4,110,727 SNP loci were retained for subsequent GWAS analysis.

Data Analysis

Data entry, organization, and statistical analysis were performed using Excel 2016 and SPSS 19.0. Descriptive statistics are presented as the mean ± standard deviation (mean ± SD). The normality of the data was assessed using the Kolmogorov-Smirnov test. The improvement in power training was represented by the percentage change in CMJ height before and after the intervention (Δ%). The overall evaluation of training effects was conducted using paired sample t tests, with a significance level of $p < 0.05$. Before GWAS analysis, population stratification was assessed using PCA. The PLINK 1.9 software was used for whole-genome association analysis, considering CMJ height baseline, sex, age, and the first five principal components from PCA as covariates. Genome-wide significance was set at the standard GWAS threshold of $P < 5 \times 10^{-8}$ and suggestive significance was set at $p < 1 \times 10^{-5}$ [15]. Lead SNPs (maximum p value of lead SNPs $< 1 \times 10^{-5}$) were identified using FUMA, and the corresponding mapping genes for these SNPs were analyzed. Polygenic scores (PGS) were calculated based on the lead SNPs, and the average PGS was calculated as per the following formula [16]:

$$\mathrm{PGS} = \sum_i \frac{SNP_i \times beta_i}{n}$$

where SNP represents the variant allele (0, 1, or 2), beta signifies the effect size, and n denotes the number of SNPs. To evaluate the explanatory power of PGS and various phenotype indicators (height, body mass, age, sex, CMJ height, lower limb muscle strength, lower limb muscle mass, and lower limb muscle thickness) on the percentage change in CMJ height, stepwise regression analysis was performed. The percentage change in CMJ height served as the dependent variable (y), while PGS and phenotype indicators were used as independent variables (x) , with gender coded as 0 for females and 1 for males. GO and pathway analysis was performed using Metascape, DAVID, KEGG, REACTOME, and Wikipathways.

RESULTS

A significant enhancement in CMJ height was observed among the participants (ΔCMJ = 16.53%, $p < 0.001$) (Figure 1A). The magnitude of change varied considerably among individuals, ranging from -35.90% to 125.71%, with males showing changes between -20.14% to 125.71% and females between -35.90% to 76.85% (Figure 1B). Among the participants, 15.59% experienced a decrease or no change (ΔCMJ ≤ 0%), 63.98% witnessed an increase between 0% and 25% (0% < ΔCMJ ≤ 25%), 13.44% observed an increase between 25% and 50% (25% < ΔCMJ ≤ 50%), and 6.99% experienced an increase exceeding 50% (ΔCMJ > 50%) (Figure 1C).

In the study, 4 genome-wide significant SNPs (rs9907859, rs12103525, rs62078596, and rs9893488) located in the PCTP gene ($p < 5 \times 10^{-8}$) and 297 SNPs with suggestive significance ($p < 1 \times 10^{-5}$) have been identified(Figure 2A). Thirty-eight SNPs were identified as lead SNPs, and the PCTP rs9907859 marker has been selected as one of the 38 lead variants (Table 1).

The genomic inflation factor (λ) was calculated to be 0.955 (λ≈1), indicating that the p values were not skewed by population stratification and that false positive results were not present (Figure 2B).

A stepwise linear regression analysis revealed that the initial CMJ value, sex, PGS, muscle strength, and body mass were significant predictors of training effects on power, resulting in a model

TABLE 1. Lead SNPs Associated with Training Effects on CMJ After Strength Training

SNP	CHR	Position	REF Allele	Minor Allele	MAF	Beta	gwasP	Overlapped Gene	Nearest Upstream Gene	Nearest Downstream Gene
rs9907859	17	53909039	C	G	0.16	56.97	$3.75 \cdot 10^{-9}$	*PCTP*	None	None
rs72894681	2	183507747	A	C	0.05	45.85	$7.49 \cdot 10^{-8}$	None	*PDE1A*	*DNAJC10*
rs7615128	3	107046665	C	A	0.18	38.56	$4.57 \cdot 10^{-7}$	*RP11-446H18.5*	None	None
rs76346437	12	130906425	G	A	0.08	23.41	$6.51 \cdot 10^{-7}$	*RIMBP2*	None	None
rs79611673	9	124537596	G	A	0.01	33.49	$7.88 \cdot 10^{-7}$	*DAB2IP*	None	None
rs3806388	1	150668799	C	A	0.01	28.61	$8.03 \cdot 10^{-7}$	*GOLPH3L*	None	None
rs78489948	6	106915177	T	A	0.07	35.32	$8.76 \cdot 10^{-7}$	None	*Y_RNA*	*AIM1*
rs141592759	19	2499683	C	A	0.07	40.9	$9.03 \cdot 10^{-7}$	None	*GADD45B*	*RNU6-993P*
rs6747425	2	233932621	C	T	0.21	27.09	$9.47 \cdot 10^{-7}$	*INPP5D*	None	None
rs1660385	1	214288379	G	C	0.24	36.51	$1.08 \cdot 10^{-6}$	None	*PROX1*	*SMYD2*
rs1495067	3	164454487	C	T	0.12	32.37	$1.11 \cdot 10^{-6}$	*RP11-71H9.1*	None	None
rs11985065	8	75630494	A	G	0.03	34.15	$1.15 \cdot 10^{-6}$	*RP11-758M4.1*	None	None
rs75438016	8	16835500	A	T	0.01	37.48	$1.52 \cdot 10^{-6}$	None	*RP11-13N12.1*	*FGF20*
rs4378870	20	23699433	A	G	0.32	28.11	$1.71 \cdot 10^{-6}$	None	*CST2P1*	*CST1*
rs701259	3	153618834	G	G	0.09	37.24	$1.76 \cdot 10^{-6}$	*RP11-23D24.2*	None	None
rs79567715	17	79410256	G	A	0.12	22.75	$2.08 \cdot 10^{-6}$	*RP11-1055B8.7*	None	None
rs976221	14	24244706	A	A	0.25	36.25	$2.13 \cdot 10^{-6}$	None	*RP11-388E23.4*	*RN7SKP205*
rs1466789	12	42126705	A	A	0.23	36.62	$2.14 \cdot 10^{-6}$	None	*MTND1P24*	*RP11-630C16.1*
rs77973780	12	31140920	C	T	0.02	30.33	$2.24 \cdot 10^{-6}$	*TSPAN11*	None	None
rs2167978	2	44353077	A	T	0.12	31.17	$2.83 \cdot 10^{-6}$	None	*AC019129.1*	*RNU6-566P*
rs113021171	11	27048503	G	T	0.15	27.66	$3.07 \cdot 10^{-6}$	None	*FIBIN*	*BBOX1*
rs118191183	3	68243115	G	T	0.02	28.24	$3.10 \cdot 10^{-6}$	*FAM19A1*	None	None
rs75380147	7	9985223	T	C	0.05	33.53	$3.40 \cdot 10^{-6}$	None	*GS1-6906.1*	*AC006373.1*
rs34337282	16	85599995	G	A	0.14	38.87	$3.66 \cdot 10^{-6}$	None	*AC092377.1*	*RP11-118F19.1*
rs61050775	4	138564605	A	G	0.15	31.66	$3.79 \cdot 10^{-6}$	None	*RP11-714L20.1*	*RP13-884E18.2*
rs12343431	9	4759946	C	A	0.16	34.24	$3.81 \cdot 10^{-6}$	None	*AK3*	*RP11-307I14.4*
rs35658380	1	34845898	C	T	0.24	21.62	$3.87 \cdot 10^{-6}$	None	*RP4-657M3.2*	*MIR552*
rs7834774	8	59631013	G	A	0.14	26.72	$3.90 \cdot 10^{-6}$	None	*snoU13*	*TOX*
rs79531236	3	29413111	A	G	0.03	33.92	$4.80 \cdot 10^{-6}$	*RBMS3*	None	None
rs2303690	19	48525507	G	G	0.31	30.22	$5.07 \cdot 10^{-6}$	*ELSPBP1*	None	None
rs72613753	2	218460125	A	G	0.06	18.49	$6.84 \cdot 10^{-6}$	*DIRC3*	None	None
rs373545195	1	31720006	T	C	0.01	39.44	$7.00 \cdot 10^{-6}$	None	*NKAIN1*	*SNRNP40*
rs80010151	1	244954099	C	T	0.05	32.9	$7.91 \cdot 10^{-6}$	None	*DESI2*	*COX20*
rs80068293	13	40144130	A	G	0.03	29.6	$8.07 \cdot 10^{-6}$	*LHFP*	None	None
rs59224847	5	63480499	G	C	0.18	30.38	$8.47 \cdot 10^{-6}$	*RNF180*	None	None
rs2284654	14	31346510	C	A	0.08	29.21	$8.48 \cdot 10^{-6}$	*COCH*	None	None
rs4265793	16	19028549	T	T	0.11	32.7	$9.41 \cdot 10^{-6}$	*TMC7*	None	None
rs61448344	19	55587668	C	T	0.16	22.93	$9.55 \cdot 10^{-6}$	*EPS8L1*	None	None

TABLE 2. Prediction Model for Training Effects on CMJ Using "PGS-Phenotypic Indicators"

Coefficient	Unstandardized Coefficients		Standardized Coefficients	Sig.	R^2	Adjusted R^2
	B	Std. Erro	BETA			
Constant	95.55	7.913		< 0.001		
Initial CMJ height	-3.029	0.189	-1.133	< 0.001	0.138	0.133
Sex	38.915	3.617	0.847	< 0.001	0.299	0.298
PGS	3.758	0.517	0.35	< 0.001	0.13	0.129
Initial 1RM squat value	-0.53	0.111	-0.281	< 0.001	0.031	0.029
Body mass	0.205	0.056	0.276	< 0.001	0.028	0.027

explanatory power of 62.6% (R^2 = 0.626) In this regard, females are coded as 0 and males as 1. A positive B or beta value indicates that the predictor is positively associated with CMJ increase, while a negative value indicates a negative association. (Table 2).

The results of the GO analysis revealed that the mapping genes of SNPs associated with the training effect of power after resistance training were primarily enriched in 29 biological process terms, 10 cellular components, and 16 molecular functions. Among these, the "musculoskeletal movement" biological process term may be related to power (Figure 3).

Enrichment analysis using the KEGG Pathway, Reactome Pathway, and WikiPathways databases yielded 4, 33, and 7 pathways, respectively (Figure 4). Of particular interest, the "Striated muscle contraction" pathway within the WikiPathways signaling pathway analysis may have relevance to the training effect of power after resistance training.

DISCUSSION

This study presents an assessment of individual differences in the training effects on power subsequent to resistance training. Notably, this is the first study to identify training-sensitive genetic markers at the whole-genome level, identifying a total of 38 lead SNPs. The predictive model developed for the training effects on power, which combines polygenic score (PGS) and phenotypic indicators, achieved a notable explanatory power of 62.6%. Specifically, PGS accounted for 13.0% of the explanatory power, while the phenotypic indicators contributed significantly to 49.6%. Furthermore, through bioinformatics analysis, the lead SNPs were found to potentially participate in key biological processes associated with musculoskeletal movement, as well as the striated muscle contraction pathway.

In this study, we observed an overall improvement in lower limb power after regular resistance training; however, individual differences in the training effects were apparent. Previous studies have demonstrated the positive impact of resistance training on increasing the

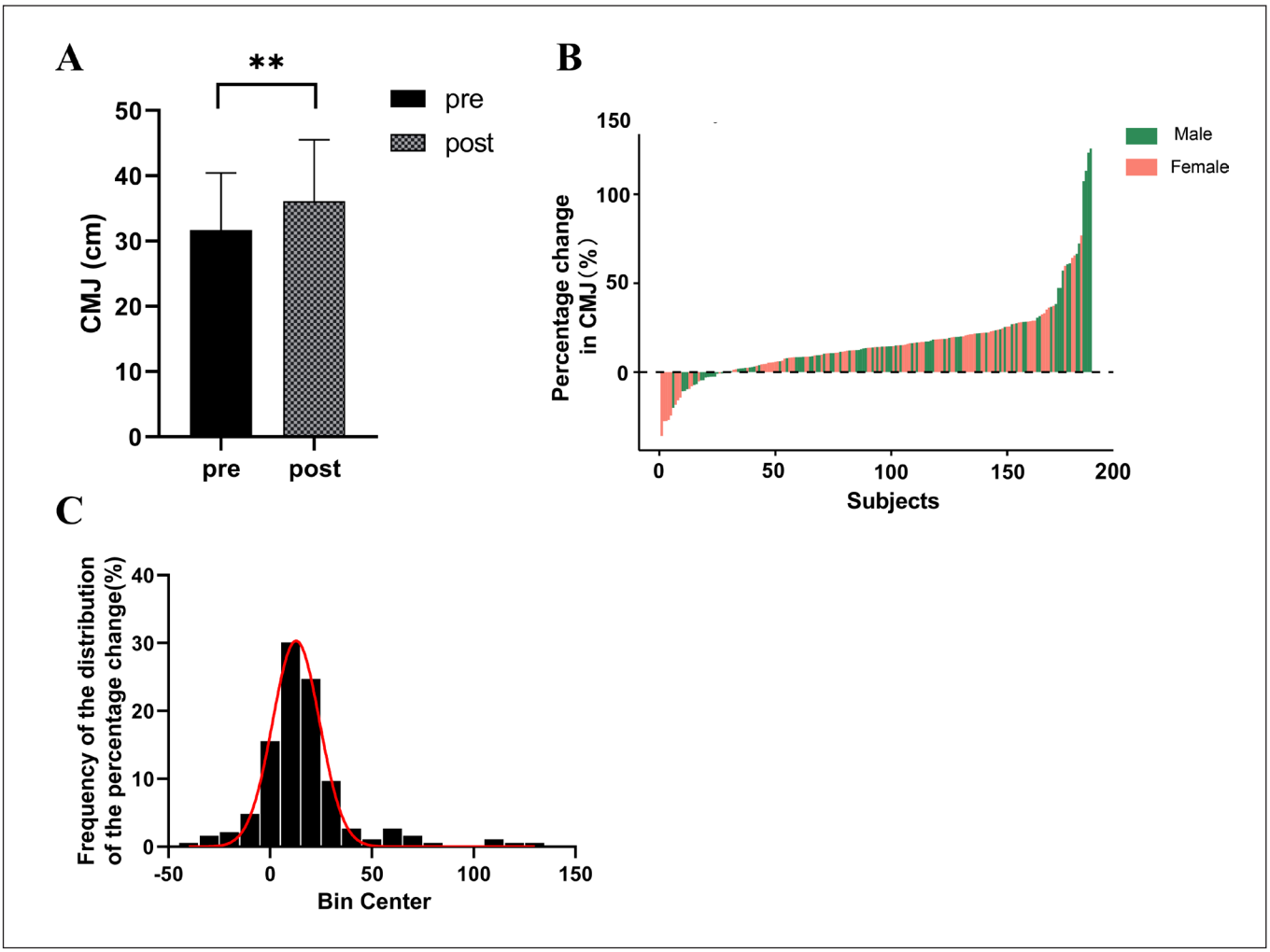


FIG. 1. Individual Differences in Training Effects on Power Following Strength Training. A. CMJ height significantly increased after strength training intervention; B. Individual differences exist in the percentage change of CMJ height after strength training intervention; C: Distribution of CMJ height changes.

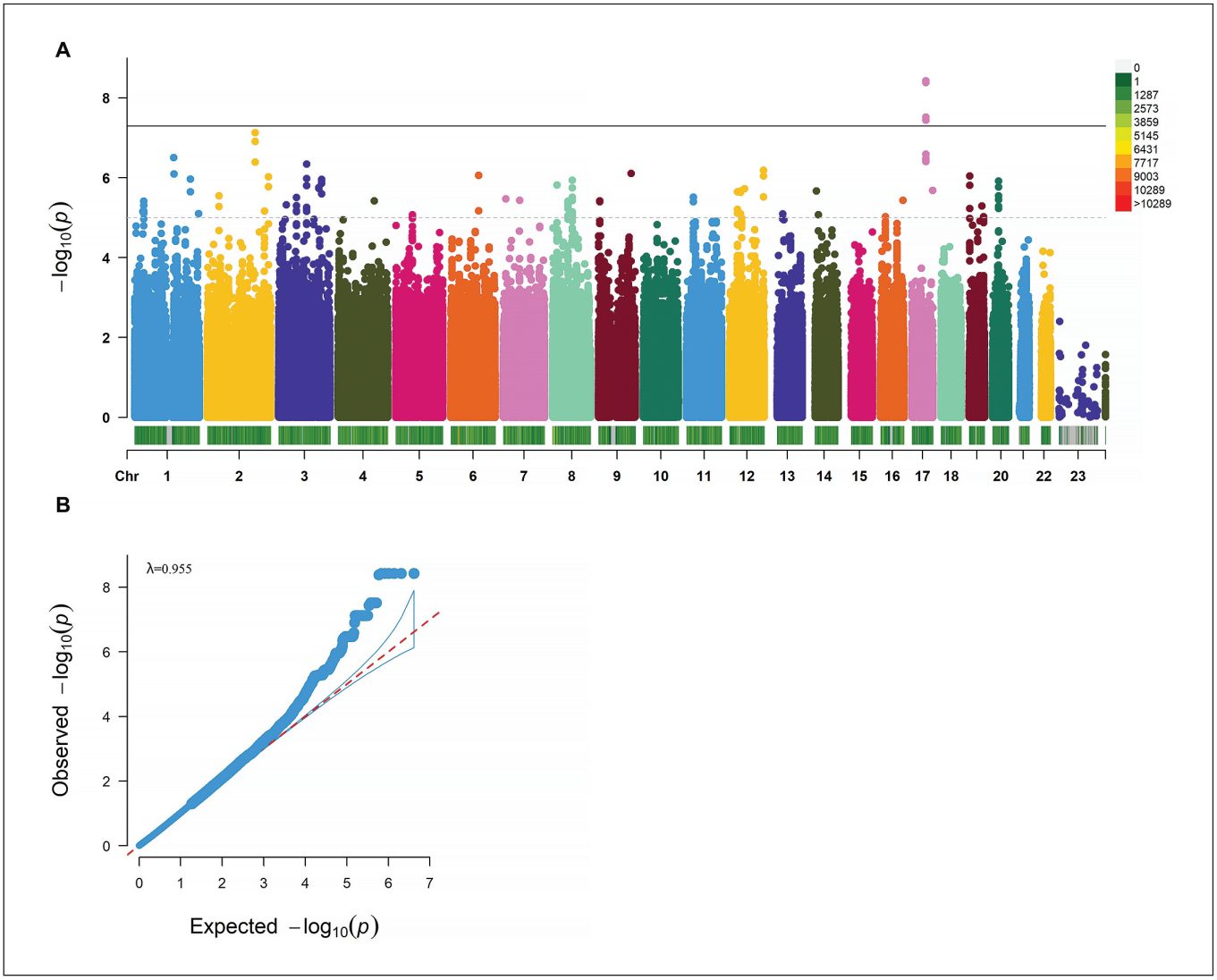


FIG. 2. GWAS Analysis of CMJ Height Changes after Resistance Training. A. Manhattan Plot of CMJ Height Change Percentage GWAS Analysis. The x-axis represents chromosomes, with different colors indicating different chromosomes. The color gradient of the bar below the chromosome bar represents the quantity of SNPs on the chromosome, ranging from gray to red to signify an increasing number of SNPs. The y-axis represents -$\log_{10}$(P) values. The dashed line represents a significance threshold of $p<1\cdot10^{-5}$, and the solid line represents a significance threshold of $p<5\cdot10^{-8}$. B. Quantile–Quantile (QQ) Plot and Genomic Inflation Factor λ.

CMJ height among athletes [17]. Untrained participants also exhibited a significant increase in CMJ height after an 8-week resistance training program (from 23.90 cm to 26.90 cm) [18]. Furthermore, even in older adults, a 12-week moderate-intensity resistance training program led to a notable 31% enhancement in CMJ vertical jump height [19]. These studies primarily focused on the intervention effects of resistance training on the population as a whole and did not delve into individual differences in response to resistance training. In reality, variations in improving 1RM muscle strength, muscle volume, muscle cross-sectional area, and other training outcomes are commonly observed among individuals undergoing resistance training [1, 20, 21]. Nonetheless, few studies have explored individual differences in CMJ height improvement through resistance training. In our study, the average increase in CMJ height among participants was 16.53%, with individual responses ranging from -35.90% to 125.71%. These findings indicate that not all participants exhibit favorable adaptations to resistance training.

Genetics and participant backgrounds are likely to be the main factors influencing individual differences in response to resistance training. Association studies have identified numerous genetic variations associated with training response and exercise-related traits. Carriers of PPARGC1A rs8192678 Gly/Gly, PPARD rs1053049 TT, PPARD rs2267668 AA, and PPARG rs1801282 Ala alleles exhibit the best response to aerobic training [3]. MCT1 rs1049434 has also been reported to be associated with athletic performance and physiological phenotypes [22]. Undoubtedly, there may be additional genetic variations associated with the response to different resistance training modalities, warranting further exploration at the genome-wide level. In this study, we identified 38 lead SNPs that exhibited significant associations with the percentage change in CMJ height

following resistance training. It is important to note that not all SNPs associated with phenotype traits have equal effects. Lead SNPs, which exert a dominant role and demonstrate the strongest correlation with the phenotype, play a crucial role in this context [23]. Although limited, several studies have already examined the association between genetic markers and baseline CMJ height. For instance, genes such as *ACE* and *ACTN3* are considered to be related to muscle phenotype. However, in Polish athletes, no association was found between *ACE* and *ACTN3* genotypes and CMJ height [24]. In Italian football players, *ACE* and *ACTN3* genotypes were found to have no significant association with CMJ height but showed associations with SJ (squat jump). Moreover, when combined with the level of competition, these genotypes explained 23.92% of the individual differences [25]. The D allele of the *ACE* gene has been observed to confer an advantage for high CMJ height in male and female sprint athletes, as well as in female endurance athletes [26]. However, research specifically focusing on genetic markers related to CMJ height responsiveness to resistance training is currently lacking.

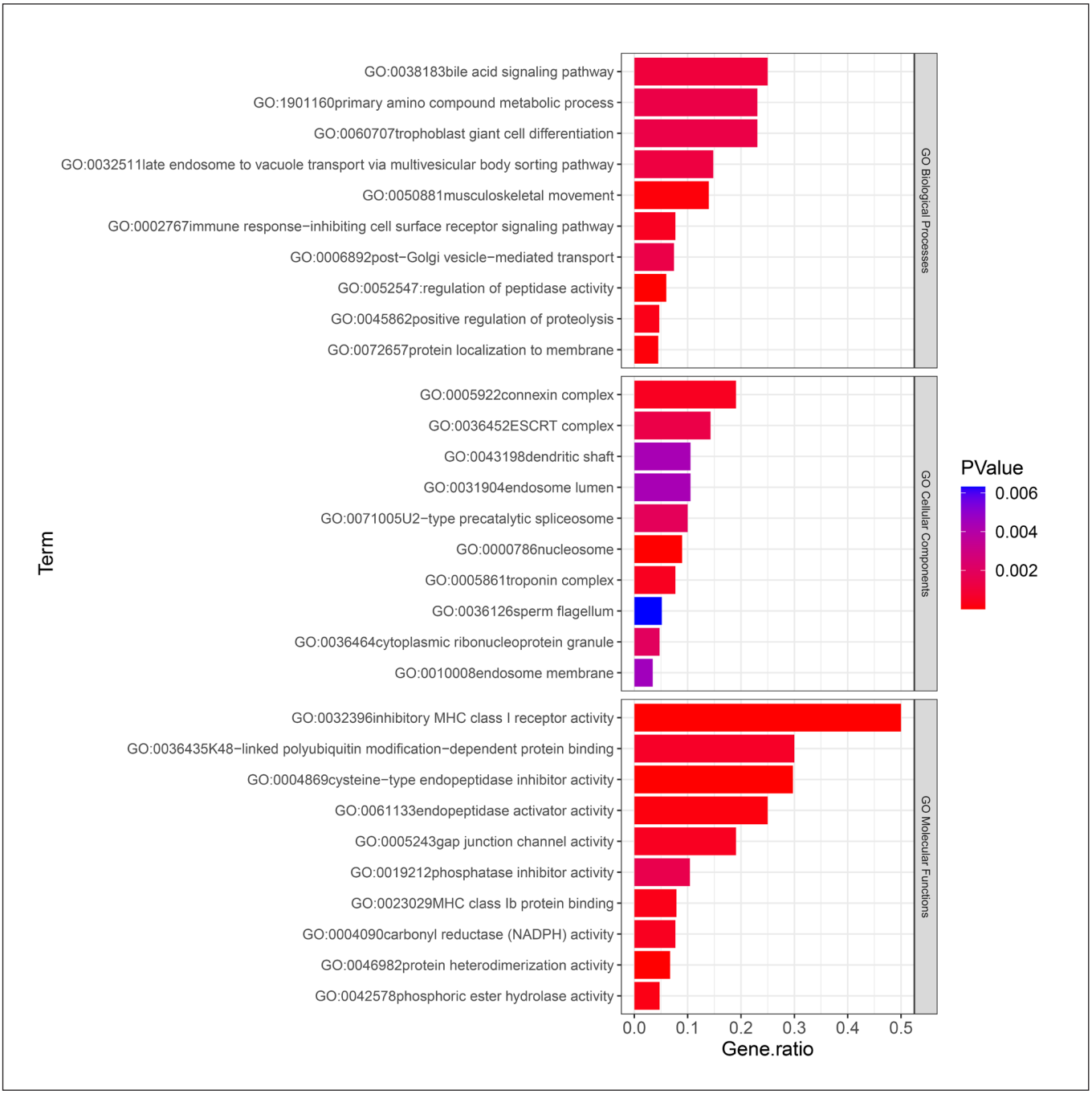


FIG. 3. GO enriched terms. Listed in order of p-values, showing the top 10 terms for Biological Processes (BP), Cellular Components (CC), and Molecular Functions (MF). The p-values are color-coded, ranging from blue to red, indicating decreasing values.

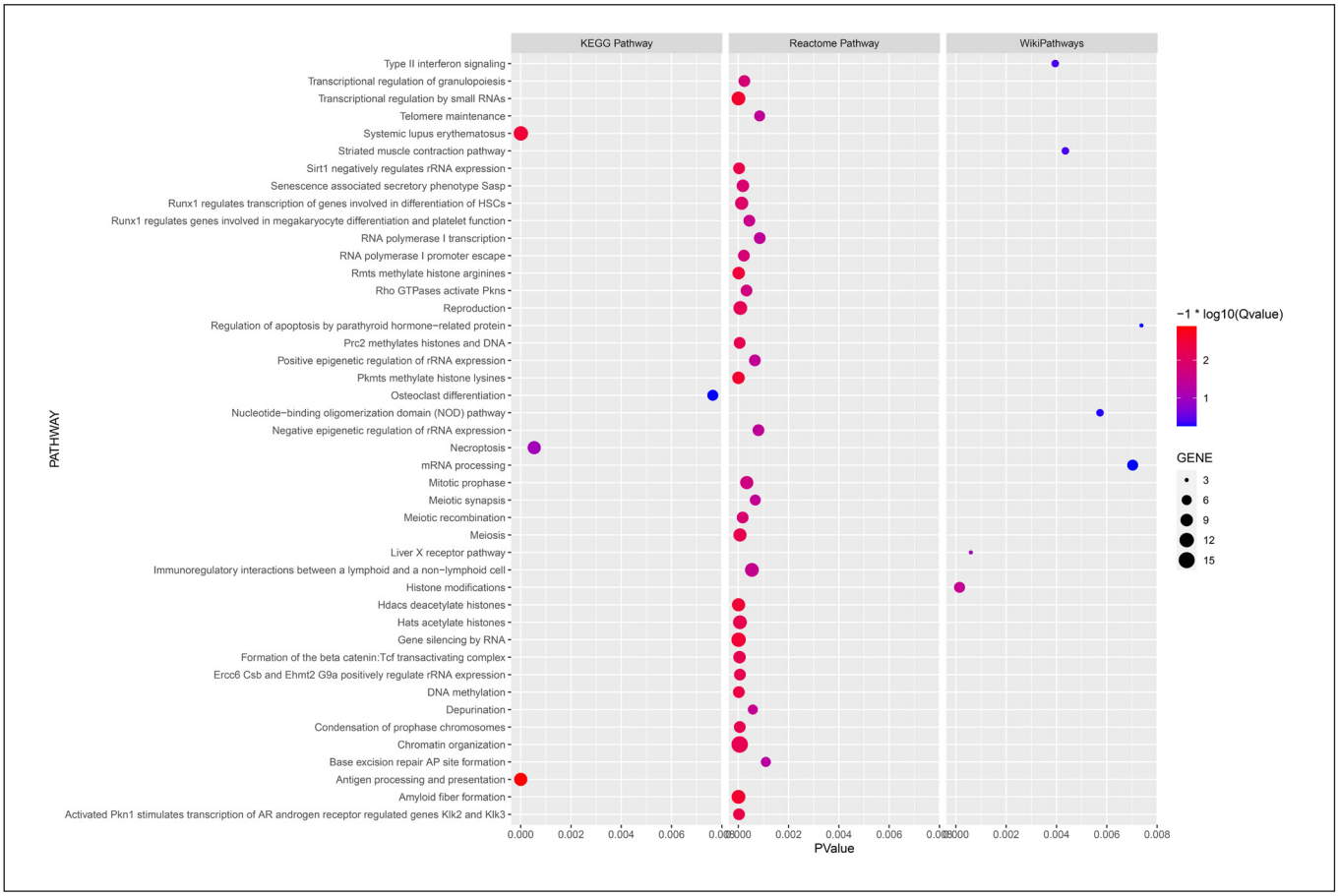


FIG. 4. KEGG enriched terms. The size of the bubbles represents the number of genes enriched in that pathway, while the color indicates the magnitude of -log10(Q-values) after p-value correction, transitioning from blue to red as the p-values decrease.

The lead SNPs identified in this study are primarily located in intronic regions, UTR regions, and intergenic regions. For example, the most significant lead SNP, rs9907859, is situated in an intronic region of the Phosphatidylcholine Transfer Protein (*PCTP*) gene. *PCTP* plays a significant role in brown adipose tissue (BAT). *PCTP* (-/-) mice lacking phosphatidylcholine transfer protein (Pctp) tend to utilize fatty acids for oxidative phosphorylation, suggesting a potential regulatory role of Pctp in the pathway of fatty acyl-CoA entry into mitochondria [27]. Hepatic deletion of *PCTP* has been shown to reduce adipose tissue mass and lower levels of triglycerides and phospholipids in skeletal muscle [28]. While this study suggests a potential impact of *PCTP* on skeletal muscle energy metabolism, research concerning rs9907859 remains limited, necessitating further investigation in the future. These findings imply that *PCTP* may have an impact on skeletal muscle energy metabolism. However, research regarding rs9907859 remains scarce, necessitating further investigation in the future. Another SNP, rs79531236, is located in an intronic region of the *RBMS3* gene, which is believed to play a role in muscle cell proliferation and gastrointestinal motility. It has also been associated with gastrointestinal abnormalities in patients with *FOXP1* syndrome [29]. Some SNPs are located on lincRNAs, referring to long noncoding RNAs with a length greater than 200 nucleotides. LncRNAs fulfill various roles, including epigenetic regulation, modulation of chromatin structure, transcriptional control, regulation of mRNA stability, translation, and posttranslational modifications [30]. The SNP rs7615128 is located on the lncRNA *RP11-446H18.5*, and it may have some impact on the functionality of the lncRNA. Additionally, there are other SNPs, such as rs72894681, rs78489948, and rs141592759, identified in this study, which are situated between genes. SNPs located between genes are potentially in proximity to transcription factor-binding sites, enhancers, promoters, or other regulatory elements that can influence the expression and regulation of both genes. However, the specific role of these SNPs in regulating gene expression and their association with muscle strength phenotypes remains unknown within the context of this study.

A regression model was constructed using PGS and phenotype indicators (initial CMJ value, sex, age, and total body muscle mass) to account for 62.6% (R^2 = 0.626) of the variance in CMJ height following resistance training. Previous studies have employed Spearman's correlations to assess the relationship between genotype score

and the percentage change in CMJ height, with the genotype score explaining 14–32% of the variance in CMJ height [31], which aligns with the findings of this study. These findings suggest that genetic markers can partially elucidate the effectiveness of power training after resistance training. Genetic factors, as represented by the PGS utilized in this study, accounted for 13.0% of the variation observed, while the phenotype indicators contributed to 49.6% of the variation in explaining the effectiveness of power training post-strength training. This comparison suggests that the genetic factors captured by the PGS constituted a proportion of the overall genetic influence on the training effect. However, it is important to note that the PGS constructed in our study is based on a subset of common SNPs and does not encompass the entirety of genetic variability. We acknowledge that there are likely other genetic elements such as rarer variants, structural variations, and unmeasured genetic factors that could contribute to the overall genetic component influencing training outcomes. Thus, while our findings highlight a partial influence of the included genetic factors, we recognize the limitations in capturing the complete spectrum of genetic determinants affecting training effects. Some SNPs in genes like *ACE*, *ACTN3*, *PPARs*, and *MCT1*, which were found in previous studies to be related to training outcomes [3, 22, 24], were not included in the PGS constructed in this study. This omission might be attributed to the focus of this study on the CMJ height indicator, which differs from previous research. It also suggests that different genetic determinants may underlie the training effects of different indicators. The negative correlation between the initial CMJ value and the training effect on CMJ height suggests that individuals with lower initial power are more likely to experience improvements through regular resistance training.

Sex is another factor influencing the effectiveness of power training. In our study, we observed variations in the extent of changes between males (-20.14% to 125.71%) and females (-35.90% to 76.85%). There are discrepancies in neuromuscular recovery after resistance training between sexes, with females displaying a more pronounced decrease in CMJ height than males [32]. This indicates that sex differences exist in the response of CMJ height to the stimulus of resistance training. Another study also identified sex and age disparities in muscle fiber types (I, IIa, and IIx) and muscle cross-sectional area following long-term resistance training [33]. Since muscle fiber type is a determinant of power, sex differences in adaptation to resistance training may contribute to the influence of sex and age on power prediction. We discovered that lower limb muscle strength (1RM) holds predictive value for power. Muscle strength serves as the foundation for generating power, and participants with superior lower limb strength can achieve greater enhancements in power after resistance training. Although body mass may not directly impact CMJ height, it exhibits a positive correlation with CMJ peak power [34]. Muscles serve as the direct source of power, and augmenting relative maximum strength can enhance performance in lower limb power movements [35]. However, in the predictive model, muscle mass was not included in the regression analysis of individual differences in power. This may suggest that the effectiveness of power training relies less on muscle mass.

The bioinformatics analysis conducted in this study revealed that the SNPs linked to the training effects of power are involved in various biological processes, molecular functions, and cellular components, extending beyond skeletal muscle or muscle strength. For instance, these SNPs may be implicated in the biological process of positive regulation of proteolysis. Positive regulation of proteolysis plays a crucial role in multiple biological processes, including cellular homeostasis, protein metabolism, and signaling pathway regulation. Moreover, the "antigen processing and presentation" pathway in the KEGG database is a vital process in the immune system, facilitating the recognition and response to various foreign antigens [36]. Additionally, the "PKMT methylate histone lysines" pathway in the Reactome Pathway has the potential to influence chromatin structure and transcriptional activity of genes, thereby regulating cellular function and phenotype. It plays a critical role in biological processes such as development, cell differentiation, and disease occurrence [37].

Research directly connecting SNPs to the power phenotype is still limited. Through bioinformatics analysis, this study identified SNPs (rs976221, rs61448344, rs6747425, rs141592759) associated with the effectiveness of power training, suggesting their potential involvement in the biological process of musculoskeletal movement. The analysis revealed four SNPs (rs976221, rs61448344, rs6747425, rs141592759) and six mapping genes (*MYH7*, *TNNI3*, *TNNT1, GIGYF2, JSRP1, PVALEF*) that are closely associated with the identified SNPs. These genes have been shown to contribute to various growth, development, or physiological processes of skeletal muscle. For instance, the *MYH7* gene, one of the genes in the human genome encoding the beta-myosin heavy chain, encodes slow/cardiac MyHC (*MyHC I*), which is expressed in slow, oxidative, type 1 fibers of skeletal muscle. It plays a role in multiple biological processes related to muscle contraction, such as regulating slow-twitch skeletal muscle fiber contraction and the force of skeletal muscle contraction [38]. Variations in the *MYH7* gene have also been confirmed to be associated with skeletal muscle diseases [39].

In this study, no muscle-specific signaling pathways were identified in the KEGG Pathway and Reactome Pathway databases. However, the Wikipathway database revealed the potential influence of SNPs on the striated muscle contraction pathway, which could be related to the effectiveness of power training. This pathway involves four mapped genes: *ACTG1*, *MYH6*, *TNNI3*, and *TNNT1*, which are closely associated with skeletal and cardiac muscles, playing crucial roles in the structure and function of skeletal muscle. For instance, the *ACTG1* gene encodes the γ-actin protein, which is a component of actin in skeletal muscle cells. Actin binds with myosin and participates in muscle contraction and movement. Studies have shown that in a mouse model with *ACTG1* deletion (Actg1-msKO), muscle development remains normal, but Actg1-msKO mice display significant muscle weakness accompanied by a progressive pattern of muscle fiber degeneration/regeneration [40].

GWASs have identified a genetic variation (rs6565586) in the *ACTG1* gene that is associated with the status of power-oriented athletes [41]. Additionally, *ACTG1* rs6565586 has been confirmed to be related to the grip strength [42]. *MYH6* and *TNNT1* are crucial for maintaining normal skeletal muscle function, and variations in these genes may lead to skeletal muscle diseases [43, 44]. In summary, these genes play essential roles in regulating skeletal muscle structure and function. Mutations or functional abnormalities in these genes may contribute to the occurrence of skeletal muscle diseases such as myopathies and muscular atrophy. They may also be involved in determining the power phenotype, although further research is necessary to confirm this.

Limitations

When reviewing our study outcomes, we acknowledge several limitations in our research. Firstly, we utilized a relatively lenient significance threshold (p-value of 1×10^{-5}) to identify associations between genes and training effects. This choice was based on the relatively modest sample size of our study cohort, the nature of the genetic markers analyzed, and the necessity to strike a balance between reducing false positives and identifying potential related genetic variations [15, 45]. This selection may have excluded potential correlations detectable under stricter thresholds, thus warranting recognition that certain crucial genetic variations might have been overlooked. Additionally, our study did not comprehensively assess the random variation in training effects among participants. For instance, we did not quantify the variability in the primary phenotype within the control group, nor did we assess the reliability (repeatability) of training effects (primary phenotype) within the training group. Evaluating these aspects would have contributed to a more comprehensive understanding of the variability and credibility of training effects. Finally, despite our efforts to screen genes related to training effects from 4 million SNPs, it is possible that other SNPs, rare variants, or structural variations were not included. This suggests that our study outcomes might not encompass all potential genetic factors contributing to training effects. We acknowledge the importance of replication studies in validating our GWAS findings, particularly those concerning the 37 suggestively significant lead SNPs, before their practical application in predicting CMJ increase. Overall, while our study provides valuable insights, these limitations remind us to interpret our results cautiously. Furthermore, they suggest directions for future research to comprehensively understand the influence of genes on training effects.

CONCLUSIONS

After 12 weeks of resistance training, individual variations were observed in the percentage change of CMJ. The predictive model developed using PGS and phenotypic indicators explained 62.6% of the variance in the percentage change of CMJ. Specifically, the PGS accounted for 13.0% of the variance, whereas phenotypic indicators contributed 49.6%. It is suggested that SNPs associated with CMJ variation may impact the training effects on CMJ changes through the striated muscle contraction pathway.

Acknowledgments

This research was funded by the Fundamental Research Funds for the Central Universities, grant number 2016SYS002 and the National Key R&D Program of China, grant number 2018YFC2000602.

Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. Ahtiainen JP, Walker S, Peltonen H, Holviala J, Sillanpaa E, Karavirta L, Sallinen J, Mikkola J, Valkeinen H, Mero A, Hulmi JJ, Hakkinen K. Heterogeneity in resistance training-induced muscle strength and mass responses in men and women of different ages [J]. Age (Dordr). 2016; 38(1):10.
2. Hubal MJ, Gordish-Dressman H, Thompson PD, Price TB, Hoffman EP, Angelopoulos TJ, Gordon PM, Moyna NM, Pescatello LS, Visich PS, Zoeller RF, Seip RL, Clarkson PM. Variability in muscle size and strength gain after unilateral resistance training [J]. Med Sci Sports Exerc. 2005; 37(6):964–972.
3. Petr M, Stastny P, Zajac A, Tufano JJ, Maciejewska-Skrendo A. The Role of Peroxisome Proliferator-Activated Receptors and Their Transcriptional Coactivators Gene Variations in Human Trainability: A Systematic Review [J]. Int J Mol Sci. 2018; 19(5):1472
4. Clarkson PM, Devaney JM, Gordish-Dressman H, Thompson PD, Hubal MJ, Urso M, Price TB, Angelopoulos TJ, Gordon PM, Moyna NM, Pescatello LS, Visich PS, Zoeller RF, Seip RL, Hoffman EP. ACTN3 genotype is associated with increases in muscle strength in response to resistance training in women [J]. J Appl Physiol (1985). 2005; 99(1):154–163.
5. Riechman SE, Balasekaran G, Roth SM, Ferrell RE. Association of interleukin-15 protein and interleukin-15 receptor genetic variation with resistance exercise training responses [J]. J Appl Physiol (1985). 2004; 97(6):2214–2219.
6. Vann CG, Morton RW, Mobley CB, Vechetti IJ, Ferguson BK, Haun CT, Osburn SC, Sexton CL, Fox CD, Romero MA, Roberson PA, Oikawa SY, Mcglory C, Young KC, Mccarthy JJ, Phillips SM, Roberts MD. An intron variant of the GLI family zinc finger 3 (GLI3) gene differentiates resistance training-induced muscle fiber hypertrophy in younger men [J]. FASEB J. 2021; 35(5):e21587.
7. Claudino J G, Cronin J, Mezencio B, Mcmaster D T, Mcguigan M, Tricoli V, Amadio A C, Serrao J C. The countermovement jump to monitor neuromuscular status: A meta-analysis [J]. J Sci Med Sport. 2017; 20(4):397–402.
8. Behm DG, Young JD, Whitten J HD, Reid JC, Quigley PJ, Low J, Li Y, Lima CD, Hodgson DD, Chaouachi A, Prieske O, Granacher U. Effectiveness of Traditional Strength vs. Power Training on Muscle Strength, Power and Speed with Youth: A Systematic Review and Meta-Analysis [J]. Front Physiol. 2017; 8:423.
9. Mckinlay BJ, Wallace P, Dotan R, Long D, Tokuno C, Gabriel DA, Falk B. Effects of Plyometric and Resistance Training on Muscle Strength, Explosiveness, and Neuromuscular Function in Young Adolescent Soccer Players [J]. J Strength Cond Res. 2018; 32(11):3039–3050.
10. Zempo H, Miyamoto-Mikami E, Kikuchi N, Fuku N, Miyachi M, Murakami H. Heritability estimates of

muscle strength-related phenotypes: A systematic review and meta-analysis [J]. Scand J Med Sci Sports. 2017; 27(12):1537–1546.
11. Weakley J, Schoenfeld BJ, Ljungberg J, Halson SL, Phillips SM. Physiological Responses and Adaptations to Lower Load Resistance Training: Implications for Health and Performance [J]. Sports Med Open. 2023; 9(1):28.
12. Anderson CA, Pettersson FH, Clarke GM, Cardon LR, Morris AP, Zondervan KT. Data quality control in genetic case-control association studies [J]. Nat Protoc. 2010; 5(9):1564–1573.
13. Van Leeuwen EM, Kanterakis A, Deelen P, Kattenberg MV, Genome of the Netherlands C, Slagboom PE, De Bakker PI, Wijmenga C, Swertz MA, Boomsma DI, Van Duijn CM, Karssen LC, Hottenga JJ. Population-specific genotype imputations using minimac or IMPUTE2 [J]. Nat Protoc. 2015; 10(9):1285–1296.
14. Marees AT, De Kluiver H, Stringer S, Vorspan F, Curis E, Marie-Claire C, Derks EM. A tutorial on conducting genome-wide association studies: Quality control and statistical analysis [J]. Int J Methods Psychiatr Res. 2018; 27(2):e1608.
15. Williams C J, Li Z, Harvey N, Lea R A, Gurd B J, Bonafiglia J T, Papadimitriou I, Jacques M, Croci I, Stensvold D, Wisloff U, Taylor J L, Gajanand T, Cox E R, Ramos J S, Fassett R G, Little J P, Francois M E, Hearon C M, Jr., Sarma S, Janssen S, Van Craenenbroeck E M, Beckers P, Cornelissen V A, Howden E J, Keating S E, Yan X, Bishop D J, Bye A, Haupt L M, Griffiths L R, Ashton K J, Brown M A, Torquati L, Eynon N, Coombes J S. Genome wide association study of response to interval and continuous exercise training: the Predict-HIIT study [J]. J Biomed Sci. 2021; 28(1):37.
16. Collister JA, Liu X, Clifton L. Calculating Polygenic Risk Scores (PRS) in UK Biobank: A Practical Guide for Epidemiologists [J]. Front Genet. 2022; 13:818574.
17. Mcquilliam SJ, Clark DR, Erskine RM, Brownlee TE. Effect of High-Intensity vs. Moderate-Intensity Resistance Training on Strength, Power, and Muscle Soreness in Male Academy Soccer Players [J]. J Strength Cond Res. 2023; 37(6):1250–1258.
18. Yapici H, Gulu M, Yagin FH, Ugurlu D, Comertpay E, Eroglu O, Kocoglu M, Aldhahi MI, Karayigit R, Badri Al-Mhanna S. The effect of 8-weeks of combined resistance training and chocolate milk consumption on maximal strength, muscle thickness, peak power and lean mass, untrained, university-aged males [J]. Front Physiol. 2023; 14:1148494.
19. Kalapotharakos V, Smilios I, Parlavatzas A, Tokmakidis SP. The effect of moderate resistance strength training and detraining on muscle strength and power in older men [J]. J Geriatr Phys Ther. 2007; 30(3):109–113.
20. Erskine RM, Jones DA, Williams AG, Stewart CE, Degens H. Inter-individual variability in the adaptation of human muscle specific tension to progressive resistance training [J]. Eur J Appl Physiol. 2010; 110(6):1117–1125.
21. Erskine RM, Jones DA, Williams AG, Stewart CE, Degens H. Resistance training increases in vivo quadriceps femoris muscle specific tension in young men [J]. Acta Physiol (Oxf). 2010; 199(1):83–89.
22. Saito M, Ginszt M, Massidda M, Cieszczyk P, Okamoto T, Majcher P, Nakazato K, Kikuchi N. Association between MCT1 T1470A polymorphism and climbing status in Polish and Japanese climbers [J]. Biol Sport. 2021; 38(2):229–234.
23. Watanabe K, Taskesen E, Van Bochoven A, Posthuma D. Functional mapping and annotation of genetic associations with FUMA [J]. Nat Commun. 2017; 8(1):1826.
24. Orysiak J, Mazur-Rozycka J, Busko K, Gajewski J, Szczepanska B, Malczewska-Lenczowska J. Individual and Combined Influence of ACE and ACTN3 Genes on Muscle Phenotypes in Polish Athletes [J]. J Strength Cond Res. 2018; 32(10):2776–2782.
25. Massidda M, Corrias L, Ibba G, Scorcu M, Vona G, Calo CM. Genetic markers and explosive leg-muscle strength in elite Italian soccer players [J]. J Sports Med Phys Fitness. 2012; 52(3):328–334.
26. Costa AM, Silva AJ, Garrido N, Louro H, Marinho DA, Cardoso Marques M, Breitenfeld L. Angiotensin-converting enzyme genotype affects skeletal muscle strength in elite athletes [J]. J Sports Sci Med. 2009; 8(3):410–418.
27. Kang HW, Ribich S, Kim BW, Hagen SJ, Bianco AC, Cohen DE. Mice lacking Pctp /StarD2 exhibit increased adaptive thermogenesis and enlarged mitochondria in brown adipose tissue [J]. J Lipid Res. 2009; 50(11):2212–2221.
28. Druzak SA, Tardelli M, Mays SG, El Bejjani M, Mo X, Maner-Smith KM, Bowen T, Cato ML, Tillman MC, Sugiyama A, Xie Y, Fu H, Cohen DE, Ortlund EA. Ligand dependent interaction between PC-TP and PPARdelta mitigates diet-induced hepatic steatosis in male mice [J]. Nat Commun. 2023; 14(1):2748.
29. Frohlich H, Kollmeyer ML, Linz VC, Stuhlinger M, Groneberg D, Reigl A, Zizer E, Friebe A, Niesler B, Rappold G. Gastrointestinal dysfunction in autism displayed by altered motility and achalasia in Foxp1(+/-) mice [J]. Proc Natl Acad Sci U SA. 2019; 116(44):22237–22245.
30. Ransohoff JD, Wei Y, Khavari PA. The functions and unique features of long intergenic non-coding RNA [J]. Nat Rev Mol Cell Biol. 2018; 19(3):143–157.
31. Jones N, Kiely J, Suraci B, Collins DJ, De Lorenzo D, Pickering C, Grimaldi KA. A genetic-based algorithm for personalized resistance training [J]. Biol Sport. 2016; 33(2):117–126.
32. Davies RW, Carson BP, Jakeman PM. Sex Differences in the Temporal Recovery of Neuromuscular Function Following Resistance Training in Resistance Trained Men and Women 18 to 35 Years [J]. Front Physiol. 2018; 9:1480.
33. Martel GF, Roth SM, Ivey FM, Lemmer JT, Tracy BL, Hurlbut DE, Metter EJ, Hurley BF, Rogers MA. Age and sex affect human muscle fibre adaptations to heavy-resistance strength training [J]. Exp Physiol. 2006; 91(2):457–464.
34. Markovic S, Mirkov DM, Nedeljkovic A, Jaric S. Body size and countermovement depth confound relationship between muscle power output and jumping performance [J]. Hum Mov Sci. 2014; 33:203–210.
35. Nuzzo JL, Mcbride JM, Cormie P, Mccaulley GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength [J]. J Strength Cond Res. 2008; 22(3):699–707.
36. Vyas JM, Van Der Veen AG, Ploegh HL. The known unknowns of antigen processing and presentation [J]. Nat Rev Immunol. 2008; 8(8):607–618.
37. He Y, Korboukh I, Jin J, Huang J. Targeting protein lysine methylation and demethylation in cancers [J]. Acta Biochim Biophys Sin (Shanghai). 2012; 44(1):70–79.
38. Gao Y, Peng L, Zhao C. MYH7 in cardiomyopathy and skeletal muscle myopathy [J]. Mol Cell Biochem. 2023,
39. Tajsharghi H, Thornell LE, Lindberg C, Lindvall B, Henriksson KG, Oldfors A. Myosin storage myopathy associated with a heterozygous missense mutation in MYH7 [J]. Ann Neurol. 2003; 54(4):494–500.
40. Sonnemann KJ, Fitzsimons DP, Patel JR, Liu Y, Schneider MF, Moss RL, Ervasti JM. Cytoplasmic gamma-actin is not required for skeletal muscle development but its absence leads to a progressive myopathy [J]. Dev Cell. 2006; 11(3):387–397.
41. Moreland E, Borisov O V, Semenova E A, Larin A K, Andryushchenko O N, Andryushchenko L B, Generozov E V, Williams A G, Ahmetov, Ii. Polygenic Profile of Elite Strength Athletes [J]. J Strength Cond Res. 2022; 36(9):2509–2514.

42. Willems SM, Wright DJ, Day FR, Trajanoska K, Joshi PK, Morris JA, Matteini AM, Garton FC, Grarup N, Oskolkov N, Thalamuthu A, Mangino M, Liu J, Demirkan A, Lek M, Xu L, Wang G, Oldmeadow C, Gaulton KJ, Lotta LA, Miyamoto-Mikami E, Rivas MA, White T, Loh PR, Aadahl M, Amin N, Attia JR, Austin K, Benyamin B, Brage S, Cheng YC, Cieszczyk P, Derave W, Eriksson KF, Eynon N, Linneberg A, Lucia A, Massidda M, Mitchell BD, Miyachi M, Murakami H, Padmanabhan S, Pandey A, Papadimitriou I, Rajpal DK, Sale C, Schnurr TM, Sessa F, Shrine N, Tobin MD, Varley I, Wain LV, Wray NR, Lindgren CM, Macarthur DG, Waterworth DM, Mccarthy MI, Pedersen O, Khaw KT, Kiel DP, Consortium G a-T OF, Pitsiladis Y, Fuku N, Franks PW, North KN, Van Duijn CM, Mather KA, Hansen T, Hansson O, Spector T, Murabito JM, Richards JB, Rivadeneira F, Langenberg C, Perry J RB, Wareham NJ, Scott RA. Large-scale GWAS identifies multiple loci for hand grip strength providing biological insights into muscular fitness [J]. Nat Commun. 2017; 8(16015.
43. Porporato PE, Filigheddu N, Reano S, Ferrara M, Angelino E, Gnocchi VF, Prodam F, Ronchi G, Fagoonee S, Fornaro M, Chianale F, Baldanzi G, Surico N, Sinigaglia F, Perroteau I, Smith RG, Sun Y, Geuna S, Graziani A. Acylated and unacylated ghrelin impair skeletal muscle atrophy in mice [J]. J Clin Invest. 2013; 123(2):611–622.
44. Oki K, Wei B, Feng HZ, Jin JP. The loss of slow skeletal muscle isoform of troponin T in spindle intrafusal fibres explains the pathophysiology of Amish nemaline myopathy [J]. J Physiol. 2019; 597(15):3999–4012.
45. Bouchard C, Sarzynski MA, Rice TK, Kraus WE, Church TS, Sung YJ, Rao DC, Rankinen T. Genomic predictors of the maximal O(2) uptake response to standardized exercise training programs [J]. J Appl Physiol (1985). 2011; 110(5):1160–1170.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.134757
© Institute of Sport – National Research Institute

A new perspective on cardiovascular function and dysfunction during endurance exercise: identifying the primary cause of cardiovascular risk

AUTHORS: Amine Souissi[1], Ismail Dergaa[2], Samia Ernez Hajri[1], Karim Chamari[3,4], Helmi Ben Saad[1]

[1] Université de Sousse, Faculté de Médecine de Sousse, Hôpital Farhat HACHED, Laboratoire de Recherche (Insuffisance Cardiaque, LR12SP09), Sousse, Tunisie
[2] Primary Health Care Corporation (PHCC), Doha, P.O. Box 26555, Qatar
[3] High Institute of Sport and Physical Education of Ksar-Said, University of La Manouba, Tunis, Tunisia
[4] Naufar Wellness & Recovery Center, Doha, Qatar

ABSTRACT: Exercise mechanical efficiency typically falls within the range of approximately 20 to 25%. This means that a great part of the metabolic energy converted to generate movement is released as heat. Therefore, the rise in core temperature during endurance exercise in humans is proportional to generated work. Cutaneous vasodilation occurs when the core temperature threshold is reached. The rise in heart rate in response to thermal stress is a cardiovascular response that increases cardiac output and skin blood flow. The cardiovascular response during endurance exercise is a complex phenomenon potentially influenced by the involvement of nitric oxide in active thermoregulatory vasodilation. Excessive exercise can create high oxidative stress by disrupting the balance between free radicals' production and scavenging, resulting in impaired cardiovascular function. The above considerations are related to the severity and duration of endurance exercise. The first focus of this narrative review is to provide an updated understanding of cardiovascular function during endurance exercise. We aim to explore the potential role of oxidative stress in causing cardiovascular dysfunction during endurance exercise from a fresh perspective. Additionally, we aim to identify the primary factors contributing to cardiovascular risk during strenuous prolonged exercise by highlighting recent progress in this area, which may shed light on previously unexplained physiological responses. To ascertain the effect of endurance exercise on cardiovascular function and dysfunction, a narrative review of the literature was undertaken using PubMed, ScienceDirect, Medline, Google Scholar, and Scopus. The review highlighted that high oxidative stress (due to high levels of catecholamines, shear stress, immune system activation, and renal dysfunction) leads to a rise in platelet aggregation during endurance exercise. Importantly, we clearly revealed for the first time that endothelial damage, vasoconstriction, and blood coagulation (inducing thrombosis) are potentially the primary factors of cardiovascular dysfunction and myocardial infarction during and/or following endurance exercise.

CITATION: Souissi A, Dergaa I, Hajri Samia E et al. A new perspective on cardiovascular function and dysfunction during endurance exercise: identifying the primary cause of cardiovascular risk. Biol Sport. 2024;41(4):131–144.

Received: 2023-07-12; Reviewed: 2023-11-12; Re-submitted: 2023-12-20; Accepted: 2024-01-04; Published: 2024-04-09.

Corresponding author:
Amine Souissi
Université de Sousse
Faculté de Médecine de Sousse
Hôpital Farhat HACHED,
Laboratoire de Recherche
(Insuffisance Cardiaque,
LR12SP09), Sousse, Tunisie
E-mail: amine.swissi@gmail.com

ORCID:
Amine Souissi
0000-0003-2072-2425

Helmi Ben Saad
0000-0002-7477-2965

Ismail Dergaa
0000-0001-8091-1856

Karim Chamari
0000-0001-9178-7678

Key words:
Cardiovascular responses
Catecholamine
Exercise
Inflammation
Heat stress
Oxidative stress
Platelet aggregation
Thermoregulation

INTRODUCTION

Prolonged exercise in hot conditions induces an important increase in body temperature that can result in impaired physical and mental performances in humans [1, 2]. The rise in core temperature depends upon exercise duration and/or intensity [3, 4]. Competition for blood flow develops between thermoregulatory and metabolic processes [5] and this may become problematic during conditions where cardiac output and arterial blood pressure are reduced due to dehydration and/or severe hyperthermia [6]. Blood flow to the active muscles is required to satisfy metabolic needs, while simultaneous blood flow to the skin ensures thermoregulatory control [5]. The major cardiovascular adjustment to heat stress is an increase in skin blood flow (SkBF) in response to the increase in cardiac output [7]. Severe heat stress conditions lead to a substantial increase in resting SkBF due to thermoregulatory vasodilation [8, 9]. However, during exercise, SkBF fails to reach high levels compared to the resting state, as active skeletal muscles require a significant increase in blood flow [7]. Furthermore, prolonged exercise under warm or neutral conditions is accompanied by a complex phenomenon known as "cardiovascular drift" [10]. Cardiovascular drift manifests as a gradual increase in heart rate over time, accompanied by a decrease in both stroke volume and mean arterial pressure [10]. Traditionally, it has been suggested that cardiovascular drift reflects cardiac fatigue [11],

serving as a marker of cardiovascular dysfunction and/or limitation [7]. However, we have previously proposed a novel phenomenon that can potentially explain cardiovascular drift [10], extending beyond the realm of cardiovascular fatigue alone. We posited that cardiovascular drift, characterized by changes in the force-frequency relationship, may serve as a protective strategy against potential damage induced by strong myocardial contractions [10]. It is important to note that the focus of this current narrative review does not revolve around cardiovascular drift and dehydration. Instead, our aim was to provide an updated (until December 2023) understanding of the molecules involved in mediating cutaneous vasodilation during strenuous endurance exercise in the heat and/or normothermia, along with potential risk factors contributing to cardiovascular dysfunction and fatigue. The present narrative review of the literature was undertaken using PubMed, ScienceDirect, Medline, Google Scholar, and Scopus.

MATERIALS AND METHODS

In this narrative review we searched databases including PubMed, ScienceDirect, Medline, Google Scholar, and Scopus for studies published up to 2023. The search focused on keywords such as "endurance exercise", "cardiovascular function & dysfunction", "thermoregulatory control", "oxidative stress", and "free radicals". Inclusion criteria targeted studies relevant to the thermoregulatory control and cardiovascular responses to strenuous endurance exercise in the heat, particularly emphasizing the role of free radicals in cardiovascular function and dysfunction. Exclusion criteria encompassed non-English publications. Data extraction emphasized study design, participant details, exercise protocols, and cardiovascular measures. The quality of each study was assessed based on its design, methodology, and analytical rigor. Findings were synthesized to align with the review's objectives, focusing on the cardiovascular responses to strenuous endurance exercise and the identified risk factors.

Thermoregulatory control during exercise

During heat exposure and/or prolonged exercise, body temperature elevation induces a rise in the diameter of cutaneous blood vessels and therefore a reduction in vascular resistance [12]. Heart rate increases to restore peripheral blood pressure. Consequently, SkBF and skin temperature increase, which enhances heat dissipation via convection [8, 13]. Moreover, heat dissipation by evaporation of sweat needs heat transfer to the skin via cutaneous vasodilation [14, 15]. Indeed, the large increase in SkBF requires a significant elevation in cardiac output and a reduction of blood flow to renal and splanchnic circulations [16]. These adjustments could be sufficient to match the demand for increased SkBF at rest [8]. However, during prolonged exercise (of moderate or high intensity) in the heat or thermoneutral conditions [4, 17, 18], the heat loss remains inferior to heat generation. Therefore, in such conditions, the body cannot stop temperature elevation or maintain steady-state core temperature. Thus, the body temperature continues to rise even after an adequate thermoregulatory response, but at a lower rate compared to when prolonged exercise was started [17, 18]. The increase in core temperature depends on both exercise intensity and duration [3, 4]. It has been identified that power output capability and integrated electromyographic activity of the muscles decrease during prolonged exercise under heat stress [19, 20]. It has been reported that the neural recruitment of skeletal muscle motor units is reduced when core body temperature rises to "critical" levels [19, 20]. The critical temperature might be one of the major factors limiting muscular function [21]. Indeed, the efferent command to active muscles is attenuated when a high core temperature is reached (e.g. ~39–40°C) [2]. The critical temperature may function as a signal for the central nervous system, which will then inhibit motor unit recruitment to protect the brain against severe hyperthermia [2, 20, 22, 23]. We confirm that the central nervous system may reduce neural drive and attenuate skeletal muscular function to prevent overheating. On the other hand, we suggest that the decrease in myocardial function cannot be considered as a strategy for preventing overheating as it may disturb the thermoregulatory control and increase the risk of heat stroke [17]. Interestingly, it is still unknown whether the decrease in cardiac performance *(i)* is simply due to an alteration in preload/afterload, and/or cardiac fatigue and/or cardiac damage, or *(ii)* it may be partially related to a protective strategy against the potential damage that could be induced by a permanent strong myocardial contraction [10].

Cutaneous vasodilation during exercise

It is well known that cutaneous vasodilation is attenuated during exercise relative to the rest condition [5, 24]. Exercise initiation induces competition between the vasoconstrictor and vasodilator cutaneous systems [5]. Cutaneous vasoconstriction occurs in response to the initiation of exercise in heat-stressing conditions [5]. Exercise places several limits on the ability of the skin to dilate, due to an increased vasoconstrictor tone and decreased vasodilator capacity [5]. Furthermore, exercise influences the temperature threshold (which tends to rise) at which cutaneous vasodilation starts [5, 25]. Consequently, the central temperature increases brusquely in the first few minutes of exercise. Otherwise, despite further significant core temperature increases particularly in severe heat stress conditions, the rise in SkBF is attenuated when the central temperature approaches 38°C [26].

It has been reported in the literature that the exercise effect is intensity-dependent; low intensity does not alter thermoregulatory cutaneous vasodilation, whereas high intensity shifts the temperature threshold (which tends to rise) for cutaneous vasodilation [27–29]. However, the stimulus behind the exercise-induced shift in the temperature threshold for cutaneous vasodilation remains unclear [26], Interestingly, since it has been observed that cutaneous vasodilation during high-intensity exercise in the heat is attenuated relative to that during low-intensity exercise due to increased oxidative stress [30, 31],

we speculate that oxidative stress is a potential factor explaining the shift in the temperature threshold.

There are several agents that have recently been found to act as vasodilators during exercise. Louie et al. [32] reported that ATP-sensitive potassium, calcium-activated potassium channels, and voltage-gated potassium channels contribute to the control of cutaneous vasodilation during exercise in heat stress conditions. Furthermore, Fujii et al. [33] highlighted that heat shock protein 90 contributed to cutaneous vasodilation during exercise via nitric oxide (NO) synthase (NOS)-dependent mechanisms. Importantly, Fujii et al. [33] also stated that NOS contributes to ~40–50% of total cutaneous vasodilation during prolonged exercise in healthy humans. This finding reflects the major role of NOS in the thermoregulatory control (vasodilation response) during endurance exercise [33–36]. The vasodilation response to heat stress appears to be potentiated by NO production at rest and during exercise. Charkoudian et al. [37] identified that the cutaneous vasodilation response to a local warming (i.e. 30 minutes at 42°C) stimulus is biphasic and NO plays an important role in both the initiation and the maintenance of the second slower phase.

Mechanisms mediating cutaneous vasodilation differ between whole-body and local skin heating [38]. However, it appears that there are some common points between them (e.g. NO-induced vasodilation) [33–36]. The skin vasodilation response to endurance exercise depends on reflex control (i.e. sensory nerve-mediated vasodilation) and free radicals (cutaneous endothelial NO-dependent vasodilation) (Figure 1). It has been demonstrated that skin vasodilation in heat stress depends on NO at rest and during exercise, with sensory nerves mediating an initial transient vasodilatory "peak" followed by a prolonged vasodilatory "plateau" mediated primarily by NO production [33, 39, 40]. We highlight that it is still unknown whether the source of NO during "local heating" is the same as the one released during exercise where the heat generation comes from the muscular work. Future research should pay more attention to such issues.

Cardiovascular fatigue related to oxidative stress during endurance exercise

Multiple factors contribute to cardiovascular fatigue during prolonged exercise and make it a complex phenomenon [41–43]. Meta-analyses revealed a reduction in left ventricular function following 24-h exercise [42, 43]. During prolonged exercise, the large displacement of blood flow toward the skin appears to play a key role in the development of cardiovascular fatigue [17].

Exercise results in an increase in heart rate, which increases the mechanical forces of blood flow on the vascular wall (i.e. shear stress and blood pressure) [44]. Shear stress has been shown to increase endothelial superoxide generation in conductance arteries in vivo [45]. Similarly, high levels of shear stress during prolonged exercise have been found to stimulate vascular superoxide and hydrogen peroxide

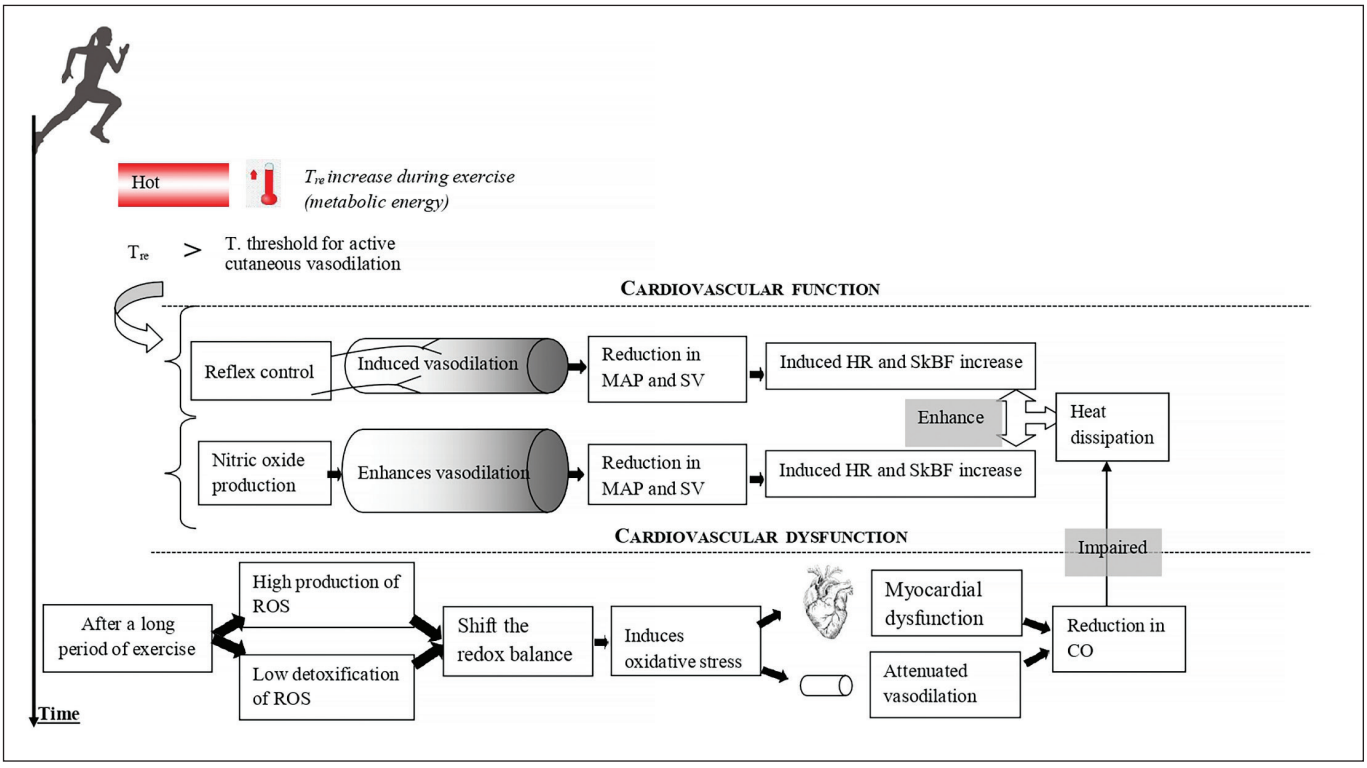


FIG. 1. Simplified representation of the cardiovascular response to prolonged exercise. CO: cardiac output. HR: heart rate. MAP: mean arterial pressure. ROS: reactive oxygen species. SkBF: skin blood flow. SV: stroke volume. T: temperature. T_{re}: rectal temperature.

production [46]. Exercise-induced oxidative stress has recently been well confirmed [47–51], and it is well established that the increased production of reactive oxygen species (ROS) during exercise has both positive and negative physiological effects [47, 51–53]. The latter may shift the redox balance to a pro-oxidant state and impair thermoregulatory vasodilation [47, 49, 51]. According to this fact, studies indicated that NOS-dependent cutaneous vasodilation during high-intensity exercise in the heat is attenuated relative to that during moderate-intensity exercise due to increased oxidative stress [30, 31].

Nicotinamide adenine dinucleotide phosphate oxidase enzyme (NADPH) is the major source of ROS in the heart [54, 55], and also well known for its role in myocardial dysfunction [55]. Interestingly, a significant link between NADPH oxidase-dependent oxidative stress and myocardial dysfunction has been identified after prolonged strenuous exercise in rats [56–58]. This might potentially represent a new trigger in the understanding of exercise-induced myocardial dysfunction. High oxidative stress was proposed to depress cardiac function through protein kinase G and cyclic monophosphate-mediated desensitization of cardiac myofilaments [59].

Furthermore, a long period of exercise increases catecholamine and pro-inflammatory markers such as tumour necrosis factor and interleukin-6 (IL-6) [60–62]. Excess catecholamines contribute to an increase in ROS formation [61], and attenuation of β-adrenergic inotropic responsiveness [63–66]. A previous study highlighted that cardiac stress induced by exercise activates both oxidative stress, inflammation and β-adrenergic pathways [67]. It is well known that oxidative stress and inflammation are potentially involved in the pathogenesis of heart failure and impaired left ventricular function [56–58, 68, 69]. Interestingly, the administration of IL-1 and tumour necrosis factor is associated with a decline in contractile function in rats' hearts, this being partially improved by treatment with an NOS inhibitor [70]. Moreover, antioxidant supplementation may attenuate the decline in myocardial function during exercise [67, 71, 72].

Does inflammation cause cardiovascular risk during endurance exercise?

For a considerable period, the notion of cardiovascular risk has been associated with increased cardiovascular stress leading to alterations (decline) in cardiovascular function [12, 17] (Figure 2). Recent studies have attributed the decline in cardiac function during exercise to adrenergic desensitization (β_1 and β_2 receptors), [10, 73, 74], which attenuates cardiac function and provides cardioprotection against acute stressors induced by exercise, such as mechanical stress, cellular damage, and mitochondrial damage [10, 42, 75]. Interestingly, alongside the controlled mechanisms of β-adrenergic receptor desensitization and β_3 activation, high levels of oxidative stress linked to inflammation [10, 62, 76, 77] may also contribute to the attenuation of cardiac function.

In fact, studies have demonstrated that inhibition of endogenous NO leads to an enhancement of the effects of catecholamines [78–80], indicating that NO may play a cardio-protective role by attenuating the effect of catecholamines, potentiating the positive inotropic effect in normal hearts. Accordingly, it has been confirmed that the increase in NO concentrations attenuates the positive inotropic effect of catecholamines [81]. Furthermore, certain molecules associated with inflammation, such as IL-10, brain-derived neurotrophic factor, and follistatin-like protein, which increase during or after exercise, may also play a cardio-protective role by facilitating tissue repair and regeneration [82]. These findings raise a crucial question regarding the initial causes of cardiovascular risk. The primary focus of the present narrative review is to elucidate our current understanding of cardiovascular dysfunction during prolonged exercise with respect to inflammation and oxidative stress. Additionally, we aim to identify the primary cause of cardiovascular risk.

Cardio-renal association and immune response activation

Renal vasoconstriction and NADPH oxidase activation

The large increase in SkBF during endurance exercise requires a significant reduction of renal blood flow [16]. The decrease in renal blood flow [16] constitutes a potential factor for the decline in renal function. Sustained levels of sympathetic activity and dehydration may contribute to the increase in plasma renin activity and circulating angiotensin II [83, 84]. Then, the activation of angiotensin II type 1 receptors *(i)* elevates ROS production through NADPH oxidase activation [85–87], and *(ii)* stimulates aldosterone secretion [88, 89]. In turn, aldosterone can directly stimulate ROS production through the activation of NADPH oxidase [90]. Importantly, the stimulation of aldosterone release is linked to an increase in galectin-3 concentration in the heart and kidney [77, 91]. Galectin-3 and other markers of cardiac damage (e.g. troponin I, suppression of tumorigenicity 2 (ST2)) increase following strenuous physical effort [92, 93].

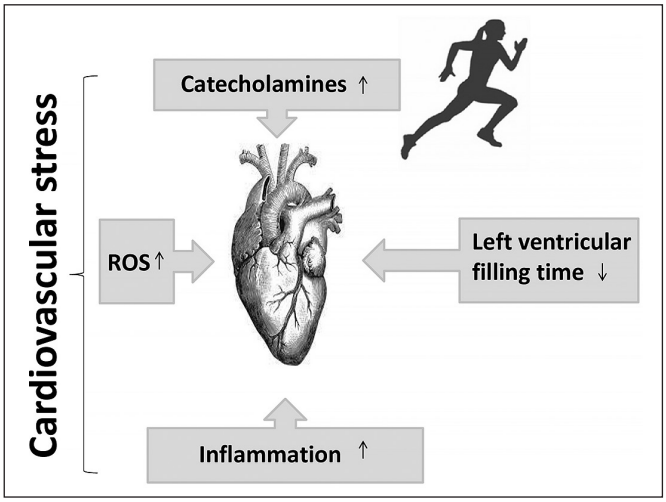


FIG. 2. Putative mechanisms leading to cardiovascular stress during exercise. ROS: reactive oxygen species.

Interestingly, as at December 2023, there remains no explanation of the reason for this increase, which has been suggested to be physiological [94, 95]. This narrative review seeks to clarify our comprehension of the factors contributing to the elevation of galectin-3 levels in reaction to strenuous endurance exercise.

Galectin-3 and inflammatory biomarkers

When cardiovascular tissues are physically damaged, the immune system is activated in order to remove the damaged cells and maintain homeostasis in the body [96]. Galectin-3 seems to play an important role in immune response activation [97] by stimulating hyperoxide secretion from neutrophils through NADPH activation [98, 99]. Neutrophils are generated and sent to the site of injury within minutes and are the hallmark of acute inflammation [100]. Suzuki [101] highlighted the protective role of neutrophils in the exercise-induced muscle damage associated with high production of ROS. Hence, neutrophil levels have been shown to double during prolonged strenuous exercise and remain elevated for at least 24 h [102].

Galectin-3 is actually considered a reasonable cardiovascular inflammatory biomarker [97]. Although galectin-3 is identified as a risk predictor of adverse events and cardiac arrest [103, 104], its levels correlate also with tissue repair [105, 106]. Galectin-3 should not be considered a pathogenic molecule inducing cardiovascular damage, since it contributes to activation of the immune system, playing a cardioprotective role during exercise. Interestingly, it was observed that the blood levels of galectin-3 in endurance athletes were more elevated than in sedentary healthy humans at the beginning and the end of exercise [107], confirming that galectin-3 can play a cardioprotective role in athletes. A 2020 review suggested that galectin-3 could be used as a novel treatment for atherosclerosis [97]. In fact, galectin-3 can play an anti-inflammatory role and exert a beneficial effect on atherosclerosis by activating M2 macrophage differentiation, via the CD98/phosphoinositide 3-kinase pathway [108]. On the other hand, we highlight that a clinical 2022 study found that galectin-3 accumulation potentiates platelet aggregation via dectin-1 activation [109], which can promote thrombosis during/or following exercise.

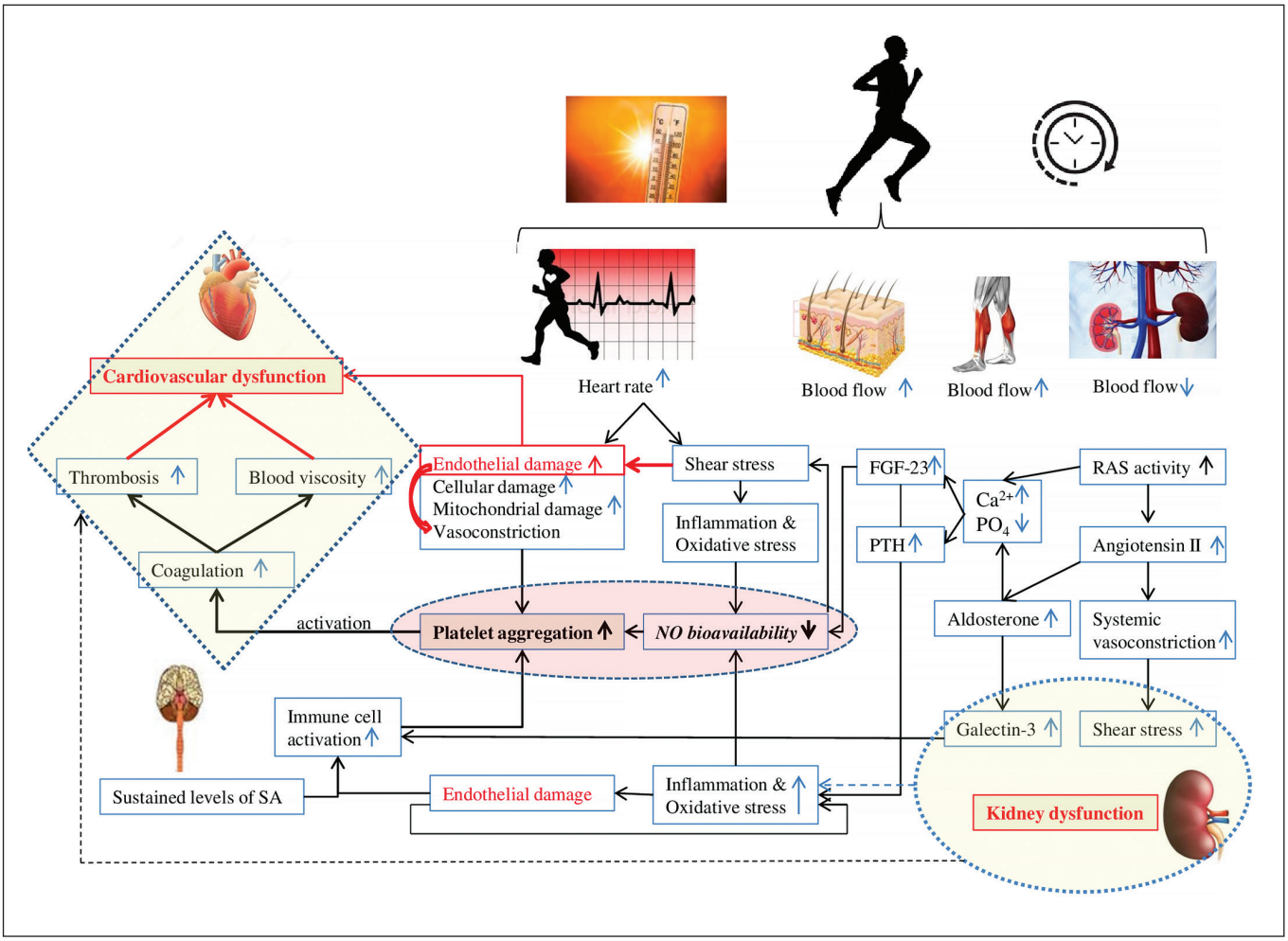


FIG. 3. Potential factors contributing to coagulation and cardiovascular dysfunction during prolonged exercise. FGF-23: fibroblast growth factor 23. PTH: parathyroid hormone. RAS: renin-angiotensin-aldosterone system. SA: sympathetic activity.

Aldosterone, fibroblast growth factor 23 and parathyroid hormone

It is well established that fibroblast growth factor 23 (FGF-23), a newly discovered hormone, and parathyroid hormone (PTH) are markers of chronic kidney injury and cardiovascular impairment (i.e. ventricular hypertrophy, vascular calcification, and arterial stiffness) [110]. The literature revealed that high-intensity endurance exercise training is associated with arterial stiffness [111], ventricular hypertrophy [112], and coronary artery calcification [113, 114]. Importantly, the increase in PTH level depends on exercise severity (intensity and duration), suggesting a complex cause-and-effect relationship between PTH and coronary artery calcification [113]. Currently (December 2023), the mechanism explaining PTH elevation during exercise is not yet well understood. In fact, RAS is activated during prolonged exercise [115], indicating a decline in renal function and then an impairment in calcium and phosphate regulation. Therefore, PTH and FGF-23 are both secreted to restore calcium and decrease phosphate levels [116].

We hypothesize that aldosterone, PTH and FGF-23 play a key role in the development of cardiovascular fatigue during exercise: Aldosterone increases oxidative stress, reduces NO levels, and promotes platelet adhesion possibly by potentiating collagen production [117, 118], triggering a cascade of coagulation. We believe that aldosterone can play a crucial role in the development of thrombosis, resulting in cardiovascular dysfunction during and following endurance exercise. FGF23 directly alters endothelial vasodilation function by reducing NO bioavailability [119] (Figure 3). Importantly, clinical studies identified a strong correlation between PTH elevation and hypercoagulability [120]. One could speculate that PTH can contribute to blood coagulation and cardiovascular dysfunction during prolonged exercise possibly by affecting calcium levels and potentiating oxidative stress [121].

Toll-like receptor 4 (tlr4) and coagulation

The analysis of TLR4 is a promising advanced orientation in the search for understanding cardiovascular dysfunction [122]. Indeed, a single bout of exercise induces TLR4 activation, promoting endoplasmic reticulum stress [122, 123], an inflammatory response [122–124], and increased markers of cardiac injury [122, 123] and apoptosis [122] (i.e. heart-damaging events), which are necessary mechanisms for remodelling and adaptation [122]. Interestingly, it has been

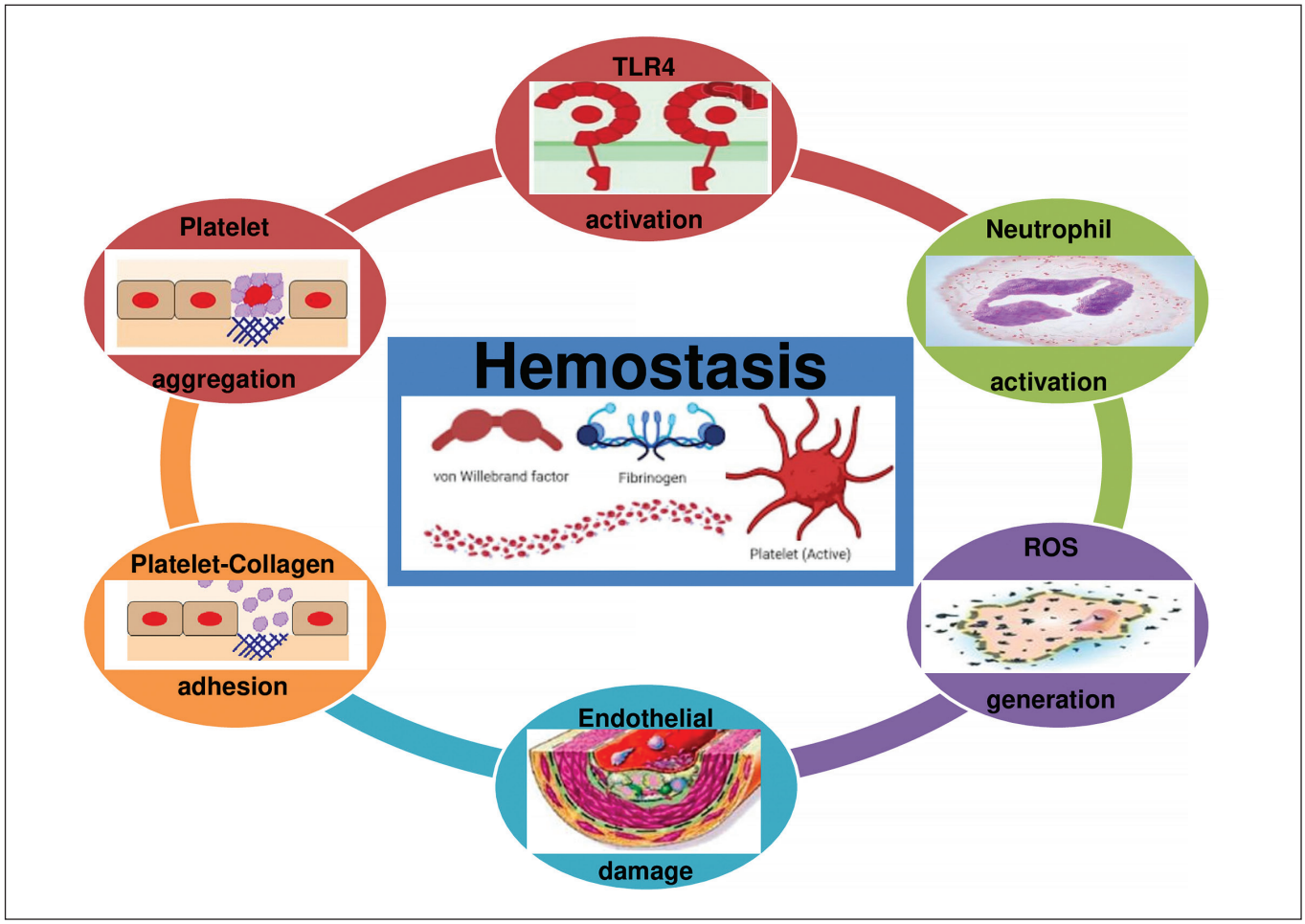


FIG. 4. Toll-like receptor 4 (TLR4) promotes acute coagulation via neutrophil activation, ROS generation and platelet aggregation. ROS: Reactive oxygen species.

recently suggested that nuclear factor-kappa B (NF-κβ) activation by TLR4 is a necessary mechanism for cardiovascular adaptations induced by physical effort [122]. According to Gordon et al. [125], NF-κβ can promote desirable adaptive responses. Cardioprotection is triggered during or immediately after exercise when cells are under oxidative stress [126].

Although TLR4 is a physiological response favouring apoptosis and tissue regeneration to assure beneficial adaptive responses to exercise, evidence suggests that TLR4 promotes acute coagulation [127] via NF-κβ activation, neutrophil activation, ROS generation, and platelet aggregation [127, 128] (Figure 4). Therefore, we highlight that TLR4 activation by acute strenuous exercise can result in undesirable cardiac events (myocardial infarction or sudden death), particularly in people with cardiovascular diseases [41].

What is the primary cause of cardiovascular risk?

To date (December 2023), inflammation has traditionally been regarded as the primary cause of cardiovascular dysfunction during endurance exercise. However, there is abundant evidence indicating that the inflammatory response is not the primary cause of dysfunction [129]. Importantly, some anti-inflammatory cytokines (e.g. IL-10) inhibit activation of coagulation and regulate thrombosis [130, 131]. Furthermore, it is well established that the IL-33/ST2 axis exhibits a cardioprotective role, reducing fibrosis and cardiomyocyte hypertrophy, and improving myocardial function in both chronic and acute heart failure [132]. Moreover, creatine kinase is traditionally considered an indicator of tissue damage and subsequent fatigue. Creatine kinase's function is intriguing. Its role in cardioprotection, particularly through the inhibition of ADP-triggered platelet activation [133], underscores the imperative for researchers to recalibrate and deepen their perspectives on the multifaceted biological responses to exercise.

White blood cells and platelet counts are reported to be elevated after prolonged strenuous exercise [134–136]. It was reported that inhibition of platelet aggregation by NO was decreased following acute prolonged strenuous exercise. The attenuated response of platelets to NO during exercise results in thrombotic complications [137]. Moreover, NADPH plays a crucial role in ROS generation and platelet activation [138]. Indeed, such activation despite its protective role through haemostasis-inducing coagulation can result in thrombosis, myocardial infarction, and cardiac arrest [139].

Moreover, it is well established that strenuous exercise induces endothelial damage/vascular injury [10]. The damage of endothelial cells results in vasoconstriction and exposes the collagen substratum to the blood circulating at high shear rates [128]. Therefore, platelets circulating at high velocity will adhere to collagen. The adherent platelets then aggregate. Platelets are then activated (by secreting ADP, serotonin and TxA2) which promotes a cascade of coagulation [128] (Figure 5). Therefore, endothelial damage can further trigger haemostasis, resulting in a high level of blood viscosity, potentiating thrombosis and cardiovascular dysfunction during and/or following exercise.

In summary, our review suggests that the primary causes of cardiovascular risk during acute endurance exercise are two-fold. Firstly, cell damage (involving endothelial and mitochondrial cells) emerges as a significant contributor. The stress imposed during exercise can lead to damage in these cells and result in vasoconstriction, potentially impacting cardiovascular function and overall risk. Secondly, blood coagulation (due to cell damage, inflammation, renal dysfunction, and high oxidative stress) leading to thrombosis and an increase in blood viscosity, plays a crucial role in cardiovascular risk. These factors can affect blood flow dynamics and potentially lead to adverse cardiovascular events. Additionally, it is important to consider coronary artery calcification as a risk factor that may be exacerbated after high-load training. This calcification process can further contribute to the overall cardiovascular risk profile.

In conclusion, the combination of several factors – *(i)* shear stress-induced endothelial damage promoting coagulation cascade and then thrombosis, *(ii)* oxidative stress, inflammation, renal dysfunction, and immune activation promoting blood coagulation and then thrombosis, and *(iii)* vasoconstriction (due to endothelial damage, oxidative

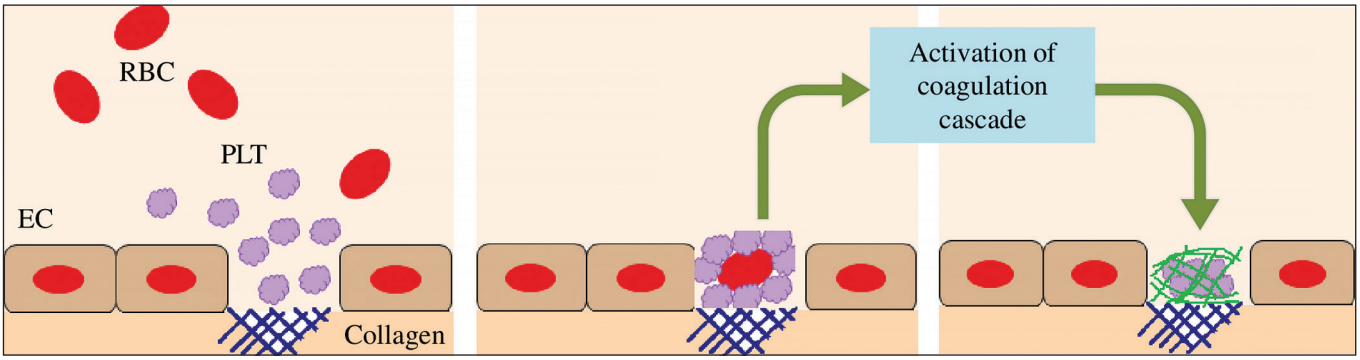


FIG. 5. Platelets are activated when binding to the collagen substratum, which promotes a cascade of coagulation. EC: endothelial cell. PLT: platelet. RBC: red blood cell.

stress, and haemostasis) promoting thrombosis – contributes to the increased cardiovascular fatigue and risk (myocardial infarction) during and/or following strenuous endurance exercise. Finally, we highlight that dehydration can potentiate cardiovascular fatigue and the risk of cardiovascular infarction.

Perspective and limitations

Our hypothesis revolves around the notion that excessive oxidative stress, potentially linked to shear stress, cellular damage, renal dysfunction, and activation of the immune response, contributes to cardiovascular dysfunction through the promotion of platelet aggregation. This hypothesis is firmly grounded, supported by compelling evidence indicating that vigorous exercise leads to a significant rise in platelet aggregation and activation [140, 141]. Additionally, there exist various other molecules associated with impaired energetic metabolism and cardiovascular dysfunction (such as free fatty acids, cholesterol, low-density lipoprotein, catecholamines, and serotonin) [142] that may further exacerbate coagulation during and/or following exercise [143, 144]. Investigating the complex association of these variables with coagulation warrants comprehensive exploration in future studies. Of particular interest, the use of antithrombotic therapy holds promising potential in counteracting coagulation-induced cardiovascular fatigue. However, caution must be exercised due to the inherent risk of bleeding complications. Markers of cardiac/renal damage (e.g. galectin-3) increase during and/or following exercise; however, there has been no explanation of the reason for this response, which has been suggested to be physiological (i.e. non-pathological), though it remains unexplained to date. Notably, this increase in markers is potentially associated with activation of TLR4. TLR4 activation promotes an inflammatory response and increases markers of cardiac injury, which are crucial for remodelling. Immune activation and inflammatory responses to acute exercise are both adequate physiological responses, ensuring a cardioprotective role by optimizing cardiovascular adaptation to physical effort (i.e. training). However, excessive immune system activation and inflammation during exercise are associated with a heightened risk of cardiac events. Although evidence suggests that galectin-3 is secreted to promote physiological cardiac remodelling and immune system activation, it is not yet clear whether galectin-3 contributes to cardiovascular dysfunction by promoting platelet activation and thrombosis (i.e. by activating dectin-1/spleen tyrosine kinase signalling). This narrative review serves as a call to researchers to explore and investigate this potential pathway for a better understanding of cardiovascular risk prevention through exercise.

The present narrative review, while providing valuable insights, does have additional perspectives. We acknowledge that not all biomarkers of inflammation (e.g. IL-6 and IL-17), iron deficiency, and numerous other factors potentially exacerbating coagulation during exercise have been discussed. Furthermore, our focus centred on oxidative stress during exercise, while neglecting the influence of other factors, including alterations in pH, calcium levels, and energy metabolism, which can also contribute to cardiovascular dysfunction [145]. We encourage further exploration in this field to enhance our understanding of cardiovascular dysfunction during prolonged exercise by incorporating additional information and complementing our current knowledge base.

CONCLUSIONS

The thermoregulatory vasodilation during prolonged exercise primarily relies on reflex control and nitric oxide production. However, extensive evidence from the literature indicates that cutaneous vasodilation during strenuous exercise is impaired by excessive ROS production and increased oxidative stress. Furthermore, reducing the inhibitory effects of nitric oxide on platelet aggregation during prolonged strenuous exercise may result in potentially dangerous thrombotic complications.

Prolonged strenuous exercise has been shown to increase NADPH oxidase activity, shift the redox balance to a pro-oxidant state, and impair renal and cardiovascular function. NADPH plays a critical role in the formation of ROS, as well as immune and platelet activation. Although such activation serves an immune-protective function, it can lead to coagulation and myocardial infarction.

Acknowledgments

Open access was provided by the Heart Failure Laboratory of Research (LR12SP09), Farhat HACHED Hospital, Sousse, Tunisia.

Competing interests

The authors declare that they have no competing interests.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT 3.5 [146, 147].

REFERENCES

1. MacDougall JD, Reddan WG, Layton CR, Dempsey JA. Effects of metabolic hyperthermia on performance during heavy prolonged exercise. J Appl Physiol. 1974; 36(5):538–44. Epub 1974/05/01. doi: 10.1152/jappl.1974.36.5.538. PubMed PMID: 4826315.
2. Nielsen B, Nybo L. Cerebral changes during exercise in the heat. Sports Med. 2003; 33(1):1–11. doi: 10.2165/00007256-200333010-00001. PubMed PMID: 12477374.
3. Kenny GP, Niedre PC. The effect of exercise intensity on the post-exercise esophageal temperature response. Eur J Appl Physiol. 2002; 86(4):342–6. doi: 10.1007/s00421-001-0538-4. PubMed PMID: 11990748.
4. Souissi A, Yousfi N, Dabboubi R, Aloui G, Haddad M, Souissi N. Effect of acute melatonin administration on physiological

response to prolonged exercise. Biol Rhythm Res. 2020; 51(6):980–7. doi: 10.1080/09291016.2019.1573462
5. Kellogg Jr D, Johnson J, Kosiba W. Competition between cutaneous active vasoconstriction and active vasodilation during exercise in humans. Am J Physiol. 1991 Oct; 261(4 Pt 2):H1184–9. doi: 10.1152/ajpheart.1991.261.4.H1184. PMID: 1928401.
6. Murray R. Dehydration, hyperthermia, and athletes: science and practice. J Athl Train. 1996; 31(3):248–52. PubMed PMID: 16558408; PubMed Central PMCID: PMC1318513.
7. Rowell LB. Human cardiovascular adjustments to exercise and thermal stress. Physiol Rev. 1974; 54(1):75–159. doi: 10.1152/physrev.1974.54.1.75. PubMed PMID: 4587247.
8. Johnson, JM and Proppe DW. Cardiovascular adjustments to heat stress. In Comprehensive Physiology, R. Terjung (Ed.). 2011. https://doi.org/10.1002/cphy.cp040111. doi: https://doi.org/10.1002/cphy.cp040111.
9. Taylor WF, Johnson JM, O'Leary D, Park MK. Effect of high local temperature on reflex cutaneous vasodilation. J Appl Physiol Respir Environ Exerc Physiol. 1984; 57(1):191–6. doi: 10.1152/jappl.1984.57.1.191. PubMed PMID: 6469780.
10. Souissi A, Haddad M, Dergaa I, Ben Saad H, Chamari K. A new perspective on cardiovascular drift during prolonged exercise. Life Sci. 2021; 287:120109. Epub 20211027. doi: 10.1016/j.lfs.2021.120109. PubMed PMID: 34717912.
11. Saltin B, Stenberg J. Circulatory response to prolonged severe exercise. J Appl Physiol. 1964; 19(5):833–8. doi: 10.1152/jappl.1964.19.5.833. PubMed PMID: 14207729.
12. Crandall CG, Gonzalez-Alonso J. Cardiovascular function in the heat-stressed human. Acta Physiol (Oxf). 2010; 199(4):407–23. Epub 20100324. doi: 10.1111/j.1748-1716.2010.02119.x. PubMed PMID: 20345414; PubMed Central PMCID: PMC3496876.
13. Johnson JM. Exercise and the cutaneous circulation. Exerc Sport Sci Rev. 1992; 20:59–97. PMID: 1623893.
14. Hargreaves M. Physiological limits to exercise performance in the heat. J Sci Med Sport. 2008; 11(1):66–71. Epub 20070827. doi: 10.1016/j.jsams.2007.07.002. PubMed PMID: 17720623.
15. Galloway SD, Maughan RJ. Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. Med Sci Sports Exerc. 1997; 29(9):1240–9. doi: 10.1097/00005768-199709000-00018. PubMed PMID: 9309637.
16. Kenney MJ, Fels RJ. Sympathetic nerve regulation to heating is altered in senescent rats. Am J Physiol Regul Integr Comp Physiol. 2002 Aug; 283(2):R513–20. doi: 10.1152/ajpregu.00683.2001. PMID: 12121865.
17. Periard JD, Caillaud C, Thompson MW. The role of aerobic fitness and exercise intensity on endurance performance in uncompensable heat stress conditions. Eur J Appl Physiol. 2012; 112(6):1989–99. Epub 20110923. doi: 10.1007/s00421-011-2165-z. PubMed PMID: 21947407.
18. Souissi A, Dergaa I, Musa S, Saad HB, Souissi N. Effects of daytime ingestion of melatonin on heart rate response during prolonged exercise. Mov Sport Sci/Sci Mot. 2022(115):25–32. doi: https://doi.org/10.1051/sm/2021020
19. Tucker R, Rauch L, Harley YX, Noakes TD. Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle recruitment. Pflugers Arch. 2004 Jul; 448(4):422–30. doi: 10.1007/s00424-004-1267-4. Epub 2004 May 8. PMID: 15138825.
20. Gordon R, Tillin NA, Tyler CJ. The effect of head and neck per-cooling on neuromuscular fatigue following exercise in the heat. Appl Physiol Nutr Metab. 2020; 45(11):1238–46. Epub 20200521. doi: 10.1139/apnm-2020-0079. PubMed PMID: 32437624.
21. Racinais S, Periard JD, Karlsen A, Nybo L. Effect of heat and heat acclimatization on cycling time trial performance and pacing. Med Sci Sports Exerc. 2015; 47(3):601–6. doi: 10.1249/MSS.0000000000000428. PubMed PMID: 24977692; PubMed Central PMCID: PMC4342312.
22. Gonzalez-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, Nielsen B. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol (1985). 1999 Mar; 86(3):1032–9. doi: 10.1152/jappl.1999.86.3.1032. PMID: 10066720.
23. Morrison SF. Central control of body temperature. F1000Res. 2016 May 12; 5:F1000 Faculty Rev-880. doi: 10.12688/f1000research.7958.1. PMID: 27239289; PMCID: PMC4870994.
24. Johnson JM, Park MK. Effect of heat stress on cutaneous vascular responses to the initiation of exercise. J Appl Physiol Respir Environ Exerc Physiol. 1982; 53(3):744–9. doi: 10.1152/jappl.1982.53.3.744. PubMed PMID: 7129999.
25. Charkoudian N. Mechanisms and modifiers of reflex induced cutaneous vasodilation and vasoconstriction in humans. J Appl Physiol (1985). 2010 Oct; 109(4):1221–8. doi: 10.1152/japplphysiol.00298.2010. Epub 2010 May 6. PMID: 20448028; PMCID: PMC2963327.
26. Kenney WL, Johnson JM. Control of skin blood flow during exercise. Med Sci Sports Exerc. 1992; 24(3):303–12. PubMed PMID: 1549024.
27. Mack GW, Nose H, Takamata A, Okuno T, Morimoto T. Influence of exercise intensity and plasma volume on active cutaneous vasodilation in humans. Med Sci Sports Exerc. 1994; 26(2):209–16. doi: 10.1249/00005768-199402000-00011. PubMed PMID: 8164538.
28. Smolander J, Saalo J, Korhonen O. Effect of work load on cutaneous vascular response to exercise. J Appl Physiol (1985). 1991 Oct; 71(4):1614–9. doi: 10.1152/jappl.1991.71.4.1614. PMID: 1757390.
29. Taylor WF, Johnson JM, Kosiba WA, Kwan CM. Graded cutaneous vascular responses to dynamic leg exercise. J Appl Physiol (1985). 1988 May; 64(5):1803–9. doi: 10.1152/jappl.1988.64.5.1803. PMID: 3391884.
30. Fujii N, McGinn R, Stapleton JM, Paull G, Meade RD, Kenny GP. Evidence for cyclooxygenase-dependent sweating in young males during intermittent exercise in the heat. J Physiol. 2014; 592(23):5327–39. Epub 20141017. doi: 10.1113/jphysiol.2014.280651. PubMed PMID: 25326453; PubMed Central PMCID: PMC4262342.
31. Meade RD, Fujii N, Alexander LM, Paull G, Louie JC, Flouris AD, et al. Local infusion of ascorbate augments NO-dependent cutaneous vasodilatation during intense exercise in the heat. J Physiol. 2015; 593(17):4055–65. Epub 20150728. doi: 10.1113/JP270787. PubMed PMID: 26110415; PubMed Central PMCID: PMC4575586.
32. Louie JC, Fujii N, Meade RD, Kenny GP. The interactive contributions of Na(+)/K(+) -ATPase and nitric oxide synthase to sweating and cutaneous vasodilatation during exercise in the heat. J Physiol. 2016; 594(12):3453–62. Epub 20160329. doi: 10.1113/JP271990. PubMed PMID: 26852741; PubMed Central PMCID: PMC4908024.
33. Fujii N, Zhang SY, McNeely BD, Nishiyasu T, Kenny GP. Heat shock protein 90 contributes to cutaneous vasodilation through activating nitric oxide synthase in young male adults exercising in the heat. J Appl Physiol (1985). 2017 Oct 1; 123(4):844–850. doi: 10.1152/japplphysiol.00446.2017. Epub 2017 Jul 27. PMID: 28751373; PMCID: PMC5668448.
34. McNamara TC, Keen JT, Simmons GH, Alexander LM, Wong BJ. Endothelial nitric oxide synthase mediates the nitric oxide component of reflex cutaneous

vasodilatation during dynamic exercise in humans. J Physiol. 2014; 592(23):5317–26. Epub 20140925. doi: 10.1113/jphysiol.2014.272898. PubMed PMID: 25260636; PubMed Central PMCID: PMC4262341.
35. Welch G, Foote KM, Hansen C, Mack GW. Nonselective NOS inhibition blunts the sweat response to exercise in a warm environment. J Appl Physiol (1985). 2009 Mar; 106(3):796–803. doi: 10.1152/japplphysiol.90809.2008. Epub 2009 Jan 8. PMID: 19131481; PMCID: PMC2660248.
36. Fujii N, Meade RD, Alexander LM, Akbari P, Foudil-Bey I, Louie JC, et al. iNOS-dependent sweating and eNOS-dependent cutaneous vasodilation are evident in younger adults, but are diminished in older adults exercising in the heat. J Appl Physiol (1985). 2016 Feb 1; 120(3):318–27. doi: 10.1152/japplphysiol.00714.2015. Epub 2015 Nov 19. PMID: 26586908; PMCID: PMC4740499.
37. Charkoudian N, Eisenach JH, Atkinson JL, Fealey RD, Joyner MJ. Effects of chronic sympathectomy on locally mediated cutaneous vasodilation in humans. J Appl Physiol (1985). 2002 Feb; 92(2):685–90. doi: 10.1152/japplphysiol.00758.2001. PMID: 11796682.
38. Kellogg DL, Jr., Zhao JL, Wu Y. Roles of nitric oxide synthase isoforms in cutaneous vasodilation induced by local warming of the skin and whole body heat stress in humans. J Appl Physiol (1985). 2009 Nov; 107(5):1438–44. doi: 10.1152/japplphysiol.00690.2009. Epub 2009 Sep 10. PMID: 19745188; PMCID: PMC2777790.
39. Kellogg DL, Jr., Liu Y, Kosiba IF, O'Donnell D. Role of nitric oxide in the vascular effects of local warming of the skin in humans. J Appl Physiol (1985). 1999 Apr; 86(4):1185–90. doi: 10.1152/jappl.1999.86.4.1185. PMID: 10194201.
40. Minson CT, Berry LT, Joyner MJ. Nitric oxide and neurally mediated regulation of skin blood flow during local heating. Nitric oxide and neurally mediated regulation of skin blood flow during local heating.
41. Eijsvogels TM, Fernandez AB, Thompson PD. Are there deleterious cardiac effects of acute and chronic endurance exercise? Physiol Rev. 2016 Jan; 96(1):99–125. doi: 10.1152/physrev.00029.2014. PMID: 26607287; PMCID: PMC4698394.
42. Lord RN, Utomi V, Oxborough DL, Curry BA, Brown M, George KP. Left ventricular function and mechanics following prolonged endurance exercise: an update and meta-analysis with insights from novel techniques. Eur J Appl Physiol. 2018; 118(7):1291–9. Epub 20180605. doi: 10.1007/s00421-018-3906-z. PubMed PMID: 29869711; PubMed Central PMCID: PMC6028893.
43. Middleton N, Shave R, George K, Whyte G, Hart E, Atkinson G. Left ventricular function immediately following prolonged exercise: A meta-analysis. Med Sci Sports Exerc. 2006; 38(4):681–7. doi: 10.1249/01.mss.0000210203.10200.12. PubMed PMID: 16679983.
44. Kojda G, Hambrecht R. Molecular mechanisms of vascular adaptations to exercise. Physical activity as an effective antioxidant therapy? Cardiovasc Res. 2005 Aug 1; 67(2):187–97. doi: 10.1016/j.cardiores.2005.04.032. PMID: 15935334.
45. Laurindo FR, Pedro Mde A, Barbeiro HV, Pileggi F, Carvalho MH, Augusto O, et al. Vascular free radical release. Ex vivo and in vivo evidence for a flow-dependent endothelial mechanism. Circ Res. 1994 Apr; 74(4):700–9. doi: 10.1161/01.res.74.4.700. PMID: 7511072.
46. Lauer N, Suvorava T, Ruther U, Jacob R, Meyer W, Harrison DG, et al. Critical involvement of hydrogen peroxide in exercise-induced up-regulation of endothelial NO synthase. Cardiovasc Res. 2005 Jan 1; 65(1):254–62. doi: 10.1016/j.cardiores.2004.09.010. PMID: 15621054.
47. Trinity JD, Broxterman RM, Richardson RS. Regulation of exercise blood flow: Role of free radicals. Free Radic Biol Med. 2016; 98:90–102. Epub 20160210. doi: 10.1016/j.freeradbiomed.2016.01.017. PubMed PMID: 26876648; PubMed Central PMCID: PMC4975999.
48. Kruk J, Aboul-Enein BH, Duchnik E. Exercise-induced oxidative stress and melatonin supplementation: current evidence. J Physiol Sci. 2021; 71(1):27. Epub 20210901. doi: 10.1186/s12576-021-00812-2. PubMed PMID: 34470608; PubMed Central PMCID: PMC8409271.
49. Powers SK, Deminice R, Ozdemir M, Yoshihara T, Bomkamp MP, Hyatt H. Exercise-induced oxidative stress: Friend or foe? J Sport Health Sci. 2020; 9(5):415–25. Epub 20200504. doi: 10.1016/j.jshs.2020.04.001. PubMed PMID: 32380253; PubMed Central PMCID: PMC7498668.
50. Powers SK, Nelson WB, Hudson MB. Exercise-induced oxidative stress in humans: cause and consequences. Free Radic Biol Med. 2011; 51(5):942–50. Epub 20101216. doi: 10.1016/j.freeradbiomed.2010.12.009. PubMed PMID: 21167935.
51. Kawamura T, Muraoka I. Exercise-induced oxidative stress and the effects of antioxidant intake from a physiological viewpoint. Antioxidants (Basel). 2018; 7(9):119. Epub 20180905. doi: 10.3390/antiox7090119. PubMed PMID: 30189660; PubMed Central PMCID: PMC6162669.
52. Souissi A, Ben Maaouia G, Dergaa I, Ghram A, Ben Saad H. The fat burning ability of melatonin during submaximal exercise. Biol Rhythm Res. 2023; 54(3):307–21. doi:10.1080/09291016.2022.2157531
53. Souissi A, Dergaa I, Chtourou H, Ben Saad H. The effect of daytime ingestion of melatonin on thyroid hormones responses to acute submaximal exercise in healthy active males: A pilot study. Am J Mens Health. 2022; 16(1):15579883211070383. doi: 10.1177/15579883211070383. PubMed PMID: 35060417; PubMed Central PMCID: PMC8785310.
54. Lambeth JD. NOX enzymes and the biology of reactive oxygen. Nat Rev Immunol. 2004; 4(3):181–9. doi: 10.1038/nri1312. PubMed PMID: 15039755.
55. Murdoch CE, Zhang M, Cave AC, Shah AM. NADPH oxidase-dependent redox signalling in cardiac hypertrophy, remodelling and failure. Cardiovasc Res. 2006 Jul 15; 71(2):208–15. doi: 10.1016/j.cardiores.2006.03.016. Epub 2006 Mar 27. PMID: 16631149.
56. Vitiello D, Boissière J, Doucende G, Gayrard S, Polge A, Faure P, et al. β-Adrenergic receptors desensitization is not involved in exercise-induced cardiac fatigue: NADPH oxidase-induced oxidative stress as a new trigger. J Appl Physiol (1985). 2011 Nov; 111(5):1242–8. doi: 10.1152/japplphysiol.00449.2011. Epub 2011 Jun 30. PMID: 21719731.
57. Nie J, Close G, George KP, Tong TK, Shi Q. Temporal association of elevations in serum cardiac troponin T and myocardial oxidative stress after prolonged exercise in rats. Eur J Appl Physiol. 2010; 110(6):1299–303. Epub 20100814. doi: 10.1007/s00421-010-1604-6. PubMed PMID: 20711602.
58. Vitiello D. Connexin 43 dephosphorylation: a potential underlying mechanism involved in exercise-induced cardiac fatigue. Austin Biol. 2016; 1(4):1018.
59. Tavernier B, Li JM, El-Omar MM, Lanone S, Yang ZK, Trayer IP, et al. Cardiac contractile impairment associated with increased phosphorylation of troponin I in endotoxemic rats. FASEB J. 2001; 15(2):294–6. Epub 20001208. doi: 10.1096/fj.00-0433fje. PubMed PMID: 11156941.
60. Jee H, Jin Y. Effects of prolonged endurance exercise on vascular

endothelial and inflammation markers. J Sports Sci Med. 2012; 11(4):719–26. Epub 20121201. PubMed PMID: 24150084; PubMed Central PMCID: PMC3763320.
61. Kruk J, Kotarska K, Aboul-Enein BH. Physical exercise and catecholamines response: benefits and health risk: possible mechanisms. Free Radic Res. 2020; 54(2–3):105–25. Epub 20200218. doi: 10.1080/10715762.2020.1726343. PubMed PMID: 32020819.
62. Krzeminski K, Buraczewska M, Miskiewicz Z, Dabrowski J, Steczkowska M, Kozacz A, et al. Effect of ultra-endurance exercise on left ventricular performance and plasma cytokines in healthy trained men. Biol Sport. 2016; 33(1):63–9. Epub 20151231. doi: 10.5604/20831862.1189767. PubMed PMID: 26985136; PubMed Central PMCID: PMC4786588.
63. Massion PB, Feron O, Dessy C, Balligand JL. Nitric oxide and cardiac function: ten years after, and continuing. Circ Res. 2003 Sep 5; 93(5):388–98. doi: 10.1161/01.RES.0000088351.58510.21. PMID: 12958142.
64. Shah AM, MacCarthy PA. Paracrine and autocrine effects of nitric oxide on myocardial function. Pharmacol Ther. 2000 Apr; 86(1):49–86. doi: 10.1016/s0163-7258(99)00072-8. PMID: 10760546.
65. Cotton JM, Kearney MT, MacCarthy PA, Grocott-Mason RM, McClean DR, Heymes C, et al. Effects of nitric oxide synthase inhibition on Basal function and the force-frequency relationship in the normal and failing human heart in vivo. Circulation. 2001; 104(19):2318–23. Epub 2001/11/07. doi: 10.1161/hc4401.098515. PubMed PMID: 11696472.
66. Ziolo MT, Katoh H, Bers DM. Positive and negative effects of nitric oxide on Ca(2+) sparks: influence of beta-adrenergic stimulation. Am J Physiol Heart Circ Physiol. 2001; 281(6):H2295–303. doi: 10.1152/ajpheart.2001.281.6.H2295. PubMed PMID: 11709395.
67. Chakouri N, Reboul C, Boulghobra D, Kleindienst A, Nottin S, Gayrard S, et al. Stress-induced protein S-glutathionylation and phosphorylation crosstalk in cardiac sarcomeric proteins - Impact on heart function. Int J Cardiol. 2018; 258:207–16. doi: 10.1016/j.ijcard.2017.12.004. PubMed PMID: 29544934.
68. Lord KC, Shenouda SK, McIlwain E, Charalampidis D, Lucchesi PA, Varner KJ. Oxidative stress contributes to methamphetamine-induced left ventricular dysfunction. Cardiovasc Res. 2010 Jul 1; 87(1):111–8. doi: 10.1093/cvr/cvq043. Epub 2010 Feb 5. PMID: 20139112; PMCID: PMC2883898.
69. Souissi A, Dergaa I, Romdhani M, Ghram A, Irandoust K, Chamari K, et al. Can melatonin reduce the severity of post-COVID-19 syndrome? EXCLI J. 2023 Feb 2; 22:173–187. doi: 10.17179/excli2023-5864. PMID: 36998709; PMCID: PMC10043401.
70. Schulz R, Panas DL, Catena R, Moncada S, Olley PM, Lopaschuk GD. The role of nitric oxide in cardiac depression induced by interleukin-1 beta and tumour necrosis factor-alpha. Br J Pharmacol. 1995 Jan; 114(1):27–34. doi: 10.1111/j.1476-5381.1995.tb14901.x. PMID: 7536096; PMCID: PMC1510184.
71. Emami A, Tofighi A, Asri-Rezaei S, Bazargani-Gilani B. The effect of short-term coenzyme Q10 supplementation and pre-cooling strategy on cardiac damage markers in elite swimmers. Br J Nutr. 2018; 119(4):381–90. doi: 10.1017/S0007114517003774. PubMed PMID: 29498347.
72. Souissi A, Dergaa I. An overview of the potential effects of melatonin supplementation on athletic performance. Int J Sport Stud Hlth. 2021; 4(1):e121714. doi: 10.5812/intjssh.121714.
73. Hart E, Dawson E, Rasmussen P, George K, Secher NH, Whyte G, et al. Beta-adrenergic receptor desensitization in man: insight into post-exercise attenuation of cardiac function. J Physiol. 2006 Dec 1; 577(Pt 2):717–25. doi: 10.1113/jphysiol.2006.116426. Epub 2006 Sep 14. PMID: 16973702; PMCID: PMC1890446.
74. Banks L, Sasson Z, Busato M, Goodman JM. Impaired left and right ventricular function following prolonged exercise in young athletes: influence of exercise intensity and responses to dobutamine stress. J Appl Physiol (1985). 2010 Jan; 108(1):112–9. doi: 10.1152/japplphysiol.00898.2009. Epub 2009 Nov 5. PMID: 19892922.
75. Coates AM, King TJ, Currie KD, Tremblay JC, Petrick HL, Slysz JT, et al. Alterations in cardiac function following endurance exercise are not duration dependent. Front Physiol. 2020; 11:581797. Epub 20200918. doi: 10.3389/fphys.2020.581797. PubMed PMID: 33071833; PubMed Central PMCID: PMC7531437.
76. Silva SD, Jr., Jara ZP, Peres R, Lima LS, Scavone C, Montezano AC, et al. Temporal changes in cardiac oxidative stress, inflammation and remodeling induced by exercise in hypertension: Role for local angiotensin II reduction. PLoS One. 2017; 12(12):e0189535. Epub 20171212. doi: 10.1371/journal.pone.0189535. PubMed PMID: 29232407; PubMed Central PMCID: PMC5726656.
77. Burtscher J, Vanderriele P-E, Legrand M, Predel H-G, Niebauer J, O'Keefe JH, et al. Could repeated cardio-renal injury trigger late cardiovascular sequelae in extreme endurance athletes? Sports Med. 2022 Dec; 52(12):2821–2836. doi: 10.1007/s40279-022-01734-8. Epub 2022 Jul 18. PMID: 35851948; PMCID: PMC9691495.
78. Muller-Strahl G, Kottenberg K, Zimmer HG, Noack E, Kojda G. Inhibition of nitric oxide synthase augments the positive inotropic effect of nitric oxide donors in the rat heart. J Physiol. 2000; 522 Pt 2(Pt 2):311–20. doi: 10.1111/j.1469-7793.2000.00311.x. PubMed PMID: 10639106; PubMed Central PMCID: PMC2269760.
79. Balligand JL, Kelly RA, Marsden PA, Smith TW, Michel T. Control of cardiac muscle cell function by an endogenous nitric oxide signaling system. Proc Natl Acad Sci U S A. 1993; 90(1):347–51. doi: 10.1073/pnas.90.1.347. PubMed PMID: 7678347; PubMed Central PMCID: PMC45657.
80. Keaney JF, Jr., Hare JM, Balligand JL, Loscalzo J, Smith TW, Colucci WS. Inhibition of nitric oxide synthase augments myocardial contractile responses to beta-adrenergic stimulation. Am J Physiol. 1996; 271(6 Pt 2):H2646–52. doi: 10.1152/ajpheart.1996.271.6.H2646. PubMed PMID: 8997327.
81. Reading S, Barclay J. The inotropic effect of nitric oxide on mammalian papillary muscle is dependent on the level of beta1-adrenergic stimulation. Can J Physiol Pharmacol. 2002 Jun; 80(6):569–77. doi: 10.1139/y02-085. PMID: 12117306.
82. Sierra APR, Martinez Galan BS, de Sousa CAZ, de Menezes DC, Branquinho JLO, Neves RL, et al. Exercise induced-cytokines response in marathon runners: Role of ACE I/D and BDKRB2 +9/-9 polymorphisms. Front Physiol. 2022; 13:919544. Epub 20220902. doi: 10.3389/fphys.2022.919544. PubMed PMID: 36117688; PubMed Central PMCID: PMC9479100.
83. Tidgren B, Hjemdahl P, Theodorsson E, Nussberger J. Renal neurohormonal and vascular responses to dynamic exercise in humans. J Appl Physiol (1985). 1991 May; 70(5):2279–86. doi: 10.1152/jappl.1991.70.5.2279. PMID: 1677937.
84. Aldigier J, Huang H, Dalmay F, Lartigue M, Baussant T, Chassain A, et al. Angiotensin-converting enzyme inhibition does not suppress plasma angiotensin II increase during exercise in humans. J Cardiovasc Pharmacol. 1993 Feb;

21(2):289–95. doi: 10.1097/00005344-199302000-00015. PMID: 7679164.
85. Griendling KK, Ushio-Fukai M. Reactive oxygen species as mediators of angiotensin II signaling. Regul Peptides. 2000; 91(1–3):21–7. doi: 10.1016/s0167-0115(00)00136-1. PubMed PMID: 10967199.
86. Hanna IR, Taniyama Y, Szöcs K, Rocic P, Griendling KK. NAD(P)H oxidase-derived reactive oxygen species as mediators of angiotensin II signaling. Antioxid Redox Signal. 2002 Dec; 4(6):899–914. doi: 10.1089/152308602762197443. PMID: 12573139.
87. Harrison DG, Cai H, Landmesser U, Griendling KK. Interactions of angiotensin II with NAD(P)H oxidase, oxidant stress and cardiovascular disease. J Renin Angiotensin Aldosterone Syst. 2003; 4(2):51–61. doi: 10.3317/jraas.2003.014. PubMed PMID: 12806586.
88. Lastra-Lastra G, Sowers JR, Restrepo-Erazo K, Manrique-Acevedo C, Lastra-Gonzalez G. Role of aldosterone and angiotensin II in insulin resistance: an update. Clin Endocrinol (Oxf). 2009; 71(1):1–6. Epub 20081205. doi: 10.1111/j.1365-2265.2008.03498.x. PubMed PMID: 19138313.
89. Li LH, Kao WF, Chiu YH, Hou SK, Meng C, How CK. Impact of renin-angiotensin-aldosterone system activation and body weight change on N-terminal pro-B-type natriuretic peptide variation in 100-km ultramarathon runners. J Chin Med Assoc. 2020; 83(1):48–54. doi: 10.1097/JCMA.0000000000000227. PubMed PMID: 31770190.
90. Miyata K, Rahman M, Shokoji T, Nagai Y, Zhang G-X, Sun G-P, et al. Aldosterone stimulates reactive oxygen species production through activation of NADPH oxidase in rat mesangial cells. J Am Soc Nephrol. 2005 Oct; 16(10):2906–12. doi: 10.1681/ASN.2005040390. Epub 2005 Aug 31. PMID: 16135774.
91. Giam B, Kaye DM, Rajapakse NW. Role of renal oxidative stress in the pathogenesis of the cardiorenal syndrome. Heart Lung Circ. 2016; 25(8):874–80. Epub 20160416. doi: 10.1016/j.hlc.2016.02.022. PubMed PMID: 27132623.
92. Hättasch R, Spethmann S, de Boer RA, Ruifrok WP, Schattke S, Wagner M, et al. Galectin-3 increase in endurance athletes. Eur J Prev Cardiol. 2014 Oct; 21(10):1192–9. doi: 10.1177/2047487313492069. Epub 2013 May 30. PMID: 23723328.
93. Shaheen HAA, Mohamed MA, Basset FHA, Rashed MH, Theruvan NB, Mosbah SA. Heart failure prediction in athletic heart remodeling among long distance runners. World J Cardiovasc Dis. 2022; 12(1):1–10. doi: 10.4236/wjcd.2022.121001.
94. Wilson M, O'Hanlon R, Prasad S, Oxborough D, Godfrey R, Alpendurada F, et al. Biological markers of cardiac damage are not related to measures of cardiac systolic and diastolic function using cardiovascular magnetic resonance and echocardiography after an acute bout of prolonged endurance exercise. Br J Sports Med. 2011; 45(10):780–4. Epub 20091023. doi: 10.1136/bjsm.2009.064089. PubMed PMID: 19854761.
95. Donnellan E, Phelan D. Biomarkers of cardiac stress and injury in athletes: What Do they mean? Curr Heart Fail Rep. 2018; 15(2):116–22. doi: 10.1007/s11897-018-0385-9. PubMed PMID: 29520707.
96. Park SA, Hyun YM. Neutrophil extravasation cascade: What can we learn from two-photon intravital imaging? Immune Netw. 2016 Dec; 16(6):317–321. doi: 10.4110/in.2016.16.6.317. Epub 2016 Dec 22. PMID: 28035206; PMCID: PMC5195840.
97. Gao Z, Liu Z, Wang R, Zheng Y, Li H, Yang L. Galectin-3 is a potential mediator for atherosclerosis. J Immunol Res. 2020 Feb 14; 2020:5284728. doi: 10.1155/2020/5284728. PMID: 32149158; PMCID: PMC7042544.
98. Karlsson A, Follin P, Leffler H, Dahlgren C. Galectin-3 activates the NADPH-oxidase in exudated but not peripheral blood neutrophils. Blood. 1998; 91(9):3430–8. PubMed PMID: 9558402.
99. Almkvist J, Faldt J, Dahlgren C, Leffler H, Karlsson A. Lipopolysaccharide-induced gelatinase granule mobilization primes neutrophils for activation by galectin-3 and formylmethionyl-Leu-Phe. Infect Immun. 2001; 69(2):832–7. doi: 10.1128/IAI.69.2.832–837.2001. PubMed PMID: 11159975; PubMed Central PMCID: PMC97959.
100. Cohen S, Burns R. Pathways of the pulp, 8th ed St. Louis CV Mosby Co St Louis Misso. 2002;64146.
101. Suzuki K. Involvement of neutrophils in exercise-induced muscle damage and its modulation. Gen Intern Med Clin Innov. 2018;3:1–8. doi: 10.15761/GIMCI.1000170.
102. Pedersen BK, Toft AD. Effects of exercise on lymphocytes and cytokines. Br J Sports Med. 2000;34(4):246–51. doi: 10.1136/bjsm.34.4.246. PubMed PMID: 10953894; PubMed Central PMCID: PMC1724218.
103. Gehlken C, Suthahar N, Meijers WC, de Boer RA. Galectin-3 in heart failure: An update of the last 3 years. Heart Fail Clin. 2018;14(1):75–92. doi: 10.1016/j.hfc.2017.08.009. PubMed PMID: 29153203.
104. Suthahar N, Meijers WC, Sillje HHW, Ho JE, Liu FT, de Boer RA. Galectin-3 Activation and inhibition in heart failure and cardiovascular disease: An update. theranostics. 2018;8(3):593–609. Epub 20180101. doi: 10.7150/thno.22196. PubMed PMID: 29344292; PubMed Central PMCID: PMC5771079.
105. Akimoto Y, Ikehara S, Yamaguchi T, Kim J, Kawakami H, Shimizu N, et al. Galectin expression in healing wounded skin treated with low-temperature plasma: Comparison with treatment by electronical coagulation. Arch Biochem Biophys. 2016;605:86–94. Epub 20160128. doi: 10.1016/j.abb.2016.01.012. PubMed PMID: 26827730.
106. González GE, Cassaglia P, Truant SN, Fernández MM, Wilensky L, Volberg V, et al. Int J Cardiol. 2014 Oct 20;176(3):1423–5. doi: 10.1016/j.ijcard.2014.08.011. Epub 2014 Aug 8. PMID: 25150483.
107. Hattasch R, Spethmann S, de Boer RA, Ruifrok WP, Schattke S, Wagner M, et al. Galectin-3 increase in endurance athletes. Eur J Prev Cardiol. 2014;21(10):1192–9. Epub 20130530. doi: 10.1177/2047487313492069. PubMed PMID: 23723328.
108. MacKinnon AC, Farnworth SL, Hodkinson PS, Henderson NC, Atkinson KM, Leffler H, et al. Regulation of alternative macrophage activation by galectin-3. J Immunol. 2008;180(4):2650–8. doi: 10.4049/jimmunol.180.4.2650. PubMed PMID: 18250477.
109. Chen Y, Fu W, Zheng Y, Yang J, Liu Y, Qi Z, et al. Galectin 3 enhances platelet aggregation and thrombosis via Dectin-1 activation: a translational study. Eur Heart J. 2022;43(37):3556–74. doi: 10.1093/eurheartj/ehac034. PubMed PMID: 35165707; PubMed Central PMCID: PMC9989600.
110. Schefold JC, Filippatos G, Hasenfuss G, Anker SD, von Haehling S. Heart failure and kidney dysfunction: epidemiology, mechanisms and management. Nat Rev Nephrol. 2016;12(10):610–23. Epub 20160830. doi: 10.1038/nrneph.2016.113. PubMed PMID: 27573728.
111. Calleja-Romero A, Vicente-Rodriguez G, Garatachea N. Acute effects of long-distance races on heart rate variability and arterial stiffness: A systematic review and meta-analysis. J Sports Sci. 2022;40(3):248–70. Epub 20211031. doi: 10.1080/02640414.2021.1986276. PubMed PMID: 34720045.

112. Ohman EM, Teo KK, Johnson AH, Collins PB, Dowsett DG, Ennis JT, et al. Abnormal cardiac enzyme responses after strenuous exercise: alternative diagnostic aids. Br Med J (Clin Res Ed). 1982;285(6354):1523–6. doi: 10.1136/bmj.285.6354.1523. PubMed PMID: 6814629; PubMed Central PMCID: PMC1500473.
113. Zambrano A, Tintut Y, Demer LL, Hsu JJ. Potential mechanisms linking high-volume exercise with coronary artery calcification. Heart. 2023;109(15):1139–45. Epub 20230712. doi: 10.1136/heartjnl-2022-321986. PubMed PMID: 36702539; PubMed Central PMCID: PMC10356745.
114. DeFina LF, Radford NB, Barlow CE, Willis BL, Leonard D, Haskell WL, et al. Association of all-cause and cardiovascular mortality with high levels of physical activity and concurrent coronary artery calcification. JAMA Cardiol. 2019;4(2):174–81. doi: 10.1001/jamacardio.2018.4628. PubMed PMID: 30698608; PubMed Central PMCID: PMC6439619.
115. Luger A, Deuster PA, Debolt JE, Loriaux DL, Chrousos GP. Acute exercise stimulates the renin-angiotensin-aldosterone axis: adaptive changes in runners. Horm Res. 1988;30(1):5–9. doi: 10.1159/000181017. PubMed PMID: 2851526.
116. Kovesdy CP, Quarles LD. The role of fibroblast growth factor-23 in cardiorenal syndrome. Nephron Clin Pract. 2013;123(3–4):194–201. Epub 20130806. doi: 10.1159/000353593. PubMed PMID: 23942553; PubMed Central PMCID: PMC5079534.
117. Gromotowicz A, Szemraj J, Stankiewicz A, Zakrzeska A, Mantur M, Jaroszewicz E et al. Study of the mechanisms of aldosterone prothrombotic effect in rats. J Renin Angiotensin Aldosterone Sys. 2011;12(4):430–439.
118. Brilla CG. Renin–angiotensin–aldosterone system and myocardial fibrosis. Cardiovasc Research. 2000; 47(1):1–3.
119. Silswal N, Touchberry CD, Daniel DR, McCarthy DL, Zhang S, Andresen J, et al. FGF23 directly impairs endothelium-dependent vasorelaxation by increasing superoxide levels and reducing nitric oxide bioavailability. Am J Physiol Endocrinol Metab. 2014;307(5):E426–36. Epub 2014 0722. doi: 10.1152/ajpendo.00264.2014. PubMed PMID: 25053401; PubMed Central PMCID: PMC4154070.
120. Squizzato A, Van Zaane B, Gerdes VE, Büller HR. The influence of pituitary, adrenal, and parathyroid hormones on hemostasis and thrombosis. Semin Thromb Hemost. 2011 Feb;37(1):41–8. doi: 10.1055/s-0030-1270070. Epub 2011 Jan 19. PMID: 21249603.
121. Lombardi G, Ziemann E, Banfi G, Corbetta S. physical activity-dependent regulation of parathyroid hormone and calcium-phosphorous metabolism. Int J Mol Sci. 2020;21(15):5388. Epub 20200729. doi: 10.3390/ijms21155388. PubMed PMID: 32751307; PubMed Central PMCID: PMC7432834.
122. de Vicente LG, Pinto AP, Munoz VR, Rovina RL, da Rocha AL, Gaspar RC, et al. Tlr4 participates in the responses of markers of apoptosis, inflammation, and ER stress to different acute exercise intensities in mice hearts. Life Sci. 2020;240:117107. Epub 20191127. doi: 10.1016/j.lfs.2019.117107. PubMed PMID: 31785241.
123. Cristi-Montero C, Sanchez-Collado P, Veneroso C, Cuevas MJ, Gonzalez-Gallego J. Effect of an acute exercise bout on Toll-like receptor 4 and inflammatory mechanisms in rat heart. Rev Med Chil. 2012;140(10):1282–8. doi: 10.4067/S0034-98872012001000007. PubMed PMID: 23559285.
124. Wang R-p, Yao Q, Xiao Y-b, Zhu S-b, Yang L, Feng J-m, et al. Toll-like receptor 4/nuclear factor-kappa B pathway is involved in myocardial injury in a rat chronic stress model. Stress. 2011 Sep;14(5):567–75. doi: 10.3109/10253890.2011.571729. Epub 2011 Jun 15. PMID: 21675862.
125. Gordon JW, Shaw JA, Kirshenbaum LA. Multiple facets of NF-κB in the heart: to be or not to NF-κB. Circ Res. 2011 Apr 29;108(9):1122–32. doi: 10.1161/CIRCRESAHA.110.226928. PMID: 21527742.
126. de Vicente LG, Pinto AP, da Rocha AL, Pauli JR, de Moura LP, Cintra DE, et al. Role of TLR4 in physical exercise and cardiovascular diseases. Cytokine. 2020;136:155273. Epub 20200912. doi: 10.1016/j.cyto.2020.155273. PubMed PMID: 32932194.
127. Ding N, Chen G, Hoffman R, Loughran PA, Sodhi CP, Hackam DJ, et al. Toll-like receptor 4 regulates platelet function and contributes to coagulation abnormality and organ injury in hemorrhagic shock and resuscitation. Circ Cardiovasc Genet. 2014; 7(5):615–24. Epub 20140721. doi: 10.1161/CIRCGENETICS.113.000398. PubMed PMID: 25049041; PubMed Central PMCID: PMC4270899.
128. Semple JW, Italiano JE, Jr., Freedman J. Platelets and the immune continuum. Nat Rev Immunol. 2011;11(4):264–74. doi: 10.1038/nri2956. PubMed PMID: 21436837.
129. Coates AM, Petrick HL, Millar PJ, Burr JF. Exercise alters cardiac function independent of acute systemic inflammation in healthy men. Am J Physiol Heart Circ Physiol. 2021;320(5):H1762–H73. Epub 20210312. doi: 10.1152/ajpheart.00809.2020. PubMed PMID: 33710926.
130. Downing LJ, Strieter RM, Kadell AM, Wilke CA, Austin JC, Hare BD, et al. IL-10 regulates thrombus-induced vein wall inflammation and thrombosis. J Immunol. 1998;161(3):1471–6. PubMed PMID: 9686613.
131. Pajkrt D, van der Poll T, Levi M, Cutler DL, Affrime MB, van den Ende A, et al. Interleukin-10 inhibits activation of coagulation and fibrinolysis during human endotoxemia. Blood. 1997;89(8):2701–5. PubMed PMID: 9108387.
132. Villacorta H, Maisel AS. Soluble ST2 Testing: A Promising biomarker in the management of heart failure. Arq Bras Cardiol. 2016;106(2):145–52. Epub 20160115. doi: 10.5935/abc.20150151. PubMed PMID: 26761075; PubMed Central PMCID: PMC4765013.
133. Horjus DL, Nieuwland R, Boateng KB, Schaap MC, van Montfrans GA, Clark JF, et al. Creatine kinase inhibits ADP-induced platelet aggregation. Sci Rep. 2014;4(1):6551. Epub 20141009. doi: 10.1038/srep06551. PubMed PMID: 25298190; PubMed Central PMCID: PMC4190537.
134. Kratz A, Lewandrowski KB, Siegel AJ, Chun KY, Flood JG, Van Cott EM, et al. Effect of marathon running on hematologic and biochemical laboratory parameters, including cardiac markers. Am J Clin Pathol. 2002;118(6):856–63. doi: 10.1309/14TY-2TDJ-1X0Y-1V6V. PubMed PMID: 12472278.
135. Reid SA, Speedy DB, Thompson JM, Noakes TD, Mulligan G, Page T, et al. Study of hematological and biochemical parameters in runners completing a standard marathon. Clin J Sport Med. 2004;14(6):344–53. doi: 10.1097/00042752-200411000-00004. PubMed PMID: 15523206.
136. Bird SR, Linden M, Hawley JA. Acute changes to biomarkers as a consequence of prolonged strenuous running. Ann Clin Biochem. 2014 Mar;51(Pt 2):137–50. doi: 10.1177/0004563213492147. Epub 2013 Sep 2. PMID: 24000373.
137. Sakita S, Kishi Y, Numano F. Acute vigorous exercise attenuates sensitivity of platelets to nitric oxide. Thromb Res. 1997;87(5):461–71. doi: 10.1016/s0049-3848(97)00162-x. PubMed PMID: 9306620.

138. Delaney MK, Kim K, Estevez B, Xu Z, Stojanovic-Terpo A, Shen B, et al. Differential roles of the NADPH-Oxidase 1 and 2 in Platelet activation and thrombosis. Arterioscler Thromb Vasc Biol. 2016;36(5):846–54. Epub 20160317. doi: 10.1161/ATVBAHA .116.307308. PubMed PMID: 26988594; PubMed Central PMCID: PMC4850088.
139. Smith JE. Effects of strenuous exercise on haemostasis. Br J Sports Med. 2003;37(5):433–5. doi: 10.1136/bjsm.37.5.433. PubMed PMID: 14514536; PubMed Central PMCID: PMC1751362.
140. Kestin AS, Ellis PA, Barnard MR, Errichetti A, Rosner BA, Michelson AD. Effect of strenuous exercise on platelet activation state and reactivity. Circulation. 1993;88(4 Pt 1):1502–11. doi: 10 .1161/01.cir.88.4.1502. PubMed PMID: 8403298.
141. el-Sayed MS. Effects of exercise on blood coagulation, fibrinolysis and platelet aggregation. Sports Med. 1996;22(5):282–98. doi: 10.2165/00007256-199622050-00002. PubMed PMID: 8923646.
142. Dawson E, George K, Shave R, Whyte G, Ball D. Does the human heart fatigue subsequent to prolonged exercise? Sports Med. 2003;33(5):365–80. doi: 10.2165/00007256-200333050 -00003. PMID: 12696984.
143. Poole JC. The effect of certain fatty acids on the coagulation of plasma in vitro. Br J Exp Pathol. 1955;36(3):248–53. PubMed PMID: 13239980; PubMed Central PMCID: PMC2082531.
144. El-Sayed MS, Ali N, El-Sayed Ali Z. Aggregation and activation of blood platelets in exercise and training. Sports Med. 2005;35(1):11–22. doi: 10.2165/00007256-200535010 -00002. PubMed PMID: 15651910.
145. Gresslien T, Agewall S. Troponin and exercise. Int J Cardiol. 2016;221:609–21. Epub 20160628. doi: 10.1016/j.ijcard.2016.06.243. PubMed PMID: 27420587.
146. Dergaa I, Chamari K, Zmijewski P, Ben Saad H. From human writing to artificial intelligence generated text: examining the prospects and potential threats of ChatGPT in academic writing. Biol Sport. 2023;40(2):615–22. Epub 20230315. doi: 10.5114/ biolsport.2023.125623. PubMed PMID: 37077800; PubMed Central PMCID: PMC10108763.
147. Dergaa I, Zakhama L, Dziri C, Saad HB. Enhancing scholarly discourse in the age of artificial intelligence: A guided approach to effective peer review process. Tunis Med 2023; 101(10):721–6.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.136090
© Institute of Sport – National Research Institute

Do all matches require the same effort? Influence of contextual factors on physical demands during official female handball competitions

AUTHORS: Carlos García-Sánchez[1], Rafael Manuel Navarro[2], Daniel Mon-López[1], Raúl Nieto-Acevedo[1], Enrique Cañadas-García[1], Alfonso de la Rubia[1]

[1] Deporte y Entrenamiento Research Group, Departamento de Deportes, Facultad de Ciencias de la Actividad Física y del Deporte (INEF), Universidad Politécnica de Madrid, C/Martín Fierro 7, 28040 Madrid, Spain
[2] Department of Sports Sciences, European University of Madrid; 28670 Villaviciosa de Odón, Spain

ABSTRACT: Understanding the influence of contextual factors on physical demands is essential to maximize performance in handball. The purpose of this study was to explore and compare the influence of contextual factors (halves of the match, level of the opponent, match outcome and player role) on external load during official matches in women's handball. Twenty-two semi-professional female players from the Spanish 2nd Division were monitored across 13 official home matches. Total distance covered (TDC), high-speed running distance (HSR), high-intensity breaking distance (HIBD), accelerations (ACC), decelerations (DEC) and PlayerLoad (PL) were collected in absolute and relative values (normalized by playing time) using a local positioning system (WIMU PRO, Realtrack Systems S.L., Almería, Spain). HSR, HSR/min and HIBD/min decreased during the second half ($p < 0.05$; small effects). Regarding the level of the opponent, high-level and middle-level teams elicited higher TDC/min, HIBD/min and PL/min than low-level teams ($p < 0.05$; small-moderate effects). Additionally, starter players exhibited higher absolute values of external load (TDC, HSR, HIBD, ACC, DEC and PL) compared to non-starters ($p < 0.05$; moderate-large effects). Match outcome did not affect the physical demands ($p > 0.05$). The study indicated that halves of the match, level of the opponent, and player role influenced external load experienced by players during official matches; specifically, starter players showed higher absolute values of external load compared to non-starters. This information should be considered in managing load and developing strategies to minimize fatigue and enhance performance during matches.

CITATION: García-Sánchez C, Manuel Navarro R, Mon-López D et al. Do all matches require the same effort? Influence of contextual factors on physical demands during official female handball competitions Biol Sport. 2024;41(4):145–154.

Received: 2023-10-31; Reviewed: 2023-12-05; Re-submitted: 2023-12-19; Accepted: 2024-03-04; Published: 2024-04-25.

Corresponding author:
Carlos García-Sánchez
Deporte y Entrenamiento Research Group, Departamento de Deportes, Facultad de Ciencias de la Actividad Física y del Deporte (INEF), Universidad Politécnica de Madrid, Spain
E-mail: c.gsanchez@upm.es

ORCID:
Carlos García-Sánchez
0000-0002-7112-3636

Rafael Manuel Navarro
0000-0003-3135-7769

Daniel Mon-López
0000-0001-8333-1304

Raúl Nieto-Acevedo
0000-0001-9509-6401

Enrique Cañadas-García
0009-0002-2979-7343

Alfonso de la Rubia
0000-0001-5249-1399

Key words:
tracking system
external load
load monitoring
local positioning sytem
ultra-wideband technology

INTRODUCTION

Success in handball is based on the ability to score more goals than the opponent at the end of two thirty-minute periods. Thus, determining and analysing performance factors is highly recommended to achieve victory [1]. Current literature indicates that handball performance is complex and multifactorial [1]. Consequently, player performance is the product of optimal integration and synergy of various attributes (e.g., health, technical and tactical skills, bioenergetics and neuromuscular abilities and capacities, anthropometric characteristics, and cognitive and psychosocial characteristics) [2, 3]. Therefore, individual performance is more strongly dependent on the interaction between a wide range of factors than on the maximum enhancement of one or two factors alone [3].

From a physical and physiological perspective, handball is considered an intermittent team sport characterized by long periods of low-intensity movements interrupted by short intervals of high-intensity actions with frequent and intense body contact against the opponents [2, 4]. During these high-intensity periods, players must perform different fundamental movement patterns (accelerations, decelerations, changes of direction, sprints and jumps) and handball-specific actions (passes, catches, throws and blocks) [2, 4]. Therefore, understanding the physical and mechanical demands during matches is essential to maximize performance, manage stress and recovery, and reduce injury risk [2, 4].

The investigation of the physical demands in handball has been developed by the analysis of the external and internal load [2, 5]. External load can be defined as the locomotor activities performed by players, which can be measured with standard units, such as kilograms, meters, seconds, velocity/speed, and power [6]. On the other hand, internal load refers to the individual psycho-physiological responses to the external load, which can be measured as heart rate, blood lactate, rating of perceived exertion, or biochemical and molecular responses [6]. In handball, the analysis of physical demands during official competitions has been done mainly through the external load assessment because internal load monitoring

presents some practical limitations (e.g. blood sampling during matches) [7].

Traditionally, in handball, researchers have mostly used time–motion analysis to measure external load during training [8] and competition [9]. However, the emergence of new monitoring tools with a good level of validity [10, 11] and reliability [12], such as local positioning system (LPS) with ultra-wideband (UWB) technology or inertial measurement units (IMU) (e.g., accelerometer, magnetometer and gyroscope), has provided a precise and accurate understanding of the physical demands in male [13, 14] and female handball [15, 16]. Given these technological advances, García-Sánchez et al. [17] demonstrated that physical demands greatly depend on gender, competition level and playing positions. Nevertheless, as indicated by some researchers, few studies have examined the impact of the contextual factors on physical demands in handball [13, 14, 17].

Recent research carried out in other team sports (e.g. basketball, soccer or ice hockey) has revealed that physical demands are strongly influenced by contextual factors, such as match location (playing home or away) [18, 19], halves of the match (first half or second half) [19, 20], level of the opponent (high-level teams, intermediate-level teams or low-level teams) [18, 19, 20], match outcome (win, draw or loss) [18, 21], score differential (balanced or unbalanced matches) [22, 23] and player role (starter or non-starter) [24]. In handball, a recent systematic review [17] on external load during official elite competitions showed that only five studies have investigated the impact of halves of the match on external load outcomes. Some of these studies found that the time spent in high-intensity running during the match decreased in the second half [25–27]. Additionally, the total distance covered in the first ten minutes was slightly higher than that covered in the last ten minutes of the game [9]. Similarly, initial values of PlayerLoad/min declined throughout the halves [16]. Moreover, a new study conducted with four LIQUI-MOLY Handball-Bundesliga teams across three seasons showed that time spent at very-high speed and very-high metabolic power decreased from the first to second half [28].

However, evidence-based knowledge about the influence of contextual factors on external load during official matches in female handball is currently limited. Thus, the aim of the present study was to explore and compare the influence of contextual factors (i.e., halves of the match, level of the opponent, match outcome and player role) on physical demands during official matches in female handball players.

MATERIALS AND METHODS

Experimental approach to the problem

We conducted a retrospective observational design to determine the influence of contextual factors on physical demands in female handball players. LPS data collected correspond to the average values of 13 official home matches from the Spanish 2nd Division during the 2021–2022 season (September-April). Players who participated for at least 1 min in each game were included in the study [15]. Goalkeepers were excluded from the analysis because running-based demands do not reflect their performance needs [29].

Participants

Twenty-two female handball players from the same team (age: 20.5 ± 3.1 years; height: 168.0 ± 4.8 cm; and body mass: 66.1 ± 10.1 kg) participated voluntarily in this study. The players belong to the third tier of competition (highly trained or national level), according to the Participant Classification Framework provided by McKay et al. [30]. During the season, players typically performed four handball training sessions and two strength training sessions per week. Also, they participated regularly in one match per week. All players were informed of the study requirements and provided written informed consent prior to the start of the study. Additionally, all the ethical procedures used in this study were in accordance with the Declaration of Helsinki and were approved by the Ethics Committee of the European University of Madrid.

Procedures and data analysis

The LPS system (WIMU PRO, Realtrack Systems SL, Almería, Spain) was installed on the official handball court where the team played their home matches according to the user manual and previous studies [13, 14]. Each player was fitted with a device on his back with an adjustable vest. Playing time was recorded only when the players were inside the court. Thereby, the manufacturer's specific software (SPRO, version 958, Realtrack Systems SL, Almería, Spain) was used to calculate the perimeter of the court to determine the effective playing time. Thus, team time-outs (a maximum of three per team), periods when the game was interrupted (e.g., consultations between the referees or interruption to wipe the court) and the 2-minute suspension were omitted. During match play, all players were continuously monitored in real time. Subsequently, the individual LPS registers were exported to external memory and analysed using the manufacturer's specific software. Finally, raw data were exported in Excel format and imported into the statistical software for statistical analysis.

Contextual factors and external load variables

Four contextual factors were considered: (1) halves of the match (first half vs. second half); (2) level of the opponent – considering the final ranking of each team at the end of the competition [18] we established three tiers: 'high-level teams' (HLT) (1st to 5th place), 'middle-level teams' (MLT) (6th to 10th place), and 'low-level teams' (LLT) (11th to 14th place); (3) match outcome (win, draw or loss); (4) player role (starters vs. non-starters), considering the field players who start the match as starters and the rest of the players as non-starters. The number of matches and individual LPS registers for each contextual factor are shown in Table 1.

In addition, a detailed description of the external load variables collected (distance, accelerometry and PlayerLoad) is shown in Table 2.

TABLE 1. Number of matches and individual LPS registers for each contextual factor.

Contextual factor	Variable	Matches	LPS registers
Halves of the match	First half	13	139
	Second half	13	133
Level of the opponent	High-level teams	4	50
	Middle-level teams	5	56
	Low-level teams	4	47
Match outcome	Win	9	107
	Loss	4	46
Player role	Starter	13	89
	Non-starter	13	64

TABLE 2. Description of external load variables.

Variable	Unit	Description
Effective playing time	h:mm:ss	Time player spent on the court (within court limits)
Total distance covered (TDC)	m	Total distance covered by the player
Total distance covered/min (TDC/min)	$m \cdot min^{-1}$	Total distance covered per minute by the player
High speed running (HSR)	m	Total distance covered above 18.1 km/h
High speed running/min (HSR/min)	$m \cdot min^{-1}$	Total distance covered per minute above 18.1 km/h
High intensity break distance (HIBD)	m	Total distance covered with deceleration above 2 $m \cdot s^{-2}$
High intensity break distance/min (HIBD/min)	$m \cdot min^{-1}$	Total distance covered per minute with deceleration above 2 $m \cdot s^{-2}$
Accelerations (ACC)	count	Total number of accelerations performed by the player
Accelerations/min	$count \cdot min^{-1}$	Total number of accelerations per minute performed by the player
Decelerations (DEC)	count	Total number of decelerations performed by player
Decelerations/min	$count \cdot min^{-1}$	Total number of decelerations per minute performed by player
PlayerLoad (PL)	a.u.	Is a vector magnitude expressed as the square root of the sum of the squared instantaneous rates of change in acceleration in each one of the three planes divided by 100
PlayerLoad/min (PL/min)	$a.u. \cdot min^{-1}$	Is a vector magnitude expressed as the square root of the sum of the squared instantaneous rates of change in acceleration in each one of the three planes divided by 100 per minute

Statistical analysis

Descriptive statistics are presented as means and standard deviations (M ± SD). The level of significance was set at $p < 0.05$. Before carrying out the analyses, the Kolmogorov-Smirnov test was performed to confirm data distribution normality and Levene's test for equality of variances. Differences between halves of the match were determined by the independent T-test (parametric variables) or Mann-Whitney U test (non-parametric variables). Level of the opponent differences were determined by one-way analysis of variance (ANOVA) followed by Games–Howell or Tukey post hoc testing (parametric variables), or the Kruskal-Wallis test followed by the Dwass-Steel-Critchlow-Fligner test (non-parametric variables). Differences according to player role and match outcome were evaluated through mixed two-way ANOVA followed by the Bonferroni post-hoc test (starter vs. non starter as repeated measure, and win vs. loss as independent measure). Furthermore, partial eta-squared (ηp^2) or epsilon-squared (ε^2) was calculated for group effects with the following interpretation: > 0.01 *small*, > 0.06 *moderate*, and > 0.14 *large* [31]. For the post-hoc analysis, Cohen's d (ES) was calculated and interpreted using Hopkins' categorization criteria: $d > 0.2$ as *small*, $d > 0.6$ as *moderate* $d > 1.2$ as *large*, and $d > 2.0$ as *very large* [32]. Data analysis was performed using SPSS for Windows (Version 26, IBM Corp., Armonk, NY, USA).

RESULTS

Halves of the match

There were significant differences between halves of the match with small effect sizes in HSR (p = 0.002, ES = 0.22), HSR/minute (p = 0.001, ES = 0.36) and HIBD/minute (p = 0.046, ES = 0.20) (Figure 1). HSR and HSR/minute distance were slightly higher during the first (124.25 ± 130.41 m; 7.19 ± 5.47 m · min^{-1}, respectively) than the second half (96.74 ± 118.99 m; 5.33 ± 4.78 m · min^{-1}, respectively) (p < 0.01, ES: 0.22; p < 0.01, ES: 0.36). Also, HIBD/minute distance was slightly higher during the first (3.41 ± 1.99 m · min^{-1}) than the second half (3.01 ± 1.95 m · min^{-1}) (p < 0.05, ES: 0.20). No significant differences in the rest of the external load variables were found (p > 0.05).

Level of the opponent

There were significant differences according to level of the opponent with a moderate to large effect size in TDC/min (p = 0.033, ηp^2 = 0.444), HIBD/min (p < 0.001, ε^2 = 0.070) and PL/min (p < 0.001, ε^2 = 0.116) (Figure 2). TDC/min was slightly higher

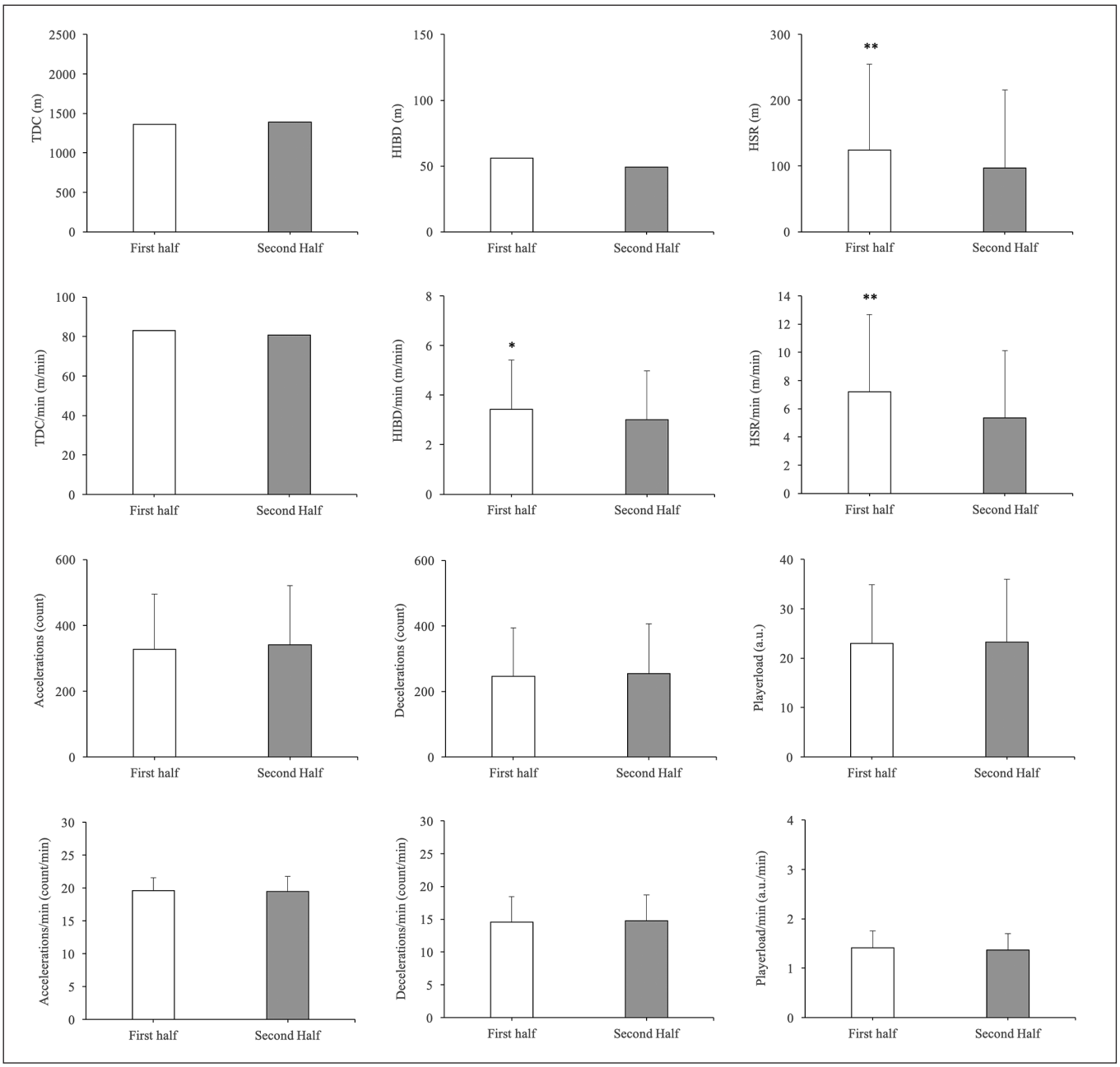


FIG. 1. Influence of halves of the match on external load variables. Significance level between first and second half = *p < 0.05; **p < 0.01; ***p < 0.001.

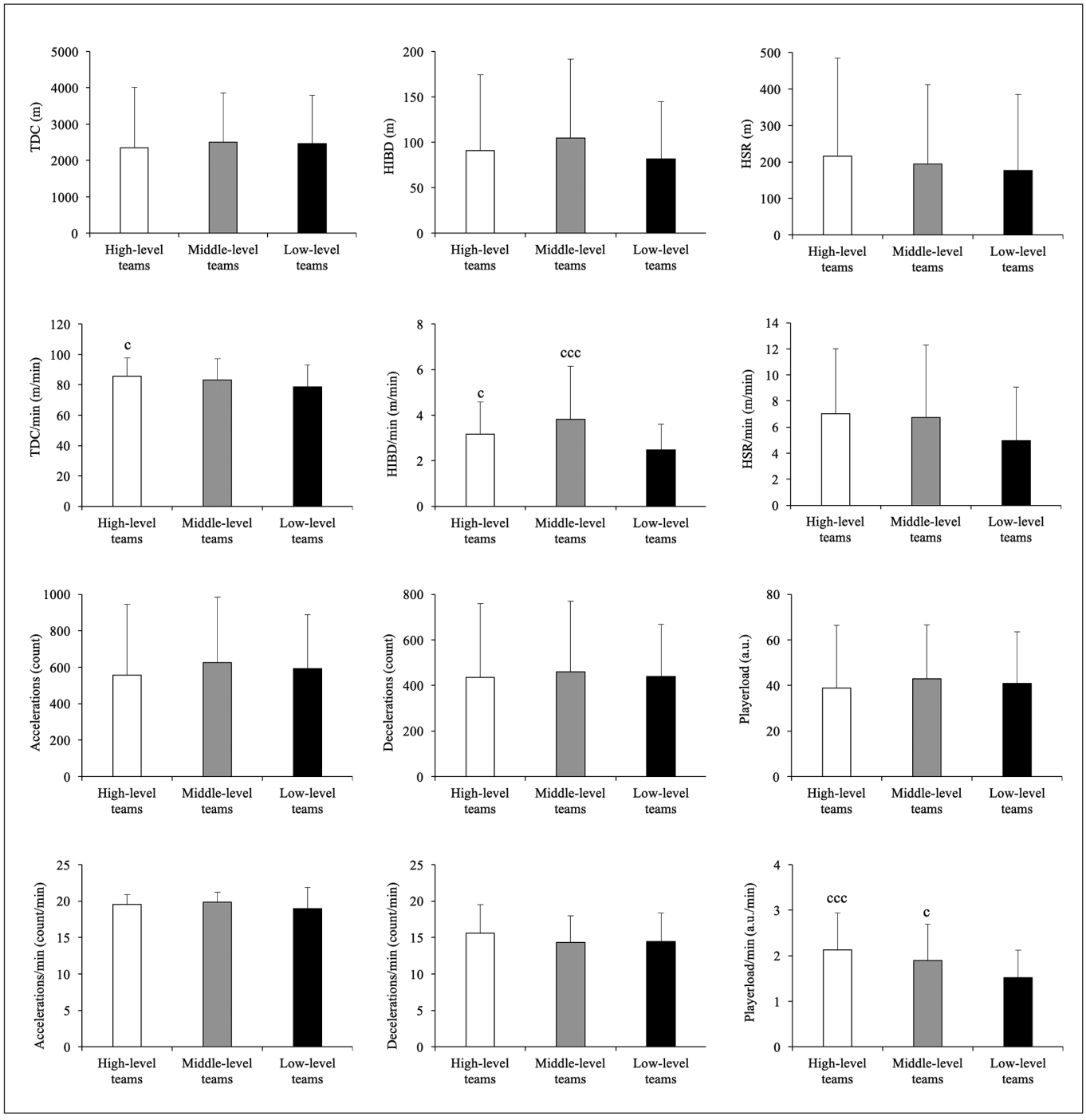


FIG. 2. Influence of level of the opponent on external load variables. Significance level is indicated by the number of symbols: one symbol for $p < 0.05$, two for $p < 0.01$, and three for $p < 0.001$. [a] indicates significant differences vs. high-level teams, [b] indicates significant differences vs. middle-level teams and [c] indicates significant differences vs. low-level teams.

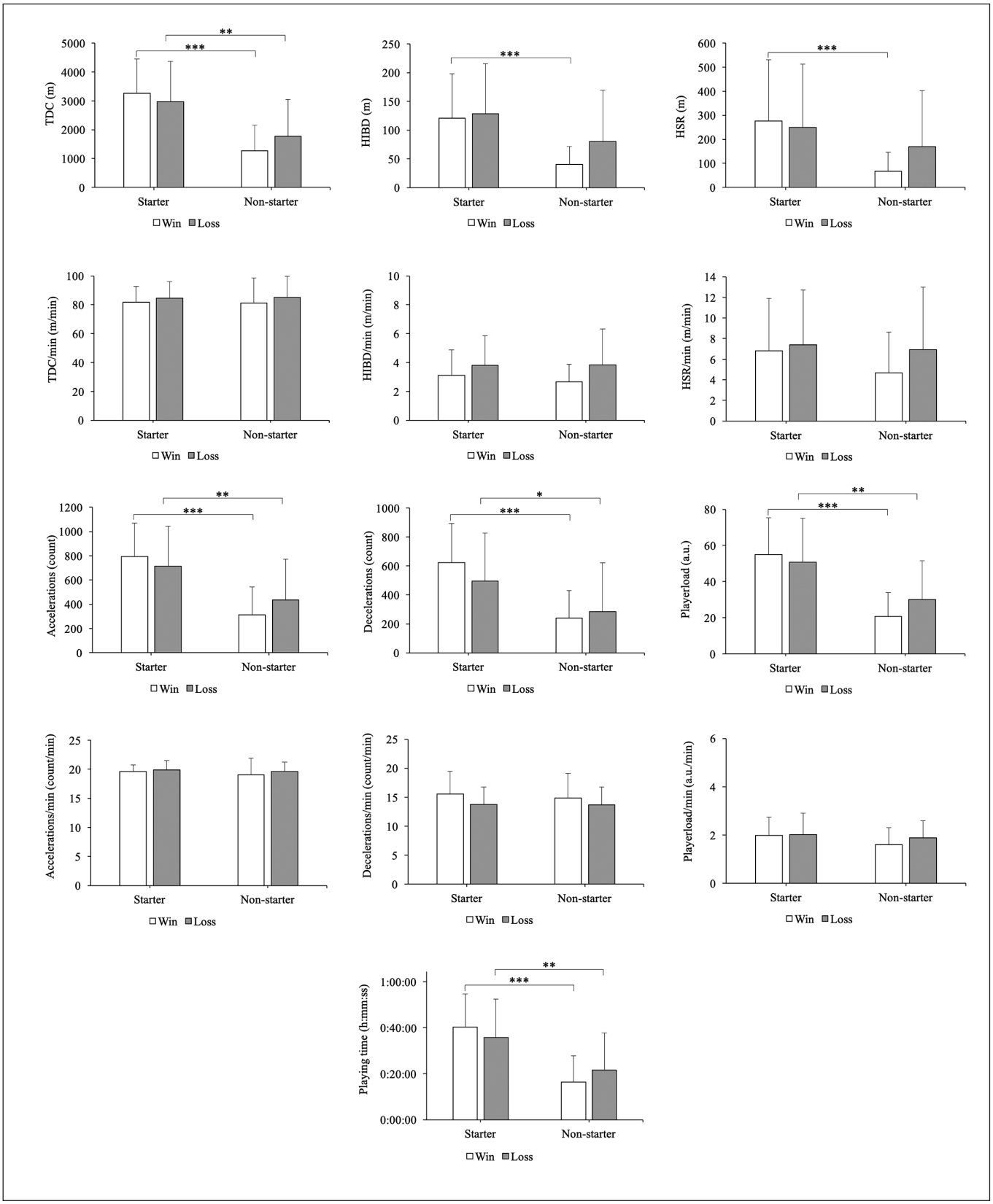


FIG 3. Influence of match outcome and player role on external load variables. Significance level is indicated by the number of symbols: one symbol for $p < 0.05$, two for $p < 0.01$, and three for $p < 0.001$. * indicates significant differences between starters and non-starters.

in matches involving HLT (85.55 ± 12.25 m·min−1) compared to matches with LLT (78.48 ± 14.36 m·min^{-1}) ($p < 0.05$, ES: 0.51). Also, HIBD/min distance was moderately higher in matches involving HLT (3.16 ± 1.41 m·min^{-1}) and MLT (3.96 ± 2.38 m·min^{-1}) compared to LLT (2.46 ± 1.13 m·min^{-1}) ($p < 0.05$, ES = 0.39; $p < 0.001$, ES = 0.84, respectively). Additionally, matches involving HLT (2.13 ± 0.80 arbitrary units (a.u.)·min^{-1}) and MLT (1.93 ± 0.82 a.u.·min^{-1}) registered moderately more PL/min compared to LLT (1.51 ± 0.60 a.u.·min^{-1}) ($p < 0.001$, ES = 0.81; $p < 0.05$, ES = 0.55, respectively).

Player role and match outcome

There were significant differences between starter and non-starter players with a moderate to large effect size in playing time ($p < 0.001$, $\eta p^2 = 0.270$), TDC ($p < 0.001$, $\eta p^2 = 0.283$), HSR ($p < 0.001$, $\eta p^2 = 0.085$), HIBD ($p < 0.001$, $\eta p^2 = 0.146$), ACC ($p < 0.001$, $\eta p^2 = 0.273$), DEC ($p < 0.001$, $\eta p^2 = 0.242$) and PL ($p < 0.001$, $\eta p^2 = 0.292$) (Figure 3). In terms of player role, starters registered, with a moderate to large effect size, more playing time than non-starters in both winning (+24.1 min, $p < 0.001$, ES = 1.68) and losing conditions (+14.1 min, $p = 0.007$, ES = 0.98). Likewise, starters evidenced a moderate to large increase in TDC compared to non-starters in both winning (+1990.43 m, $p < 0.001$, ES = 1.71) and losing conditions (+1203.99 m, $p = 0.004$, ES = 1.04). In addition, starters performed, with a moderate to large effect size, more ACC, DEC and PL than non-starters in both winning (+479.75, $p < 0.001$, ES = 1.70; +382.83, $p < 0.001$, ES = 1.60; +34.27 a.u., $p < 0.001$, ES = 1.75, respectively) and losing conditions (+277.53 m, $p = 0.007$, ES = 0.98; +210.92, $p = 0.021$, ES = 0.88; +20.72 a.u., $p < 0.05$, ES = 1.06, respectively). Lastly, starters covered moderately more HSR and HIBD distance than non-starters in the win matches (+207.94 m; $p < 0.001$, ES = 0.96; +80.11 m, $p < 0.001$, ES = 1.13, respectively). In contrast, the comparative analysis according to match outcome (win vs. loss) dis not reveal significant differences in external load variables ($p > 0.05$). Furthermore, no significant interaction effect (player role vs. match outcome) was found in any external load variables ($p > 0.05$).

DISCUSSION

The aim of this study was to explore and compare the external load measured during official matches according to halves of the match (first vs. second), level of the opponent (HLT vs. MLT vs. LLT), match outcome (win vs. loss) and player role (starter vs. non-starter) in semi-professional female handball. The main findings indicated that: (1) there were significant decreases from the first to the second half in high-intensity distance variables (HSR and HIBD); (2) HLT elicited higher TDC/min, HIBD/min and PL/min (moderate to large effect) than LLT; (3) starters exhibited higher absolute values of external load (moderate to large effect) compared to non-starters; (4) there were no significant differences in the external load between win and loss matches.

Regarding halves of the match, there was a significant decrease with small effect sizes in HSR, HSR/min and HIBD/min in the second half. In this regard, other studies carried out with elite male and female handball players have demonstrated that the time spent in high-intensity running [25–28] and the values of PL/min decreased in the second half [16]. Similar results were found in basketball, where high-intensity variables studied during the first quarter were higher than in all other quarters [20], and in soccer, where external load was higher during the first half than the second half [19]. There are many factors contributing to the decline in HSR, HSR/min and HIBD/min. First, it is well documented that repeated high-intensity actions (associated with intense eccentric contractions) and received multiple collisions and contacts during the match may produce fatigue, tissue damage and inflammatory responses, and impair neuromuscular performance [33, 34]. In addition to fatigue mechanisms, the decline in HSR, HSR/min and HIBD/min may be related to contextual factors such as score differential (balance vs. unbalance matches) [22, 23] or tactical strategies (e.g. different defensive systems or pacing strategies) [13]. Therefore, handball coaches should incorporate four types of interventions to minimize the occurrence of fatigue during the match: (1) increase player rotations to avoid excessive physiological load [9, 13, 15]; (2) improve basic (aerobic) and specific endurance to repeat high-intensity actions [1, 2]; (3) increase the capacity of muscles and tendons to attenuate efficiently high braking eccentric forces [34, 35]; (4) include half-time strategies (e.g. rehydrate, re-fuel, ergogenic aids, heat maintenance, re-warm up) to increase second-half performance [36].

Findings from the present study also showed that HLT elicited higher TDC/min, HIBD/min and PL/min than LLT. This difference may be explained by the faster play and the higher number of fast breaks performed by HLT compared to LLT [37, 38]. Similarly, previous studies with other modalities (e.g. soccer) have observed that the distance covered at high-intensity running was greater in matches against HLT [39, 40]. Consequently, players must be physically well prepared (i.e., strength and endurance) to play against HLT. Therefore, our findings suggest that handball coaches should design and implement three types of interventions against HLT: (1) develop a substitutions strategy to ensure that players perform at high intensity during the entire match [9, 13, 15]; (2) adapt or reduce training load days prior to the competition to avoid excessive fatigue and ensure optimal player readiness (micro-tapering) [41]; (3) incorporate some priming strategies to elicit a delayed potentiation (e.g. traditional strength exercises performed with low volume, high load and maximal intended velocity) [42, 43] or nutrition and supplementation practices (e.g. caffeine intake) [41] to enhance neuromuscular performance during a match.

Although unlimited substitutions are allowed in handball, our study revealed that starters accumulate more TDC, HSR, HIBD, ACC, DEC and PL than non-starters. Nevertheless, when these values were normalized according to the effective playing time (n·min^{-1}), the differences in external load between starters and non-starters

disappeared. It is difficult to compare the findings of the present study with previous research because there is a lack of scientific evidence comparing differences in external load between starters and non-starters in handball. However, we found similar results in soccer, where external load was higher in players from the starting lineups [44]. Thus, our results could be explained in part by the higher playing time for starters, due to the fact that there is a direct relationship between time on court and external load (in absolute values) accumulated by players. Several inferences can be drawn from our findings: (1) if we want to compare better the external load registered by starters and non-starters, we should use normalized values according to playing time; (2) the coach's decisions (game plan and substitutions) have a direct impact on the external load that the players accumulated. Therefore, it could be expected that proper management of substitutions can contribute to a better load distribution among all players in order to minimize the occurrence of fatigue during the match, reduce injury risk, improve post-match recovery and increase player availability during match-congested schedules [3]. Also, as in other team sports (e.g. soccer and basketball), handball staff should consider the different absolute external load accumulated by starters and non-starters to better prescribe the training load across the microcycle [24, 45]. For example, practitioners should balance the chronic workload of non-starters who only play "junk minutes" [45] with compensatory training interventions during the microcycle.

Regarding match outcome, there are no significant differences in the external load between win and loss matches. These results are consistent with a previous study [46] confirming that there were no differences between winners and losers in the total distance covered and running pace during the matches. In the same line, a recent study conducted with four LIQUI-MOLY Handball-Bundesliga teams across three seasons reported that winning teams did not differ from drawing teams in terms of high-intensity running actions [28].

Some limitations should be considered when interpreting the current findings. First, external load was monitored only during thirteen official home matches. Accordingly, it should be noted that some variables could have influenced our results, such as match location (away matches were not monitored) and score differential (balance vs. unbalance matches). Second, a very particular sample (i.e., a Spanish 2nd Division team) and not particularly large (n = 22) was used. Thirdly, our results did not differentiate playing position and attacking or defensive specialist players. Lastly, as it was an observational study, player rotations could not be controlled or influenced by researchers. Thus, coaches and practitioners should generalize and extrapolate the results with caution. In this regard, future research should include a larger number of teams and different levels of competition.

CONCLUSIONS

The present study indicates that the physical demands of semi-professional female players are influenced by halves of the match, level of the opponent and player role. However, match outcome does not affect the physical demands. Specifically, HSR, HSR/min and HIBD/min decreased during the second half. Regarding the level of the opponent, high-level teams elicited higher TDC/min, HIBD/min and PL/min than low-level teams. Additionally, starter players exhibited higher absolute values of external load compared to non-starters. Consequently, handball coaches should incorporate different interventions (e.g. player rotations) to minimize the occurrence of fatigue during the second halves of matches. Likewise, they should include several strategies (e.g. priming resistance training or micro-tapering) to enhance neuromuscular performance against high-level teams. Lastly, they should consider the different absolute external load experienced by starters and non-starters to better prescribe the training load across the microcycle.

Acknowledgements

We wish to thank the Faculty of Physical Activity and Sport Sciences (INEF) and the Universidad Politécnica de Madrid (UPM) for their support. Also, we wish to thank the players who participated in this study.

Conflict of Interest

The authors declare no conflict of interest.

REFERENCES

1. Wagner H, Finkenzeller T, Würth S, von Duvillard S.P. Individual and team performance in team-handball: A review. J. Sports Sci. Med. 2014; 13(4):808–816.
2. Manchado C, Tortosa-Martínez J, Vila H, Ferragut C, Platen P. Performance factors in women's team handball: physical and physiological aspects--a review. J Strength Cond Res. 2013; 27(6):1708–1719. doi: 10.1519/JSC.0b013e3182891535.
3. Calleja-González J, Mallo J, Cos F, et al. A commentary of factors related to player availability and its influence on performance in elite team sports. Front Sports Act Living. 2023; 4:1077934. doi: 10.3389/fspor.2022.1077934.
4. Karcher C, Buchheit M. On-court demands of elite handball, with special reference to playing positions. Sports Med. 2014; 44(6):797–814. doi: 10.1007/s40279-014-0164-z.
5. Corvino M, Tessitore A, Minganti C, Sibila M. Effect of Court Dimensions on Players' External and Internal Load during Small-Sided Handball Games. J Sports Sci Med. 2014; 13(2):297–303.
6. Boullosa D, Claudino JG, Fernandez-Fernandez J, et al. The Fine-Tuning Approach for Training Monitoring [published online ahead of print, 2023 Sep 9]. Int J Sports Physiol Perform. 2023; 1–6. doi: 10.1123/ijspp.2023-0154.
7. Torres-Ronda L, Beanland E, Whitehead S, Sweeting A, Clubb J. Tracking Systems in Team Sports: A Narrative Review of Applications of the Data and Sport Specific Analysis. Sports Med Open. 2022; 8(1):15. doi: 10.1186/s40798-022-00408-z.
8. Bělka J, Hulka, K, Safar M, Duskova L, Weisser R, Riedel, V. Time-motion analysis and physiological responses of small-sided team handball games in

youth male players: Influence of player number. Acta Gymn. 2016; 46.
9. Cardinale M, Whiteley R, Hosny AA, Popovic N. Activity Profiles and Positional Differences of Handball Players During the World Championships in Qatar 2015. Int J Sports Physiol Perform. 2017; 12(7):908–915. doi: 10.1123/ijspp.2016-0314.
10. Bastida-Castillo A, Gómez-Carmona CD, De la Cruz-Sánchez, E, Reche-Royo X, Ibáñez SJ, Pino-Ortega J. Accuracy and inter-unit reliability of ultra-wide-band tracking system in indoor exercise. App Sci. 2019; 9(939):1–11.
11. Fleureau A, Lacome M, Buchheit M, Couturier A, Rabita G. Validity of an ultra-wideband local positioning system to assess specific movements in handball. Biol Sport. 2020; 37(4):351–357. doi: 10.5114/biolsport.2020.96850.
12. Luteberget LS, Holme BR, Spencer M. Reliability of Wearable Inertial Measurement Units to Measure Physical Activity in Team Handball. Int J Sports Physiol Perform. 2018; 13(4):467–473. doi: 10.1123/ijspp.2017-0036.
13. Font Ribas R, Karcher C, Reche X, Carmona G, Tremps V, Irurtia A. Monitoring external load in elite male handball players depending on playing positions. Biol Sport. 2021; 38(3):3–9. doi: 10.5114/biolsport.2021.101123.
14. Font Ribas R, Karcher C, Loscos-Fàbregas E, et al. The effect of training schedule and playing positions on training loads and game demands in professional handball players. Biol Sport. 2023; 40(3):857–866. doi: 10.5114/biolsport.2023.121323.
15. Wik EH, Luteberget LS, Spencer M. Activity profiles in international women's team handball using PlayerLoad. Int J Sports Physiol Perform. 2017; 12(7):934–42. doi: 10.1123/ijspp.2015-0732.
16. Luteberget LS, Spencer M. High-Intensity Events in International Women's Team Handball Matches. Int J Sports Physiol Perform. 2017; 12(1):56–61. doi: 10.1123/ijspp.2015-0641.
17. García-Sánchez C, Navarro RM, Karcher C, de la Rubia A. Physical Demands during Official Competitions in Elite Handball: A Systematic Review. Int J Environ Res Public Health. 2023; 20(4):3353. doi: 10.3390/ijerph20043353.
18. Augusto D, Brito J, Aquino R, et al. Contextual Variables Affect Running Performance in Professional Soccer Players: A Brief Report. Front Sports Act Living. 2021; 3:778813. doi: 10.3389/fspor.2021.778813.
19. García-Unanue J, Pérez-Gómez J, Giménez JV, et al. Influence of contextual variables and the pressure to keep category on physical match performance in soccer players. PLoS One. 2018; 13(9):e0204256. doi: 10.1371/journal.pone.0204256.
20. Pino-Ortega J, Rojas-Valverde D, Gómez-Carmona CD, et al. Impact of Contextual Factors on External Load During a Congested-Fixture Tournament in Elite U'18 Basketball Players. Front Psychol. 2019; 10:1100. doi: 10.3389/fpsyg.2019.01100.
21. Douglas A, Johnston K, Baker J, Rotondi MA, Jamnik VK, Macpherson AK. On-Ice Measures of External Load in Relation to Match Outcome in Elite Female Ice Hockey. Sports (Basel). 2019; 7(7):173. doi: 10.3390/sports7070173.
22. Alonso Pérez-Chao E, Gómez MÁ, Scanlan A, Ribas C, Trapero J, Lorenzo A. Influence of game and quarter results on external peak demands during games in under-18 years, male basketball players. Biol Sport. 2023; 40(2):365–375. doi: 10.5114/biolsport.2023.116010.
23. Fox JL, Stanton R, Sargent C, O'Grady CJ, Scanlan AT. The Impact of Contextual Factors on Game Demands in Starting, Semiprofessional, Male Basketball Players. Int J Sports Physiol Perform. 2019; 1–7. doi: 10.1123/ijspp.2019-0203.
24. Oliveira R, Canário-Lemos R, Morgans R, Rafael-Moreira T, Vilaça-Alves J, Paulo Brito J. Are non-starters accumulating enough load compared with starters? Examining load, wellness, and training/match ratios of a European professional soccer team. BMC Sports Sci Med Rehabil 15, 129 (2023). https://doi.org/10.1186/s13102-023-00743-y.
25. Michalsik LB, Aagaard P, Madsen K. Locomotion characteristics and match-induced impairments in physical performance in male elite team handball players. Int J Sports Med. 2013; 34(7):590–599. doi: 10.1055/s-0032-1329989.
26. Michalsik LB, Madsen K, Aagaard P. Match performance and physiological capacity of female elite team handball players. Int J Sports Med. 2014; 35(7):595–607. doi: 10.1055/s-0033-1358713.
27. Póvoas SC, Seabra AF, Ascensão AA, Magalhães J, Soares JM, Rebelo AN. Physical and physiological demands of elite team handball. J Strength Cond Res. 2012; 26(12):3365–3375. doi: 10.1519/JSC.0b013e318248aeee.
28. Saal C, Baumgart C, Wegener F, Ackermann N, Sölter F, Hoppe MW. Physical match demands of four LIQUI-MOLY Handball-Bundesliga teams from 2019–2022: effects of season, team, match outcome, playing position, and halftime. Front Sports Act Living. 2023; 5:1183881. doi: 10.3389/fspor.2023.1183881.
29. Ortega-Becerra M, Belloso-Vergara A, Pareja-Blanco F. Physical and Physiological Demands During Handball Matches in Male Adolescent Players. J Hum Kinet. 2020; 72:253–263. doi: 10.2478/hukin-2019-0111.
30. McKay AKA, Stellingwerff T, Smith ES, et al. Defining Training and Performance Caliber: A Participant Classification Framework. Int J Sports Physiol Perform. 2022; 17(2):317–331. doi: 10.1123/ijspp.2021-0451.
31. Cohen J. Statistical Power Analysis for the Behavioral Sciences. 2nd Ed. Hillsdale, NJ: Erlbaum. 1988.
32. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1):3–13.
33. Markus I, Constantini K, Hoffman JR, Bartolomei S, Gepner Y. Exercise-induced muscle damage: mechanism, assessment and nutritional factors to accelerate recovery. Eur J Appl Physiol. 2021; 121(4):969–992. doi: 10.1007/s00421-020-04566-4.
34. Harper, D.J.; Carling, C.; Kiely, J. High-Intensity Acceleration and Deceleration Demands in Elite Team Sports Competitive Match Play: A Systematic Review and Meta-Analysis of Observational Studies. Sports Med. 2019, 49, 1923–1947. doi: 10.1007/s40279-019-01170-1.
35. Harper DJ, McBurnie AJ, Santos TD, et al. Biomechanical and Neuromuscular Performance Requirements of Horizontal Deceleration: A Review with Implications for Random Intermittent Multi-Directional Sports. Sports Med. 2022; 52(10):2321–2354. doi: 10.1007/s40279-022-01693-0.
36. Russell M, West DJ, Harper LD, Cook CJ, Kilduff LP. Half-time strategies to enhance second-half performance in team-sports players: a review and recommendations. Sports Med. 2015; 45(3):353–364. doi: 10.1007/s40279-014-0297-0.
37. Hatzimanouil D, Lola A, Giatsis G, Skandalis V. The Effect of the 'Fast Game' in Handball on the Final Ranking of Teams in Major International Competitions. Int. J. Instr. 2023; 16(4):247–262.
38. Milanović D, Vuleta D, Ohnjec K. Performance Indicators of Winning and Defeated Female Handball Teams in Matches of the 2012 Olympic Games Tournament. J Hum Kinet. 2018; 64:247–253. doi: 10.1515/hukin-2017-0198.
39. Rampinini E, Coutts AJ, Castagna C, Sassi R, Impellizzeri FM. Variation in top level soccer match performance. Int

J Sports Med. 2007; 28(12):1018–1024. doi: 10.1055 /s-2007-965158.
40. Folgado H, Duarte R, Fernandes O, Sampaio J. Competing with lower level opponents decreases intra-team movement synchronization and time-motion demands during pre-season soccer matches [published correction appears in PLoS One. 2015; 10(3):e0120461]. PLoS One. 2014; 9(5):e97145. doi: 10.1371/journal .pone.0097145.
41. Mujika I, Halson S, Burke LM, Balagué G, Farrow D. An Integrated, Multifactorial Approach to Periodization for Optimal Performance in Individual and Team Sports. Int J Sports Physiol Perform. 2018; 13(5):538–561. doi: 10.1123/ijspp.2018-0093.
42. Mason B, McKune A, Pumpa K, Ball N. The Use of Acute Exercise Interventions as Game Day Priming Strategies to Improve Physical Performance and Athlete Readiness in Team-Sport Athletes: A Systematic Review. Sports Med. 2020; 50(11):1943–1962. doi: 10.1007/s40279-020-01329-1.
43. Harrison PW, James LP, McGuigan MR, Jenkins DG, Kelly VG. Resistance Priming to Enhance Neuromuscular Performance in Sport: Evidence, Potential Mechanisms and Directions for Future Research. Sports Med. 2019; 49(10):1499–1514. doi: 10.1007/s40279-019-01136-3.
44. Dalen T, Lorås H. Monitoring Training and Match Physical Load in Junior Soccer Players: Starters versus Substitutes. Sports (Basel). 2019; 7(3):70. doi: 10.3390/sports7030070.
45. Alonso Pérez-Chao E, Gómez MÁ, Lisboa P, Trapero J, Jiménez SL, Lorenzo A. Fluctuations in External Peak Demands Across Quarters During Basketball Games. Front Physiol. 2022; 13:868009. doi: 10.3389/fphys .2022.868009.
46. Manchado C, Pueo B, Chirosa-Rios LJ, Tortosa-Martínez J. Time-Motion Analysis by Playing Positions of Male Handball Players during the European Championship 2020. Int J Environ Res Public Health. 2021; 18(6):2787. Published 2021 Mar 10. doi: 10.3390 /ijerph18062787.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.133668
© Institute of Sport – National Research Institute

Weekly external load distribution in football teams of different competitive levels

AUTHORS: Diogo Coutinho[1,2], Diogo Oliveira[1], Pedro Lisboa[3], Fábio Campos[4], Fábio Yuzo Nakamura[1,2], Jorge Baptista[1,2], Eduardo Abade[2,5,6]

[1] Department of Sports Sciences and Physical Education, University of Maia, Maia, Portugal
[2] Research Center in Sports Sciences, Health Sciences and Human Development, CIDESD, 5000-801 Vila Real, Portugal
[3] Catapult Sports, Melbourne, Australia
[4] Performance Department, Futebol clube Famalicão SAD, Vila Nova de Famalicão, Braga, Portugal
[5] Portugal Football School, Portuguese Football Federation, Oeiras, Portugal.
[6] Department of Sports Sciences, Exercise and Health, University of Trás-os-Montes and Alto Douro, Vila Real, Portugal

Corresponding author:
Diogo Coutinho
Research Center in Sports Sciences, Health Sciences and Human Development
CIDESD, University of Maia
Av. Carlos Oliveira Campos – Castelo da Maia, 4475-690 Maia, Portugal
Tel.: +351918232787
E-mail: diogoamcoutinho@gmail.com

ORCID:
Diogo Coutinho
0000-0001-6605-9505

Fábio Nakamura
0000-0002-5336-3652

Jorge Baptista
0000-0002-3259-5550

Eduardo Abade
0000-0002-4766-896X

ABSTRACT: This study aimed to compare the microcycle load distribution between teams from different competitive levels. A total of 22 microcycles from one team of each competitive level (first division, 1st DIV, n = 32 players; second division, 2nd DIV, n = 23 players; third division, 3rd DIV, n = 23 players) were monitored using GPS (10 Hz, Catapult). During the match, a higher number of high accelerations (i.e., > 3 m/s, per min) were found in the 3rd DIV team compared to the 1st and 2nd DIV teams. On match day (MD) +1&+2, the 1st DIV team covered more total (per min, $p < 0.001$) and high-speed running distance (HSR per min, $p < 0.001$ and $p = 0.042$, respectively) than both the 2nd and 3rd DIV teams. The 2nd DIV team showed lower values in most distance-related variables (total distance covered per min, $p < 0.001$; running distance per min, $p < 0.001$; HSR per min, $p < 0.001$; and sprinting distance per min, $p < 0.001$) for both MD-4 and MD-3 compared to the 1st and 3rd DIV teams. In contrast, it showed higher sprinting distance per min ($p < 0.001$) on MD-2. In general, the 3rd DIV team showed higher values in the number of high accelerations (per min, $p < 0.001$) across all sessions. These results suggest that distance-related variables may be a priority when planning microcycles for the 1st DIV team, while accelerations are relevant for the 3rd DIV team. A higher emphasis on external load during MD-2 by the 2nd DIV team may explain the lower external loads across the microcycle.

CITATION: Coutinho D, Oliveira D, Lisboa P et al. Weekly external load distribution in football teams of different competitive levels. Biol Sport. 2024;41(4):155–164.

Received: 2023-08-04; Reviewed: 2023-08-26; Re-submitted: 2023-09-04; Accepted: 2024-04-05; Published: 2024-04-25.

Key words:
Periodization
Distance-related variables
Acceleration and deceleration
Training load
Time-motion analyses

INTRODUCTION

Designing appropriate short- and mid-term plans for elite players poses a challenge for the technical staff, as it requires development of players' collective movement abilities while adjusting training tasks to promote variations in the physical stimulus [1]. To address this, coaches have been using structured microcycles [2], which involve adopting similar weekly training session structures throughout the season, known as the match-day (MD) approach, but varying the target stimulus each day to ensure proper player development and recovery [3]. For instance, MD+1 or MD+2 is typically focused on recovering players who played more than 60 min in the previous match, while also simulating a similar period of activity for players with less playing time or no playing time [2]. During MD-4, coaches design agility, plyometric, and change-of-direction circuits, followed by rondos, sectorial tasks, and small-sided games (SSG) [3, 4] to target acceleration and deceleration patterns [5]. MD-3 emphasizes tasks that involve distance covered and distance covered at high speeds [3, 6], often employing large-sided games (LSG), collective sectorial tasks, and 11 v 11 conditioned games [2, 7]. As the upcoming game approaches, a tapering strategy is implemented, characterized by a decrease in external load [7, 8]. Consequently, MD-2 focuses on tasks that emphasize a number of sprints, combined with low-intensity activities to tactically prepare the team for the upcoming match [2, 4, 6]. Lastly, MD-1 typically has the lowest external load [9], incorporating rondos, reaction speed drills, and set pieces [2]. Despite this characterization of the microcycle structure, variations in external load may be expected when considering different training methodologies [3, 6], microcycles lengths [4, 10], contextual and cultural factors [11, 12], playing level and positional role [13].

Differences across playing levels have been extensively studied in youth players [14]. For instance, Coutinho et al. [15] compared MD+1, weekly sessions (excluding the first and last sessions of the

week), and MD-1 among under-15, under-17, and under-19 teams. They found that the under-17 team covered more total distance per minute during all sessions than their counterparts. Moreover, the technical focus on the under-15 team seemed to result in lower variation between training days, while the higher emphasis on tactical preparation by the under-19 team limited players' external load, particularly in the last session before the match. Similarly, a recent study compared an under-18 team with the corresponding senior team of the club and observed that the younger team performed more accelerations and decelerations in all training sessions [13]. Additionally, they covered more total distance during MD-4, MD-2, and MD-1, but displayed lower values of high-intensity and sprinting distance on MD-3 when compared to the senior team [13]. Although these studies have made valuable contributions, they primarily focus on the weekly load distribution in youth players. However, research exploring how senior teams from different playing levels manage their load distribution across the week is limited. From a scientific perspective, it is crucial to advance knowledge in this domain, particularly in relation to scouting and player selection from various competitive leagues. The inclusion of players from different leagues in higher-standard teams, and occasionally vice versa, raises important questions. Can a player from a lower-level league handle the external load expected in higher competitive levels? Additionally, it is essential to consider whether coaches from different competitive levels expose their players to training stimuli that can help them cope with the demands of matches. Understanding which external load may show more variability during the training week according to the competitive level will provide valuable insights into player development and performance. Consequently, the primary aim of this study is to characterize and identify differences in the weekly external load distribution among teams belonging to different playing levels. By shedding light on this aspect, this research aims to gain valuable insights to understand how teams of different competitive levels manage their training load distribution throughout the week.

MATERIALS AND METHODS

Experimental Approach to the Problem

This study intended to measure the differences in match and training sessions' external load across different competitive leagues within the same country during the 2022–2023 season. A total of twenty-two training microcycles (~7 microcycles per team, see Table 1) were collected from three teams (1st DIV, n = 1; 2nd DIV, n = 1 and 3rd DIV, n = 1). The teams from the 1st and 2nd DIV participated in three national competitions (League Competition, Portugal Cup and League Cup), while the team from the 3rd DIV participated in two national competitions (League Competition and Portugal Cup). While additional microcycles were collected (n = 2–3 per team), they were excluded as result of [5]: i) having less than 5 training days; ii) microcycles from congested fixtures; iii) having a day off between the match and MD-4; and iv) microcycles from weeks without any competitive fixture. In addition, individual training sessions focused on refining movement patterns, rehabilitation or recovery sessions were excluded from the analyses [8, 10]. All matches and sessions were monitored on natural grass pitches (i.e., length ~100 m × ~64 m), under similar weather conditions (i.e., all teams were located in a similar zone, maximum distance ~75 km) and similar time periods (i.e., training sessions collected within a period from 9.00 a.m. to 12.00 a.m., while matches were played from 2.00 p.m. to 6.00 p.m.). While the duration of training tasks included the warm-up, main phase and cool down, data from matches included only the match information.

Participants

A total of 78 professional outfield football players from Portugal Competitions during the 2022–2023 season participated in the present study (see Table 2, 1st DIV, n = 32 players; 2nd DIV, n = 23 players; 3rd DIV, n = 23 players). While additional players engaged in the team training microcycles and competitive matches, only the players that took part in the full session or match during the data collection were considered for the planned analyses [6, 10]. In addition, the goalkeepers were excluded due to their restricted positioning on the pitch and different nature of training sessions [9, 16]. The study protocol followed the recommendations of the Declaration of Helsinki; however, following previous guidelines regarding data collection in elite sports [17], ethics committee clearance was not required.

Procedures

Player's external load during each training session was monitored using portable 10 Hz Global Positioning System devices (GPS, Catapult, Vector S7, Catapult Sports, Melbourne, Australia). These units have been shown to be accurate in capturing players' external load variables [18, 19]. To guarantee higher data reliability, and reduce inter-unit error, each player was assigned with a specific GPS unit that was used during all data collections [20, 21]. The GPS data from training sessions and matches were then downloaded to the manufacturer's specific software (Catapult Openfield, version 3.10; Firmware 8.1).

The following variables were collected and expressed per minute [22–25]: total distance covered expressed in metres (m/min), distance covered while running (m/min, 14.4 $km \cdot h^{-1}$–19.7 $km \cdot h^{-1}$), high-speed running (HSR, m/min, > 19.8 $km \cdot h^{-1}$), sprinting distance (m/min, > 25.2 $km \cdot h^{-1}$), number of high accelerations (counts/min, > 3 m/s) and high decelerations (counts/min, > 3 m/s).

Statistical Analysis

All data were preliminary tested for outliers, homogeneity and assumptions of normality and distribution through the Kolmogorov-Smirnov test. Descriptive statistics in tables and figures were expressed as mean (M) and standard deviation (SD). Further, a linear mixed model was used to compare players' external load (i.e., total distance covered, running distance, HSR, sprinting distance,

TABLE 1. Characteristics of training days.

	1st DIV	Duration (M ± SD)	Description
Match	8	97.31 ± 2.67	Match session that included all players' who undertook at least 90-min of the match.
MD+1&+2	4	75.52 ± 8.39	Top up session loading players with less than 60-min of match play. Tasks included exercises performed in small to moderate sizes, such as ball possession related tasks, followed by speed finishing drills and ending with SSG.
MD-4	8	113.38 ± 24.28	Session characterized by small to medium spaces to promote high-intensity accelerations and decelerations while focusing on specific offensive and defensive principles of play (from 1v1 to 5v5).
MD-3	8	69.27 ± 9.06	Session dedicated to team collective play, based on large-sided games (e.g., 10v10, 10v8) to refine specific movement patterns (e.g., building up from the back). This mostly involved ball possession, sectorial and 11v11 conditioned tasks.
MD-2	8	65.41 ± 7.33	Tapering session, often composed by passing drills, specific movement patterns with low complexity (i.e., passive opposition) and finishing tasks.
MD-1	8	42.6 ± 6.99	Low-intensity session aiming to decrease load and foster a positive psychological state by using teambuilding activities, team strategical movement patterns and preparing match set-pieces.
Training Day	**2nd DIV**	**Duration (M ± SD)**	**Description**
Match	6	96.38 ± 4.07	Match session, that included all players' that performed at least 90-min of the match.
MD+1&+2	5	65.37 ± 11.28	Top up session loading players with less than 60-min of match play. Accordingly, the players were introduced to BPG, followed by practicing shooting and finalization exercises and ending with SSG.
MD-4	6	76.77 ± 12.97	Session characterized using small to moderate spaces. Often the session started with BPG or SSG, progressing to intra-sectorial and inter-sectorial tasks to emphasize defensive performance.
MD-3	6	79.6 ± 5.97	Session in which the team tactical behaviour was the focus. Often the first task consisted in a LSG based on possession, progressing to defensive and offensive transitions using 8v8 and 10v10 LSG and ending with a competitive 11v11 game.
MD-2	6	68.63 ± 14.2	Session with major aim of tailoring the team offensive behaviour. Often tasks included passing patterns involving the 10 players, progressing to speed drills during finishing actions (e.g., 6vs3 + 1+ Gk) to develop crossing and finishing and ending with 11v11 game.
MD-1	6	62.14 ± 8.48	Session aiming to promote positive psychological state by using recreative and fun activities, often using reaction speed drills (e.g., reacting to colours with roles of catcher and runner), and ending with offensive and defensive set pieces.
Training Day	**3rd DIV**	**Duration (M ± SD)**	**Description**
Match	8	97.86 ± 3.77	Match session, that included all players' that performed at least 90-min of the match.
MD+1&+2	5	73.99 ± 5.12	Top up session loading players with less than 60-min of match play. Training session consisted in exercises performed in small to moderate sizes. Session started with BPG, progressed to 1v1 and 2v2 situations and ended with SSG.
MD-4	6	76.04 ± 8.88	Training focused on acceleration and deceleration profiles by using BPG and SSG with 3 teams in small areas, and sectorial tasks consisting of 5v5 and 6v6 to foster defensive behaviour.
MD-3	8	92.36 ± 7.69	Training focused on reviewing the defensive patterns and developing the offensive organization in larger playing areas to stress distance covered. Often, it started with SSG and then progress to tasks based on BPG in numerical superiority (9v9+2J) and both sectorial and collective tasks (from Gk+8v8+Gk to Gk+10v10+Gk).
MD-2	7	76.0 ± 8.49	Session that targets sprinting number and distance, while focusing on tapering to guarantee a proper recovery. Tasks often involved ball-passing patterns, BPG and SSG. Subsequently, the session was divided between attackers (i.e., wings and strikers) that practiced shooting and finalization, and defenders (i.e., centre-backs and fullbacks) who were planned to review the defensive principles.
MD-1	7	58.0 ± 7.95	Session started with light warm-up, followed by rondos, BPG and reaction speed tasks. The main session was focused on preparing both the offensive and defensive set pieces.

Note: MD+1&+2: 1 or 2 days after the match; MD-4: 4 days prior to next match; MD-3: 3 days prior to next match; MD-2: 2 days prior to the next match; MD-1: 1 day prior to the next match.

accelerations and decelerations) according to the competition level of the team (i.e., 1st DIV, 2nd DIV and 3rd DIV), microcycle days (i.e., match, MD+1&+2, MD-4, MD-3, MD-2 and MD-1) and the interaction between competition level of the team and microcycle days. For that purpose, the competition level of the team and microcycle days were defined as categorical fixed effects, while individual players were considered as random effects. The pairwise comparisons between conditions were assessed using the Bonferroni *post-hoc* test. Complementarily, the magnitude of differences was quantified using the partial omega squared (ω_p^2) and interpreted based on the following thresholds: small: < 0.01; medium: < 0.06; large, < 0.14. All statistical analyses were performed using the Jamovi Project software (Computer Software Version 2.3.21.0, 2023), with $p < 0.05$ as statistical significance.

RESULTS

The descriptive and inferential data from the differences between teams' playing level (i.e., 1st DIV, 2nd DIV and 3rd DIV) at the different times (i.e., match, MD+1&+2, MD-4, MD-3, MD-2 and MD-1) are presented in Figure 1, Figure 2 and Table 3. The statistical analyses revealed statistically significant effects for the interaction (team × match day) in all variables. Interestingly, statistically significant effects in the match were only found for the number of accelerations (> 3 m/s), in which the 3rd DIV team presented higher values than both 1st and 2nd DIV ($p < 0.001$). Despite this, statistically significant differences between competitive levels of teams were identified in all days of the microcycle. In addition, the 1st DIV team reported higher distance-related variables on most days of the microcycle compared to their counterparts, with the exception of MD-2. Accordingly, the 1st DIV team showed greater total distance covered ($F = 122.7$, $p < 0.001$, large effects) on M+1&+2, MD-4, MD-3 and MD-1 than both 2nd DIV and 3rd DIV teams. Similarly, greater running ($F = 62.6$, $p < 0.001$, moderate effects) and HSR distance ($F = 62.4$, $p < 0.001$, moderate effects) were found in the 1st DIV team for MD+1&+2, MD-4 and MD-3 when compared to both 2nd and 3rd DIV teams. The 1st DIV also accumulated higher running and HSR on MD-1 compared to the 3rd DIV team. In contrast, these variables (total distance, running distance and HSR distance) were

TABLE 2. Players' characterization according to their playing positions.

Variables			**1st DIV**		
	Center Backs	Fullbacks	Midfielders	Wings	Strikers
	n = 8	n = 4	n = 8	n = 8	n = 4
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Age (years)	21.29 ± 2.65	27.25 ± 4.19	24.49 ± 5.49	22.58 ± 2.94	27.65 ± 3.92
Height (m)	1.87 ± 0.02	1.79 ± 0.02	1.82 ± 0.04	1.82 ± 0.03	1.85 ± 0.04
Weight (kg)	79.71 ± 2.50	72.50 ± 5.20	75.5 ± 4.66	73.38 ± 4.00	75.25 ± 2.22
Playing Experience (years)	3.75 ± 3.06	8.00 ± 5.35	6.88 ± 5.33	5.00 ± 2.58	9.25 ± 5.32
Variables			**2nd DIV**		
	Center Backs	Fullbacks	Midfielders	Wings	Strikers
	n = 4	n = 4	n = 8	n = 4	n = 3
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Age (years)	27.83 ± 6.22	26.69 ± 3.58	25.72 ± 4.01	25.79 ± 2.85	29.56 ± 2.34
Height (m)	1.87 ± 2.50	1.79 ± 2.22	1.80 ± 8.63	1.72 ± 7.00	1.82 ± 3.79
Weight (kg)	83.00 ± 5.94	69.75 ± 2.87	70.63 ± 7.37	64.25 ± 8.42	78.67 ± 9.02
Playing Experience (years)	10.25 ± 5.50	8.45 ± 3.12	8.25 ± 3.30	9.00 ± 1.83	11.67 ± 1.53
Variables			**3rd DIV**		
	Center Backs	Fullbacks	Midfielders	Wings	Strikers
	n = 4	n = 4	n = 6	n = 4	n = 5
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Age (years)	26.10 ± 4.11	22.75 ± 1.00	23.29 ± 2.65	16.79 ± 11.16	26.52 ± 6.36
Height (m)	1.87 ± 0.01	1.78 ± 0.02	1.80 ± 0.08	1.77 ± 0.05	1.82 ± 0.03
Weight (kg)	82.10 ± 5.09	71.10 ± 2.33	74.32 ± 6.21	74.18 ± 9.81	76.12 ± 6.97
Playing Experience (years)	8.25 ± 4.11	5.75 ± 1.89	5.67 ± 2.80	4.50 ± 1.91	8.80 ± 5.81

Note: m = meters; kg = kilograms; n = number.

TABLE 3. Descriptive statistics (M ± SD) from the external load according to the training days in relation to the team competitive level

Variables		1st DIV	2nd DIV	3rd DIV	*F (p-value)*	*η*2p (magnitude)	Post-hoc
		Mean ± SD	Mean ± SD	Mean ± SD			
Total Distance Covered (m)	Match	108.16 ± 8.34	109.73 ± 8.54	108.16 ± 8.76	122.7 (p < 0.001)	0.06 (large)	
	MD+1|2	109.09 ± 8.68	86.54 ± 13.99	73.14 ± 6.94			1st v 2nd; 1st v 3rd; 2nd v 3rd
	MD-4	99.60 ± 18.26	66.23 ± 15.36	89.15 ± 7.18			1st v 2nd; 1st v 3rd; 2nd v 3rd
	MD-3	103.97 ± 9.95	73.19 ± 8.43	77.85 ± 9.71			1st v 2nd; 1st v 3rd
	MD-2	48.89 ± 14.03	64.65 ± 7.75	65.30 ± 7.32			1st v 2nd; 1st v 3rd
	MD-1	70.73 ± 12.69	53.73 ± 12.53	44.69 ± 5.80			1st v 2nd; 1st v 3rd; 2nd v 3rd
Running Distance (13.9–19.8 km/h, m)	Match	17.61 ± 4.16	19.86 ± 5.39	18.68 ± 4.36	62.6 (p < 0.001)	0.03 (moderate)	
	MD+1|2	14.35 ± 4.78	11.70 ± 5.05	7.38 ± 1.97			1st v 3rd; 2nd v 3rd
	MD-4	14.78 ± 7.18	9.70 ± 4.01	13.24 ± 3.67			1st v 2nd; 2nd v 3rd
	MD-3	17.37 ± 4.89	11.59 ± 3.13	9.78 ± 3.22			1st v 2nd; 1st v 3rd
	MD-2	4.09 ± 3.11	9.24 ± 2.93	6.54 ± 2.90			1st v 2nd; 1st v 3rd; 2nd v 3rd
	MD-1	6.68 ± 3.60	6.32 ± 2.52	3.31 ± 1.66			1st v 3rd; 2nd v 3rd
High-Speed Running Distance (> 19.8 km/h, m)	Match	6.41 ± 2.40	6.35 ± 2.42	7.21 ± 3.01	62.4 (p < 0.001)	0.03 (moderate)	
	MD+1|2	7.12 ± 1.91	2.08 ± 1.41	5.52 ± 2.16			1st v 2nd; 1st v 3rd; 2nd v 3rd
	MD-4	4.41 ± 3.23	2.43 ± 1.63	3.20 ± 1.53			1st v 2nd; 1st v 3rd
	MD-3	6.80 ± 2.31	3.10 ± 1.43	5.53 ± 2.25			1st v 2nd; 1st v 3rd; 2nd v 3rd
	MD-2	1.28 ± 1.28	3.03 ± 1.26	1.96 ± 1.52			1st v 2nd
	MD-1	1.27 ± 1.19	1.3 ± 1.11	0.51 ± 0.58			
Sprinting Distance (> 25.2 km/h, m)	Match	1.25 ± 0.91	1.57 ± 0.96	1.28 ± 1.00	71.1 (p < 0.001)	0.04 (moderate)	
	MD+1|2	1.85 ± 1.18	0.15 ± 0.27	2.68 ± 1.58			1st v 2nd; 1st v 3rd; 2nd v 3rd
	MD-4	0.46 ± 0.59	0.36 ± 0.64	0.21 ± 0.22			
	MD-3	1.42 ± 1.03	0.57 ± 0.55	1.58 ± 0.98			1st v 2nd; 2nd v 3rd
	MD-2	0.20 ± 0.39	0.89 ± 0.54	0.20 ± 0.28			1st v 2nd; 2nd v 3rd
	MD-1	0.07 ± 0.18	0.12 ± 0.24	0.03 ± 0.11			
Accelerations (counts, > 3m/s)	Match	0.27 ± 0.10	0.29 ± 0.10	0.54 ± 0.19	29.5 (p < 0.001)	0.02 (moderate)	1st v 3rd; 2nd v 3rd
	MD+1|2	0.43 ± 0.16	0.32 ± 0.19	0.85 ± 0.35			1st v 3rd; 2nd v 3rd
	MD-4	0.44 ± 0.18	0.37 ± 0.15	0.49 ± 0.22			2nd v 3rd
	MD-3	0.28 ± 0.11	0.21 ± 0.10	0.48 ± 0.17			1st v 3rd; 2nd v 3rd
	MD-2	0.14 ± 0.11	0.20 ± 0.09	0.50 ± 0.24			1st v 3rd; 2nd v 3rd
	MD-1	0.30 ± 0.15	0.16 ± 0.08	0.52 ± 0.2			1st v 2nd; 1st v 3rd; 2nd v 3rd
Decelerations (counts, > 3m/s)	Match	0.45 ± 0.11	0.38 ± 0.15	0.43 ± 0.13	28.5 (p < 0.001)	0.02 (moderate)	
	MD+1|2	0.41 ± 0.14	0.28 ± 0.16	0.40 ± 0.14			1st v 2nd; 2nd v 3rd
	MD-4	0.45 ± 0.17	0.37 ± 0.12	0.39 ± 0.15			
	MD-3	0.37 ± 0.13	0.23 ± 0.10	0.30 ± 0.11			1st v 2nd;
	MD-2	0.14 ± 0.11	0.21 ± 0.10	0.26 ± 0.12			1st v 3rd
	MD-1	0.21 ± 0.14	0.14 ± 0.08	0.12 ± 0.09			1st v 3rd

Note: 1st v 2nd) Differences between 1st DIV and 2nd Div ($p < 0.05$); 1st v 3rd) Differences between 1st DIV and 3rd Div ($p < 0.05$); 2nd v 3rd) Differences between 2nd DIV and 3rd Div ($p < 0.05$).

lower on MD-2 for the 1st DIV team when compared to the 2nd DIV team. Regarding the sprinting variable ($F = 71.1$, $p < 0.001$, moderate effects), the main statistically significant differences were found on MD-3 and MD-2, in which the 2nd DIV team reported lower and higher values, respectively, than their counterparts. Another interesting result was the higher number of high accelerations ($F = 29.5$, $p < 0.001$, moderate effects) found in the 3rd DIV team across all days of the microcycle when compared to the 1st and 2nd DIV teams. Accordingly, a higher number of acceleration events was noted in the 3rd DIV team when compared to both 1st and 2nd DIV teams during MD+1& +2 and MD-1. Meanwhile, a higher number of accelerations on MD-4 and MD-2 were found in the 3rd DIV team when compared to the 1st DIV team, and on MD-3 when compared to the 2nd DIV team.

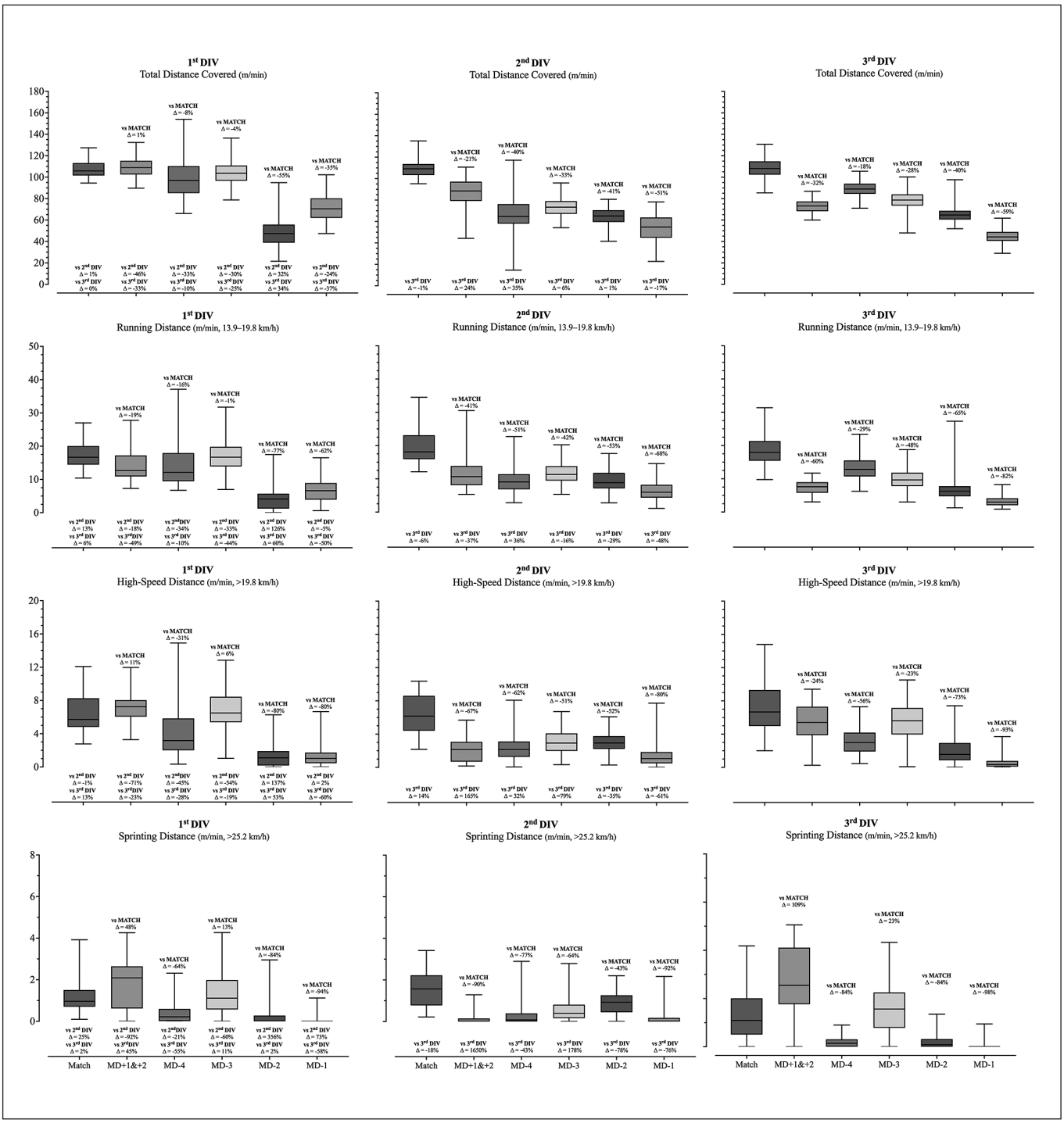


FIG. 1. Descriptive (Mean, minimum and Maximum) data from the different moments (i.e., Match, MD+1&+2, MD-4, MD-3, MD-2 and MD-1) and the percentage difference between each moment and corresponding match and between different competitive levels for the distance-related variables.

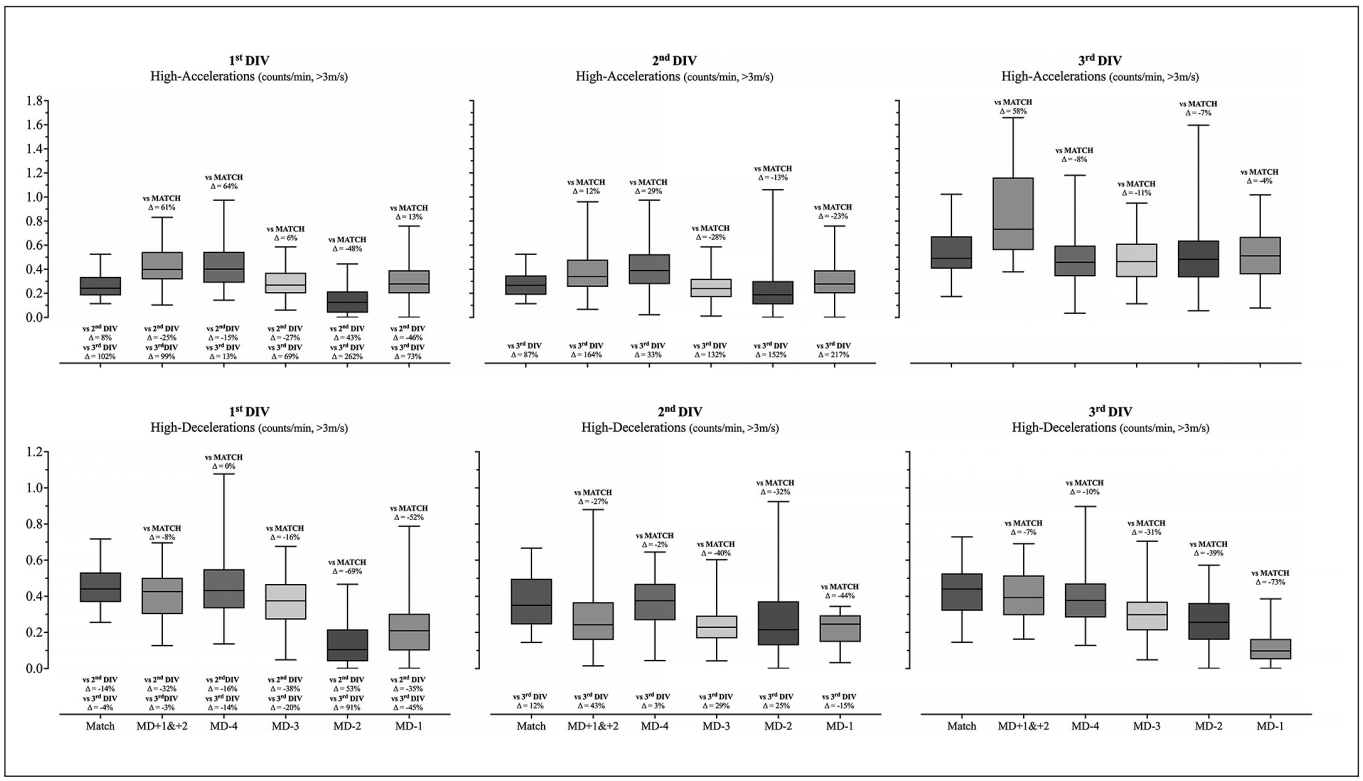


FIG. 2. Descriptive (Mean, minimum and Maximum) data from the different moments (i.e., Match, MD+1&+2, MD-4, MD-3, MD-2 and MD-1) and the percentage difference between each moment and corresponding match and between different competitive levels for the acceleration and deceleration profile.

DISCUSSION

The aim of this study was to compare the load distribution within regular microcycles among teams from different competitive levels (1st DIV, 2nd DIV, and 3rd DIV). The results revealed statistically significant differences between all teams on each day of the week, except for the match day, which only showed variations in the number of high accelerations.

Significant differences between teams for the match were only identified for accelerations. The literature in this domain has shown inconsistent results in the playing level comparisons. For instance, Mohr, Krustrup and Bangsbo [26] found that players competing at higher levels (i.e., big league and champions league) performed more high-speed running and sprinting than players from a moderate level (i.e., teams from the Danish first league). Similarly, higher-ranked teams from the 1st DIV in the Spanish La Liga covered more total distance than those belonging to the 2nd DIV [27]. In contrast, Bradley, Carling [28] found that players from the 2nd DIV covered more high-intensity running distance than those in the 1st DIV. More recently, García-Calvo, Ponce-Bordón [29] found no differences when comparing 1st and 2nd DIV teams from Spain regarding high-metabolic load distance variables. The authors suggested that such results might be related to comparing team performance without considering players' roles, and the same possibility could be considered in the present study. Considering that players' roles are determinant for the accumulated match external load, further research may include comparing differences in match physical load of the different playing positions according to team competitive level. Nevertheless, 3rd DIV teams presented a higher number of accelerations than both 1st and 2nd DIV teams. Teams from higher playing levels are more capable of maintaining ball possession, performing a higher number of frontal passes, and touching the ball more often [28], contributing to greater use of width [27]. In contrast, teams from lower competitive levels show higher values for headers, interceptions, and clearances [28]. These indicators may suggest that teams from lower competing levels may adopt a more "direct" playing style, emphasizing long balls and second balls, which can lead to more changes in ball possession between teams. As a result, players may need to accelerate often to press the opposition, move close to the ball location, or even explore possible counterattacks.

In this study, the analysis from MD+1&+2 sessions considered only players who performed the top-up session (i.e., players who were not exposed to a minimum of 60 min of the match) to better understand the session demands [2]. Consequently, higher values for distance-related variables were found for the 1st DIV team, while the 3rd DIV team showed higher values for acceleration. Non-starters (i.e., substituted players) seems to cover less than 40% running compared to starting players [30]. Accordingly, 1st DIV teams seem to recognize this difference, and consequently, emphasize the distance covered for non-starters in the first session. However, a previous study exploring the differences in training load between starters and

non-starters throughout an entire competitive season from an elite team found no differences in players' training load distribution [31]. This evidence suggests that coaches from higher competitive levels may be more aware of the crucial role of compensatory strategies for non-starter players. The availability of resources also plays a role, as teams from higher competitive levels often count on "alternative" teams such as B or under-23 teams, which allows them to have more players to stress players' physical load using game-based situations. On the other hand, teams from lower levels may be more limited in having additional players during training sessions, leading them to adopt the use of SSG, which often induce a higher number of accelerations compared to match formats involving more players [32]. While it is possible that coaches from lower competitive levels use SSG more often due to the lower number of available players, especially during MD+1&+2, it is also plausible that coaches from teams of such levels are aware of the matches' physical demands. Therefore, they design specific tasks to prepare the players for the actual competitive demands. In fact, the results from the 3rd DIV team showed a higher number of accelerations throughout the entire week when compared to both 1st and 2nd DIV teams. Since differences between competitive levels during the match in this study were only found for high accelerations, it seems to suggest that coaches from lower levels adjust the weekly training loads to match the competition demands. Despite that, it is important to note that players with more playing time across the season are likely to manifest higher accumulative weekly load compared to players who are less frequently selected [33]. Consequently, further research exploring different strategies on how to decrease the differences between line-up players, substitutes and reserves is required, mainly when considering MD+1&+2, MD-1 and MD [33].

The MD-4 session is often focused on developing intra-sectorial movement patterns within the team, such as movement coordination within the defensive sector while emphasizing neuromuscular actions (e.g., changes of direction) [2, 34]. Coaches from all competitive levels in this study seem to recognize the importance of neuromuscular overload on MD-4, as differences in acceleration were only evident between the 2nd DIV and 3rd DIV teams, with higher values for the latter. In fact, results from a diversity of backgrounds had shown a higher emphasis on acceleration and deceleration on MD-4, in which coaches uses SSG to emphasize such external load metrics [7].

In contrast to MD-4, MD-3 is often focused on the total distance covered and distance covered at high speed [6]. Coaches use larger formats of the match and include a higher number of players to develop inter-player and collective team movement patterns. However, a curious observation in the 2nd DIV team was that it reported lower values for most variables during the first three training sessions (i.e., MD+1&+2, MD-4, and MD-3), contradicting the results found in most studies exploring microcycle external load distribution [4, 5, 11] and 'periodization' models in team sports [1, 4]. Nevertheless, coaches' main priority during the competitive period is refining the team's technical and tactical behaviour [8], and different pedagogical approaches may emerge as a result of the coaches' profiles. For example, one coach may use short-period tasks to emphasize intensity and use rest periods to provide feedback, while another coach may adopt more continuous tasks and stop more often to provide tactical rearrangements of the team, which could impact their external load profile [15]. Interestingly, the 1st DIV coach adopted the longer session on MD-4, which may support the above suggestion. Coaches from higher levels are expected to possess a deeper understanding of the match, enabling them to identify and correct team errors more precisely. Hence, they may adopt longer sessions to use the rest periods to adjust the team's positioning. Additionally, the higher values for the distance-related variables on this day may support the suggestion that the coach from the 1st DIV used the stoppages to provide feedback, contributing to differences mainly in the total distance covered.

The 2nd DIV teams reported lower values of external load in most of the previous training sessions compared to both 1st and 3rd DIV teams. In contrast, higher values of distance covered at high intensities were identified on MD-2, and thus it is possible that the technical staff decided to induce a high stimulus to expose the players to an appropriate level of intensity, which has been found to be crucial in preventing injuries [35]. Coaches may adopt different methodological approaches based on the team's characteristics. For example, when comparing teams from Portugal and the Netherlands belonging to the 2nd DIV, Clemente, Owen [11] found that the Portuguese team covered more distance in the first two sessions (~73% and ~62% more), while covering less in the last (~20 less). The same authors also found that the Portuguese team performed a higher number of sprints. Thus, it is possible that, like the acceleration and deceleration profile identified in the 3rd DIV team, sprinting is a parameter that characterizes 2nd DIV teams. For instance, coaches of 2nd DIV teams may use transition-based tasks, crossing, and finishing actions on MD-2 [36], which may contribute to the higher sprinting demands.

A decrease in all external load parameters is evident on MD-1, in line with observations in research exploring weekly load distribution in youth academies [7] and semi-professional players [9]. However, despite this general decrease, statistically significant differences were still identified between competitive levels. For example, the 3rd DIV team reported higher values for the number of high accelerations than both the 1st and 2nd DIV teams. While it might be expected for there to be a decrease in players' acceleration profile as the microcycle progresses, a previous study found a constant distribution of acceleration volume across the microcycle [9]. This suggests that while the increase in accelerations throughout the week may help players be better prepared for the match demands, it could also lead to excessive fatigue [9]. It is worth noting that the 3rd DIV team reported using SSG during all sessions of the week (see Table 1), which may have contributed to the high values in accelerations for all days of the microcycle [6, 32]. SSG are known to induce a higher number of accelerations due to the nature of the match format and the increased involvement of players in quick changes of direction and intense

actions [32]. As a result, the frequent use of SSG by the 3rd DIV team could explain the higher number of accelerations observed throughout the microcycle.

While this study provides important insights for coaches and sports practitioners, there are several limitations that should be acknowledged. Firstly, the analysis in this study is based on data from only one team from each competitive level, and thus the results from the external load may rely on coaches' specific training methodology. In addition, players' role within and between the team may also impact the present findings, and thus further research may consider including playing position as a covariate. These limitations may restrict the generalizability of the findings, as load distribution across the week can vary based on the training methodology employed by different teams [3, 6]. Including multiple teams from each competitive level would strengthen the study's inferences and provide a more comprehensive understanding of load distribution patterns. Actually, programming characteristics of the technical staff might explain some of the differences reported herein, and they might not be solely related to the playing level. Additionally, previous research has highlighted that a team's weekly external load may decrease when facing high-level opposition [12]. This factor was not considered in the present study, which could impact the load distribution within the microcycle. Future studies should account for the influence of the level of opposition on load distribution to gain a more comprehensive understanding of how teams adjust their training load based on the upcoming match difficulty.

CONCLUSIONS

The results of this study revealed significant differences in microcycle load distribution between different competitive levels. Interestingly, only the number of high accelerations revealed statistically significant differences during the match, with higher values reported by the 3rd DIV team. In contrast, there were substantial differences in the weekly load distribution, suggesting that different 'periodization' models emerge based on the competitive level. This may reflect varying coaching philosophies, training methodologies, playing styles, and contextual factors such as previous match scores and the quality of subsequent match opponents. Nonetheless, coaches, sports scientists, and strength and conditioning coaches can use these findings to obtain comparative values across different playing levels.

Funding

This work was funded by National Funds by FCT - Foundation for Science and Technology under the following project UIDB/04045/2020 (https://doi.org/10.54499/UIDB/04045/2020).

Conflict of interest

The authors declared no conflict of interest.

REFERENCES

1. Los Arcos A, Mendez-Villanueva A, Martínez-Santos R. In-season training periodization of professional soccer players. Biol Sport. 2017; 34(2):149–55. Epub 20170101. doi: 10.5114/biolsport.2017.64588. PubMed PMID: 28566808; PubMed Central PMCID: PMC5424454.
2. Martin-Garcia A, Gomez Diaz A, Bradley PS, Morera F, Casamichana D. Quantification of a Professional Football Team's External Load Using a Microcycle Structure. J Strength Cond Res. 2018; 32(12):3511–8. doi: 10.1519/JSC .0000000000002816. PubMed PMID: 30199452.
3. Buchheit M, Lacome M, Cholley Y, Simpson BM. Neuromuscular Responses to Conditioned Soccer Sessions Assessed via GPS-Embedded Accelerometers: Insights Into Tactical Periodization. Int J Sports Physiol Perform. 2018; 13(5):577–83. Epub 20180522. doi: 10.1123/ijspp.2017-0045. PubMed PMID: 28872370.
4. Oliva-Lozano JM, Gómez-Carmona CD, Fortes V, Pino-Ortega J. Effect of training day, match, and length of the microcycle on workload periodization in professional soccer players: a full-season study. Biol Sport. 2022; 39(2):397–406. Epub 20210601. doi: 10.5114/biolsport .2022.106148. PubMed PMID: 35309541; PubMed Central PMCID: PMC8919886.
5. Akenhead R, Harley JA, Tweddle SP. Examining the External Training Load of an English Premier League Football Team With Special Reference to Acceleration. J Strength Cond Res. 2016; 30(9):2424–32. Epub 2016/01/29. doi: 10.1519/jsc.0000000000001343. PubMed PMID: 26817740.
6. Castillo D, Raya-González J, Weston M, Yanci J. Distribution of External Load During Acquisition Training Sessions and Match Play of a Professional Soccer Team. J Strength Cond Res. 2021; 35(12):3453–8. doi: 10.1519/jsc .0000000000003363. PubMed PMID: 31469765.
7. Douchet T, Paizis C, Carling C, Cometti C, Babault N. Typical weekly physical periodization in French academy soccer teams: a survey. Biol Sport. 2023; 40(3):731–40. Epub 20221014. doi: 10.5114/biolsport.2023.119988. PubMed PMID: 37398965; PubMed Central PMCID: PMC10286623.
8. Malone JJ, Di Michele R, Morgans R, Burgess D, Morton JP, Drust B. Seasonal training-load quantification in elite English premier league soccer players. Int J Sports Physiol Perform. 2015; 10(4):489–97. Epub 20141113. doi: 10.1123/ijspp .2014-0352. PubMed PMID: 25393111.
9. Swallow WE, Skidmore N, Page RM, Malone JJ. An examination of in-season external training load in semi-professional soccer players: considerations of one and two match weekly microcycles. Int J Sports Sci Coach. 2021; 16(1):192–9. doi: 10.1177/1747954120951762.
10. Oliveira R, Brito J, Martins A, Mendes B, Calvete F, Carriço S, et al. In-season training load quantification of one-, two- and three-game week schedules in a top European professional soccer team. Physiol Behav. 2019; 201:146–56. Epub 2018 1206. doi: 10.1016/j.physbeh.2018 .11.036. PubMed PMID: 30529511.
11. Clemente FM, Owen A, Serra-Olivares J, Nikolaidis PT, van der Linden CMI, Mendes B. Characterization of the Weekly External Load Profile of Professional Soccer Teams from Portugal and the Netherlands. J Hum Kinet. 2019; 66:155–64. doi: 10.2478/hukin -2018-0054. PubMed PMID: 30988849.
12. Chena M, Morcillo JA, Rodríguez- -Hernández ML, Zapardiel JC, Owen A, Lozano D. The Effect of Weekly Training Load across a Competitive Microcycle on Contextual Variables in Professional Soccer. Int J Environ Res Public Health. 2021; 18(10). Epub 20210511. doi: 10.3390/ijerph18105091. PubMed PMID: 34064978; PubMed Central PMCID: PMC8151593.

13. Morgans R, Rhodes D, Teixeira J, Modric T, Versic S, Oliveira R. Quantification of training load across two competitive seasons in elite senior and youth male soccer players from an English Premiership club. Biol Sport. 2023:1197–205. doi: 10.5114/biolsport.2023.126667.
14. Abade EA, Gonçalves BV, Leite NM, Sampaio JE. Time-motion and physiological profile of football training sessions performed by under-15, under-17 and under-19 elite Portuguese players. Int J Sports Physiol Perform 2014; 9(3):463–70. doi: 10.1123/ijspp .2013-0120. PubMed PMID: 23920425.
15. Coutinho D, Goncalves B, Figueira B, Abade E, Marcelino R, Sampaio J. Typical weekly workload of under 15, under 17, and under 19 elite Portuguese football players. J Sports Sci. 2015; 33(12):1229–37. doi: 10.1080 /02640414.2015.1022575. PubMed PMID: WOS:000353402200004.
16. White A, Hills SP, Cooke CB, Batten T, Kilduff LP, Cook CJ, et al. Match-Play and Performance Test Responses of Soccer Goalkeepers: A Review of Current Literature. Sports Med. 2018; 48(11):2497–516. doi: 10.1007/s402 79-018-0977-2. PubMed PMID: 30144021.
17. Winter EM, Maughan RJ. Requirements for ethics approvals. J Sports Sci. 2009; 27(10):985. doi: 10.1080/026404 10903178344.
18. Scott MT, Scott TJ, Kelly VG. The Validity and Reliability of Global Positioning Systems in Team Sport: A Brief Review. J Strength Cond Res. 2016; 30(5):1470–90. doi: 10.1519/jsc .0000000000001221. PubMed PMID: 26439776.
19. Bastida Castillo A, Gómez Carmona CD, De la Cruz Sánchez E, Pino Ortega J. Accuracy, intra- and inter-unit reliability, and comparison between GPS and UWB-based position-tracking systems used for time-motion analyses in soccer. Eur J Sport Sci. 2018; 18(4):450–7. Epub 20180131. doi: 10.1080 /17461391.2018.1427796. PubMed PMID: 29385963.
20. Castellano J, Casamichana D, Calleja-González J, Román JS, Ostojic SM. Reliability and Accuracy of 10 Hz GPS Devices for Short-Distance Exercise. J Sports Sci Med. 2011; 10(1):233–4. Epub 20110301. PubMed PMID: 24137056; PubMed Central PMCID: PMC3737891.
21. Jennings D, Cormack S, Coutts AJ, Boyd LJ, Aughey RJ. Variability of GPS units for measuring distance in team sport movements. Int J Sports Physiol Perform. 2010; 5(4):565–9. doi: 10.1123/ijspp.5.4.565. PubMed PMID: 21266740.
22. Clemente FM, Rabbani A, Conte D, Castillo D, Afonso J, Truman Clark CC, et al. Training/Match External Load Ratios in Professional Soccer Players: A Full-Season Study. Int J Environ Res Public Health. 2019; 16(17):3057. PubMed PMID. doi: 10.3390/ijerph 16173057.
23. Gregson W, Drust B, Atkinson G, Salvo VD. Match-to-Match Variability of High-Speed Activities in Premier League Soccer. International journal of sports medicine. 2010; 31(04):237–42. Epub 2010/02/15. doi: 10.1055/s-0030 -1247546.
24. Ade JD, Harley JA, Bradley PS. Physiological response, time-motion characteristics, and reproducibility of various speed-endurance drills in elite youth soccer players: small-sided games versus generic running. International Journal of Sports Physiology and Performance. 2014; 9(3):471–9. doi: 10.1123/ijspp.2013-0390.
25. Clemente FM, Silva R, Castillo D, Los Arcos A, Mendes B, Afonso J. Weekly Load Variations of Distance-Based Variables in Professional Soccer Players: A Full-Season Study. International Journal of Environmental Research and Public Health. 2020; 17(9):3300. PubMed PMID. doi: 10.3390/ijerph 17093300.
26. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sports Sci. 2003; 21(7):519–28. Epub 2003/07/10. doi: 10.1080/02640410 31000071182. PubMed PMID: 12848386.
27. Castellano J, Casamichana D. What are the differences between first and second divisions of Spanish football teams? Int J Perform Anal Sport. 2015;15(1):135–46. doi: 10.1080/24748668.2015 .11868782.
28. Bradley PS, Carling C, Gomez Diaz A, Hood P, Barnes C, Ade J, et al. Match performance and physical capacity of players in the top three competitive standards of English professional soccer. Hum Mov Sci. 2013; 32(4):808–21. doi: https://doi.org /10.1016/j. humov.2013.06.002.
29. García-Calvo T, Ponce-Bordón JC, Pons E, López Del Campo R, Resta R, Raya-González J. High metabolic load distance in professional soccer according to competitive level and playing positions. PeerJ. 2022; 10:e13318. Epub 20220920. doi: 10.7717/peerj.13318. PubMed PMID: 36157060; PubMed Central PMCID: PMC9504445.
30. Young WB, Newton RU, Doyle TL, Chapman D, Cormack S, Stewart G, Dawson B. Physiological and anthropometric characteristics of starters and non-starters and playing positions in elite Australian Rules Football: a case study. J Sci Med Sport. 2005; 8(3):333–45. doi: 10.1016/s1440 -2440(05)80044-1. PubMed PMID: 16248474.
31. Oliveira R, Palucci Vieira LH, Martins A, Brito JP, Nalha M, Mendes B, Clemente FM. In-Season Internal and External Workload Variations between Starters and Non-Starters-A Case Study of a Top Elite European Soccer Team. Medicina (Kaunas). 2021; 57(7). Epub 20210623. doi: 10.3390/medicina 57070645. PubMed PMID: 34201642; PubMed Central PMCID: PMC8306595.
32. Rebelo AN, Silva P, Rago V, Barreira D, Krustrup P. Differences in strength and speed demands between 4v4 and 8v8 small-sided football games. J Sports Sci. 2016; 34(24):2246–54. Epub 2016/06/10. doi: 10.1080/02640414.2016 .1194527. PubMed PMID: 27278256.
33. Casamichana D, Martín-García A, Díaz AG, Bradley PS, Castellano J. Accumulative weekly load in a professional football team: with special reference to match playing time and game position. Biol Sport. 2022; 39(1):115–24. Epub 20210304. doi: 10.5114/biolsport.2021.102924. PubMed PMID: 35173370; PubMed Central PMCID: PMC8805368.
34. Rey E, Corredoira FJ, Costa PB, Pérez-Ferreirós A, Fernández- -Villarino MA. Acute effects of training load on contractile properties during a competitive microcycle in elite soccer players. Biol Sport. 2020; 37(2):157–63. Epub 20200330. doi: 10.5114/biolsport.2020.93041. PubMed PMID: 32508383; PubMed Central PMCID: PMC7249794.
35. Clemente FM, Silva R, Castillo D, Los Arcos A, Mendes B, Afonso J. Weekly Load Variations of Distance-Based Variables in Professional Soccer Players: A Full-Season Study. Int J Environ Res Public Health. 2020; 17(9). Epub 20200509. doi: 10.3390 /ijerph17093300. PubMed PMID: 32397398; PubMed Central PMCID: PMC7246436.
36. Lewis G, Towlson C, Roversi P, Domogalla C, Herrington L, Barrett S. Quantifying volume and high-speed technical actions of professional soccer players using foot-mounted inertial measurement units. Plos One. 2022; 17(2):e0263518. doi: 10.1371/journal .pone.0263518.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.136091
© Institute of Sport – National Research Institute

The influence of meteorological factors on the technical performance of football teams during matches

AUTHORS: Yonghan Zhong[1], Shaoliang Zhang[2], Qing Yi[3], Miguel Ángel Gómez Ruano[4]

[1] School of Athletic Performance, Shanghai University of Sport, Shanghai, China
[2] Division of Sports Science and Physical Education, Tsinghua University, Beijing, China
[3] College of Physical Education, Dalian University, Dalian, China
[4] Facultad de Ciencias de la Actividad Física y del Deporte (INEF), Universidad Politécnica de Madrid, Madrid, Spain

ABSTRACT: This study explored the impact of the meteorological factors air temperature, relative humidity, and wind speed on teams' technical performance during the Union of European Football Associations Champions League (UCL). Technical match statistics were collected for five seasons (2016/2017–2020/2021). Thirty-one technical actions and events were categorized into three groups (goal scoring, offense, and defence). Meteorological data were collected from the official UEFA website (air temperature (°C): 11.59 ± 6.87, relative humidity (%): 71.40 ± 17.82, wind speed (km/h): 11.52 ± 7.02). LASSO regression analysis was employed to identify important indicators that affect match outcomes, while separate Poisson regression models were used in generalized linear modelling to determine the effects of meteorological factors on key technical performance indicators. The results revealed that offensive variables were instrumental in distinguishing match outcomes (winning, drawing, and losing), with meteorological factors significantly influencing these variables. Notably, "shot from counter attack" was the most significantly affected variable, being exclusively influenced by air temperature (OR = 0.55, 95% CI: 0.30 to 0.98). Two technical indicators, "dribbles won" and "shots from the 6-yard box," were both significantly influenced by two meteorological factors. "Cards per foul," an understudied variable, displayed a close association with all the three meteorological factors. These findings offer valuable insights for coaches and analysts in comprehending the influence of meteorological conditions on crucial technical variables during the performance evaluation of teams. Moreover, they provide valuable information to help coaches devise appropriate tactics for players before or during a match, considering the potential changes in meteorological conditions.

CITATION: Zhong Y, Zhang S, Yi Q, Gómez Ruano MA. The influence of meteorological factors on the technical performance of football teams during matches. Biol Sport. 2024;41(4):165–172.

Received: 2023-08-28; Reviewed: 2023-10-10; Re-submitted: 2024-02-21; Accepted: 2024-02-27; Published: 2024-04-25

Corresponding author:
Qing Yi
College of Physical Education, Dalian University, Dalian, China
E-mail: yiqing1771@outlook.com

ORCID:
Yonghan Zhong
0009-0007-0177-5843

Shaoliang Zhang
0000-0002-0543-7135

Qing Yi
0000-0001-8543-1974

Miguel Ángel Gómez Ruano
0000-0002-9585-3158

Key words:
Soccer
Team sport
Environmental effect
Technical performance
Match analysis

INTRODUCTION

Factors affecting the performance of football teams are complex. Most previous studies have shown that a football team's technical performance is affected by situational factors [1, 2]. The emergence of global warming in addition to situational factors has led researchers to increasingly focus on football players' performance in different weather conditions to explore the key factors that enhance technical and physical performance in different playing meteorological conditions and to prevent sports injuries.

In previous studies, the wet bulb globe temperature (WBGT) has been widely used to explain meteorological factors. It assesses air temperature, relative humidity, wind speed, and solar radiation in its output [3]. However, d'Ambrosio Alfano et al. [4] recently critically reviewed the WBGT and clearly demonstrated that it is becoming obsolete. As with all indices that integrate elements of the thermal environment, measurement errors due to substandard instruments and poor calibration procedures are common. Due to its limitations, WBGT can provide only a general guide to the likelihood of adverse effects of heat [5]. Based on the above, choosing the four basic weather elements over the WBGT index is preferable [6]. In 2011, the proposal of a new heat stress index for outdoor thermal environments began to slowly replace the WBGT: the universal thermal climate index (UTCI) [7]. However, it has been argued that the UTCI is less suitable for assessing environments with high wind speeds [8]. To avoid potential errors in the process of calculating the index, this study evaluated three meteorological variables directly: air temperature, relative humidity, and wind speed.

The football match is played under complex meteorological conditions. Understanding the impacts of meteorological factors on the team's technical performance may help coaches to prepare the upcoming matches better [9]. Many studies have shown that air temperature, relative humidity, and wind speed can have an impact on football technical performance. All the parameters related to

technical performance change when relative humidity and the WBGT index increase by two standard deviations (SDs) [1]. A qualitative analysis by Nassis et al. (2015) demonstrated that successful passing, a technical performance indicator (PI), is significantly correlated with meteorological factors [10]. Grantham et al. (2010) stated that players are not at risk of heat stress when they play in environments below 22°C, are at low risk of heat stress when they play in 22–28°C environments, and at high risk when they play in environments above 28°C [11]. In addition, air temperature and relative humidity also affect the evaporation of sweat and hence body temperature, which subsequently affects the performance of players [12]. Zhou et al. explored the influence of the environment on the sports performance of Chinese Super League players. They found that to improve player performance, a comfort zone of air temperature (10.6 to 22°C) may exist and higher or lower air temperatures may affect player performance during football matches [13]. As relative humidity increases, an athlete's exercise ability in a high-temperature environment gradually decreases, mainly due to the rapid increase of core and skin temperatures, which leads to premature entry into the fatigue stage [12].

Few studies have directly examined the influences of air temperature, relative humidity, and wind speed on team technical performance. Available literature has mainly focused on variance analysis by analysing the differences in game performance in different meteorological environments, but few researchers have performed predictive analysis. Predictive analysis can better predict risk and facilitate better decision making [14]. Therefore, such analysis results can provide more valuable references for team preparation.

Regarding indicator selection, few scholars have screened the PIs included in the analysis. A model with more regressors may reduce bias as well as the accuracy of predictions; therefore, choosing the most important variables is essential [15]. Consequently, the current study aimed to explore the impacts of meteorological variables (air temperature, relative humidity, and wind speed) on the technical performance of teams during UCL. Important features were selected from 31 technical performance variables. Including as many technical variables as possible will allow more accurate screening of variables in the future.

MATERIALS AND METHODS

Sample and variables

This paper explores the impact of meteorological factors on the technical performance of the whole team. Match statistics of teams in the Union of European Football Associations Champions League (UCL) from season 2016/2017 to 2020/2021 were collected from two sources; the data on technical performance and match outcomes were collected from "whoscored.com" (http://www.whoscored.com), whose original data from the company OPTA Sportsdata have been tested with a respectable level of inter-operator reliability (kappa values > 0.90) [16]. The data of air temperature, relative humidity, and wind speed for each match were retrieved from the official UEFA website (http://www.uefa.com). A total of 583 matches (1,166 observations) were selected as the sample based on available data on the official UEFA website after excluding matches without meteorological data. This included 1,166 sets of match outcomes. Thirty-one technical performance-related variables were included in the statistical modelling. Technical actions or events were classified into the following three groups (Table 1): (1) goal scoring, (2) offense, and (3) defence [17]. No human being or animal was involved in this study. Therefore, no written informed consent from the participants or ethical review was required.

Data standardization

Before statistical analysis, data normalization for air temperature, relative humidity, and wind speed data was performed using the min-max method (linear normalization). This method's key advantage is the ability to preserve the relationships between the initial data [18]. Equation (1) shows the formula for min-max normalization.

$$Y = (X_{original} - X_{min}) / (X_{max} - X_{min}) \quad (1)$$

where Xoriginal is the original value of the independent variable, and X_{min} and X_{max} are the minimum and maximum values of the independent variables, respectively. The final adjusted value, Y, is obtained. The descriptive statistics of three meteorological variables are presented in Table 2.

TABLE 1. Selected technical performance-related match variables.

Groups	Variables
Variables related to goal scoring	Shot, Shot on target, Shot from open play, Shot from set piece, Shot from counterattack, Shot from 6 yards box, Shot from 18 yards box, Shot from outside of box
Variables related to offense	Dribble won, Dribble attempt, Dribble past, Dribble success, Corner, Corner accuracy, Accurate pass, Key pass, Pass success, Cross, Through ball, Long ball, Short ball, Possession, Aerial won, Touch
Variables related to defense	Tackle, Tackle attempt, Tackle success, Interception, Foul, Yellow card, Card per foul

TABLE 2. Descriptive statistics for Meteorological variables.

Variables	n	Mean	Standardized mean	Min.	Max.
Temperature (°C)	1166	11.6	0.53	-9	30
Humidity (%)	1166	71.4	0.7	5	100
Wind speed (km/h)	1166	11.5	0.24	1	29

Procedure and statistical analysis

The present study employed the LASSO method to regularize and select features in the regression analysis; this method is reliable for variable selection by regularization, applicable to a large class of linear models. LASSO penalizes models by adding an L1 norm of the model parameters to the cost function. The L1 norm favours models with many coefficients set to 0, effectively performing feature selection by suppressing variables that have a small influence on the target variable, weak predictors correlated to stronger variables, and, in this particular case, variables for which it was not possible to decide on the direction of the effect on match outcome on the basis of the analysed data set [19]. In the LASSO, each regression coefficient is transformed using a constant parameter, λ. As λ increases, the regression coefficient related to the independent variable progressively diminishes and eventually reaches zero. Consequently, the selection of the optimal λ value becomes crucial, as it determines the significant variables with non-zero regression coefficients. The optimal λ value is determined via cross-validation, aiming to minimize the mean squared error (minMSE) or minMSE plus one standard error (minMSE + 1SE) [20].

The LASSO regression approach is employed to select influential feature variables that impact the match outcomes. The match outcomes were used as multi-categorical variable: 3 – win, 1 – draw, and 0 – loss. The technical performance-related variables were employed as the predictors, while the match outcomes were the dependent variables. Cross-validation was performed to obtain the best λ, the minMSE, and minMSE + 1SE values. The primary function employed for cross-validation was cv.glmnet. Notably, when λ equals the minMSE value, most variables exhibit a non-zero regression coefficient, encompassing a more comprehensive range of technical performance measures compared with the minMSE + 1SE scenario. Hence, the minMSE value was used to identify the feature variables with non-zero regression coefficient values, a task accomplished using the coef function. These aforementioned methods were implemented within the glmnet R package [21].

Subsequently, a generalized linear model (GLM) was employed to forecast the influence of air temperature, relative humidity, and wind speed on technical performance. The GLM was implemented using the glmnet function in R (RStudio 4.2.1 version). Distinct Poisson regression analysis was conducted within the model, designating each of the 15 chosen technical performance-related variables as the dependent variable. Meanwhile, three normalized meteorological variables were selected as the independent variables. Given that both teams in a football match are subjected to identical meteorological conditions, the impact of other internal factors pertaining to the teams (e.g., home and away, team ability, or opponent's strength) is extensively mitigated when matches are analysed holistically. To estimate the specific influence of meteorological variables on technical performance-related variables, odds ratios (ORs)

TABLE 3. Descriptive statistics for fifteen technical performance variables.

Variables	n	Mean	SD	Min.	Max.
Shot	1166	12.82	5.723	1	35
Shot from Open Play	1166	9.14	4.443	0	29
Shot from Counterattack	1166	0.39	0.742	0	4
Shot from 6 Yards Box	1166	6.50	7.896	0	45
Shot from Outside of Box	1166	39.49	17.161	0	100
Long Ball	1166	58.38	13.828	15	120
Through Ball	1166	1.59	1.921	0	14
Cross	1166	16.45	8.548	0	62
Corner Accuracy	1166	45.20	29.766	0	100
Accurate Pass	1166	418.14	140.487	100	979
Possession	1166	50.00	12.079	19	81
Dribble Success	1166	60.02	13.846	0	100
Dribble Won	1166	10.49	4.721	0	33
Tackle Success	1166	62.67	11.197	16	100
Card per Foul	1166	16.52	11.335	0	71

accompanied by 95% confidence intervals (CIs) were employed. The point estimate of the OR was deemed statistically significant at a P level below 0.05 if the 95% CI did not include 1 [22]. Notably, a 10% change corresponds to a 1SD increase in the air temperature, relative humidity, and wind speed variables, yielding a 10% likelihood of change in the technical performance-related variables. This change is considered as the minimum meaningful alteration in value [23, 24].

RESULTS

Indicator selection

Figure 1 shows the number of technical performance variables for λ values of minMSE and minMSE + 1SE. We found that λ values of minMSE provided the following 15 technical performance variables: shot, shot from open play, shot from counter attack, shot from the 6-yard box, shot from outside of the box, long ball, through ball, cross, corner accuracy, accurate pass, possession, dribble success, dribbles won, tackle success, and cards per foul. These 15 technical performance variables were identified as important factors that could significantly influence match outcomes. Figure 2 shows the screened variables and their regression coefficients, ranked according to their importance regarding their impact on match outcomes. Descriptive statistics (mean ± SD) for these 15 technical performance variables are presented in Table 3.

The results showed that shot from counterattack had the greatest impact on match outcome, and a positive correlation was identified (regression coefficient, RC = 0.2722). Through ball, shot, shot from open play, tackle success, shot from the 6-yard box, possession, accurate pass, long ball, dribble success, dribbles won, and corner accuracy had positive impacts on match outcome (RC = 0.0737, 0.0664, 0.0121, 0.0086, 0.0070, 0.0067, 0.0018, 0.0015, 0.0013, 0.0007, and 0.0002, respectively). Cards per foul, shot from outside of the box, and cross were negatively correlated with match outcome (RC = -0.0095, -0.0174, and -0.0698, respectively).

Influence of meteorological factors on technical performance

Figures 3, 4, and 5 present the effects of air temperature, relative humidity, and wind speed on the technical performance variables. The results revealed that nine technical performance variables were significantly affected by air temperature. Air temperature had the most significant and negatively correlated effect on shot from counterattack, indicating that every unit increase in air temperature was associated with a 45% decrease in the odds of shot from counterattack (OR = 0.55, 95% CI: 0.30 to 0.98). Corner accuracy (OR = 1.10, 95% CI: 1.04 to 1.16), tackle success (OR = 1.10; 95% CI: 1.05 to 1.15), and shot from outside of the box (OR = 1.06, 95% CI: 1.01 to 1.13) were positively affected by air temperature, but only small effects were observed. Accurate pass (OR = 0.95, CI: 0.93 to 0.97) and dribble success (OR = 0.92, CI: 0.87 to 0.96) were also negatively affected by air temperature, but the odds were less than 10%.

The results also showed that dribbles won was significantly affected by air temperature and relative humidity; each unit increase in air temperature and relative humidity had a 25% (OR = 0.75, 95% CI: 0.67 to 0.84) and 13% (OR = 0.87, 95% CI: 0.78 to 0.96) odds of a decrease in the number of dribbles won, respectively. An increase in wind speed increased the odds of shot from the 6-yard box by 21% (OR = 1.21, 95% CI: 1.05 to 1.39), while an increase in air temperature decreased the odds of shot from the 6-yard box by 17% (OR = 0.83, 95% CI: 0.72 to 0.96). Cards per

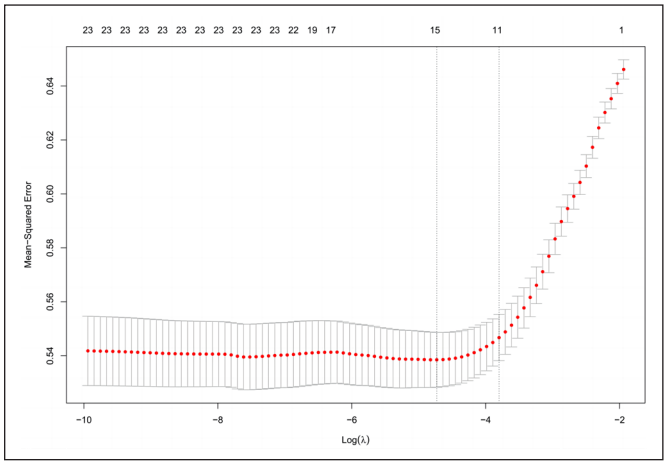


FIG. 1. Plot of the Mean-Squared Error (MSE) and the number of technical performance variables in the model as functions of log( ) for the cross-validation analyses. The red dots are the mean form the cross-validation and the bars indicate mean + 1SE and mean − 1SE, respectively. The minMSE + 1SE of minMSE (right) and minMSE (left) are indicated by the dashed vertical lines.

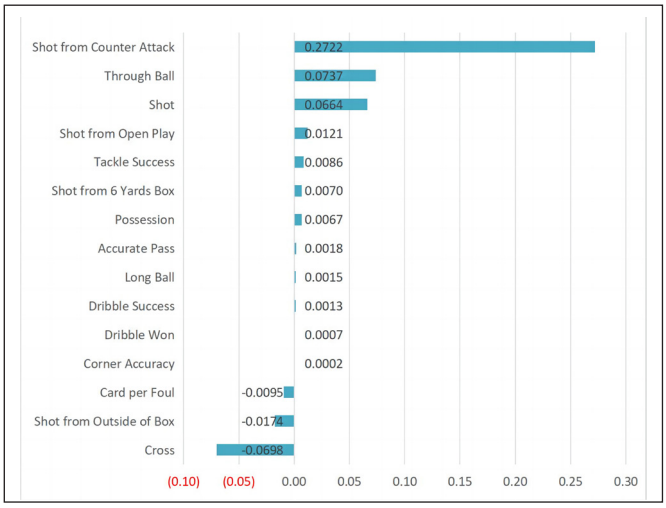


FIG. 2. Regression coefficients for LASSO screening variables.

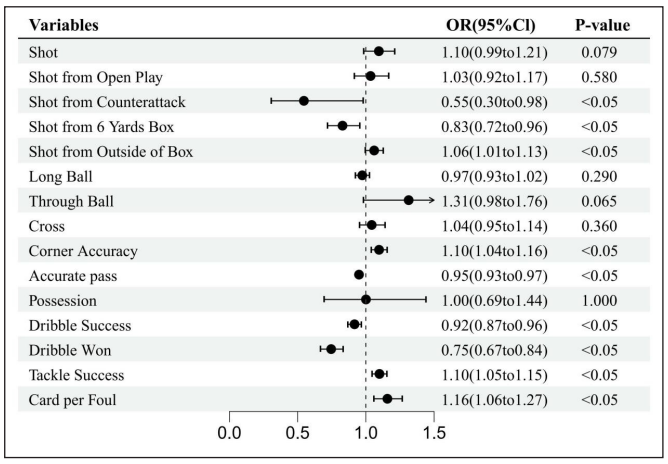


FIG. 3. Forest diagrams illustrating the results of the effects of temperature on technical performance variables. Effects are shown as for each standard deviation increase in temperature, the odds that the variable will increase by 1 unit is (1-OR)*100%. OR odds ratio, CI confidence interval.

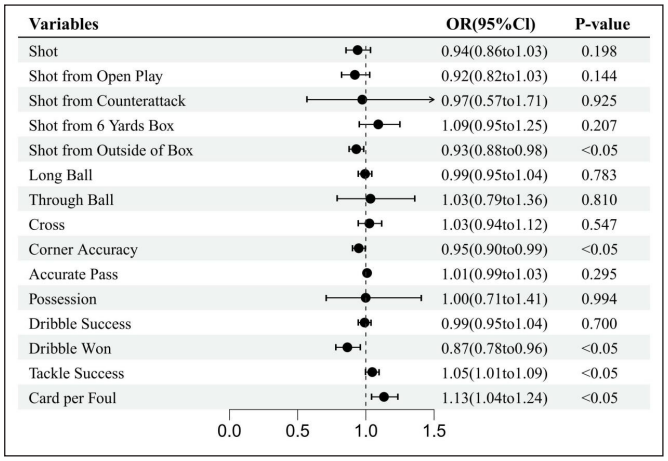


FIG. 4. Forest diagrams illustrating the results of the effects of humidity on technical performance variables. Effects are shown as for each standard deviation increase in humidity, the odds that the variable will increase by 1 unit is (1-OR)*100%. OR odds ratio, CI confidence interval.

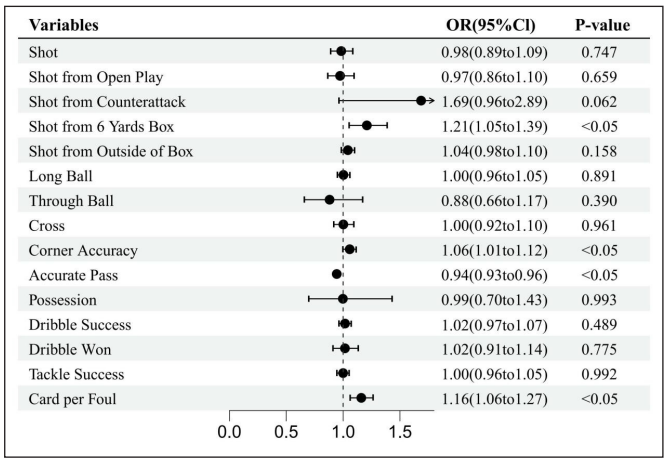


FIG. 5. Forest diagrams illustrating the results of the effects of wind speed on technical performance variables. Effects are shown as for each standard deviation increase in wind speed, the odds that the variable will increase by 1 unit is (1-OR)*100%. OR odds ratio, CI confidence interval.

foul was the only variable that was significantly affected by air temperature, relative humidity, and wind speed. A unit increase in air temperature, relative humidity, and wind speed led to a 16% increase (OR = 1.16, 95% CI: 1.06 to 1.27), 13% (OR = 1.13, 95% CI: 1.04 to 1.24), and 16% (OR = 1.16, 95% CI: 1.06 to 1.27) increase, respectively, in the odds of cards per foul.

DISCUSSION

The current study identified the key PIs that can significantly affect match outcome, and a predictive analysis was performed to quantify the impacts of meteorological factors on teams' technical performance in the UEFA Champions League. The results showed that 1) shot, shot from open play, shot from counter attack, shot from the 6-yard box, shot from outside of the box, long ball, through ball, cross, corner accuracy, accurate pass, possession, dribble success, dribbles won, tackle success, and card per foul were the important technical PIs that significantly affected match outcome, and shot from counterattack had the greatest impact; and 2) air temperature, relative humidity, and wind speed had the most significant influence on shot from counterattack, dribbles won, shot from the 6-yard box, and cards per foul.

Factors influenced by a single meteorological factor

The results revealed that most of the variables related to shot and offense (shot from open play, shot from counterattack, dribbles won, and possession) were important technical indicators that distinguished the match results (winning, drawing, and losing). This finding is consistent with those of previous studies [25, 17]. The LASSO regression results showed that shot from counterattack was the most important technical PI. This means that when there are more shots from counterattacks, the probability of winning the match is high. This trend is partially similar to the research conducted by Sarmento et al. (2018), who argued that teams that use counterattacking tactics compared with positional play were 40% more likely to win a game [26]. However, in the current study, we found that teams' performance in counterattack was strongly influenced by air temperature. Previous studies have shown that higher air temperature reduced the high-intensity effort of players in all playing positions [1]. When a player or team made a counterattack, most of their behaviour was associated with high-intensity actions [27]; the higher the air temperature was, the lower was the number of counterattacks, with correspondingly less chance of counterattack shots. From a physiological perspective, counterattack in football is a short-term, high-intensity action [28]. This action is characterized by anaerobic metabolism [29], and anaerobic exercise is largely influenced by air temperature [30]. Therefore, when the meteorological condition worsens, a more direct or faster attack may make it harder for the team to achieve the desired goal [31]. These findings highlighted the importance of considering the effects of air temperature on team performance during a match.

Factors influenced by two meteorological factors

Contrary to the previous view that meteorological factors have little impact on a player's technical performance [1], one new finding in this study was that both dribbles won and shot from the 6-yard box were significantly influenced by two meteorological factors. The reason for this difference may be attributed to the cumulative effect of player performance, implying that small differences in player technical performance can contribute to significant differences at the team level [2]. Our results show that when air temperature and relative humidity increase, the odds of dribbles won decrease. Previous studies have shown that playing football in hot and humid conditions increases the body's sweating rate, leading to dehydration. Since electrolytes help to produce nerve impulses and transmit these impulses to the muscles and brain, imbalances in electrolyte concentrations caused by sweating can impair or reduce muscle, cognitive, and neurotransmission functions [32]. When a player's cognitive function and reaction decrease, it can severely affect their judgment of movement and, consequently, dribble performance. This means that when the air temperature and relative humidity on the field are high, players should keep the ball for the shortest possible time.

It is well known that the higher the wind speed is, the greater is the ball and player resistance [33]. The current study demonstrated that the odds of increasing the number of shots from the 6-yard box with increasing wind speed was 21%. However, the trajectory of a football depends not only on wind speed but also on wind direction and other factors [34]. Since this study only considered wind speed indicators, it is not possible to confirm that a player's willingness to shoot from close range is caused by the wind's resistance to the ball. Another interesting finding of this study is that teams were more likely to try shooting from a distance when air temperature increased. This may be because an increase in air temperature leads to a warmer core temperature in the attacking players, making them prone to fatigue [12]. Consequently, the players do not have a strong desire to increase the passes or physically confront their opponents inside the 6-yard box. Depending on the air temperature at the time of the match, coaches should decide whether they want their players to play more long-range shots or pass into the 6-yard box to try scoring a goal.

Factors influenced by three meteorological factors

"Cards per foul" has rarely been mentioned as an indicator in other articles. However, as an important indicator in this study that affects match outcome, it is influenced by air temperature, relative humidity, and wind speed. The findings showed that these three meteorological conditions increase the cards per foul.

In fact, researchers have demonstrated that climatic environments affect mood and cognition to a great extent, and air temperature is a major factor in this relationship [35]. A consequence of decreased positive affect in hot weather is the increase in aggressive acts of violence [36, 37]. During autumn and winter, when wind speed increases, people's autonomous attention naturally decreases [38]. This means that as the air temperature and relative humidity increase, players will become more 'aggressive,' leading to more foul play and, therefore, higher likelihood of receiving a red or yellow card. As the referees are also on the football field during a match, their decisions are influenced by meteorology. When referees, both central and assistant referees, are in a mildly dehydrated state, their concentration and distance judgment are affected, which affects their decisions [39]. This can better explain why all the three meteorological factors affect "cards per foul." Therefore, when air temperature, relative humidity, and wind speed increase, players must control their emotions and avoid physical violations. In future research, more meteorological variables such as altitude and site conditions should be considered. Similarly, future research should not be limited to variance analysis alone but should include predictive analysis.

The findings of the current study may help coaches and analysts to better understand the influences of meteorological factors on important technical variables during the evaluation of teams' technical performance. However, the limitations of the current study should be noted. Firstly, only the statistics of technical actions and events during matches were analysed, while information on physical and tactical behaviours was not considered due to the availability of match data. This may have restricted the understanding of teams' match performance. Secondly, situational variables were not included in this study, which could have led to a less comprehensive understanding of the influence of meteorological factors. Further studies should assess the interactive effects of meteorological factors. Exploring the impact of meteorological factors on more dimensions of technical performance and assessing more meteorological factors can be incorporated in future studies. Lastly, only technical variables and three meteorological variables were analysed in this study. More variables that can affect the team's match performance, such as tactical and physical variables, and more meteorological factors, such as wind direction, should also be considered in future research to provide more valuable insights for coaches.

CONCLUSIONS

In summary, most of the important technical performance variables in the UCL are shot-related and passing-related variables. Among these variables, shot from counterattack is the variable that was most significantly influenced by only air temperature. "Dribbles won" and "shots from the 6-yard box" were significantly influenced by a humid and hot environment while "shots from the 6-yard box" was also positively affected by wind speed. Cards per foul can be positively influenced by all three meteorological factors simultaneously.

This study emphasizes the need for coaches to pay close attention to changes in meteorology before and during each match. During matches, meteorological conditions changed dynamically; effective tactical adjustments should be made in the second half based on changes in any of these three factors.

Acknowledgements

The contributions of the authors are gratefully acknowledged. This research project received no external financial assistance. The results of this study do not constitute endorsement for or against the FMS by the authors, or the editors of Biology of Sport.

Conflict of interest declaration

The authors declared no conflict of interest.

REFERENCES

1. Chmura P, Liu H, Andrzejewski M, Chmura J, Kowalczuk E, Rokita A, Konefal M. Is there meaningful influence from situational and environmental factors on the physical and technical activity of elite football players? Evidence from the data of 5 consecutive seasons of the German Bundesliga. PLoS One. 2021; 16(3):e0247771. doi: https://doi.org/10.1371/journal.pone.0247771.
2. Yi Q, Yang J, Wang X, Gai Y, Gomez-Ruano MA. Interactive Effects of Situational Variables Regarding Teams' Technical Performance in the UEFA Champions League. Front Psychol. 2022; 13:781376. doi: https://doi.org/10.3389/fpsyg.2022.781376.
3. Liljegren JC, Carhart RA, Lawday P, Tschopp S, Sharp R. Modeling the wet bulb globe temperature using standard meteorological measurements. J Occup Environ Hyg. 2008; 5(10):645–655. doi: https://doi.org/10.1080/15459620802310770.
4. d'Ambrosio Alfano FR, Malchaire J, Palella BI, Riccio G. WBGT Index Revisited After 60 Years of Use. Ann Occup Hyg. 2014; 58(8):955–70. doi: https://doi.org/10.1093/annhyg/meu050.
5. Budd GM. Wet-bulb globe temperature (WBGT)--its history and its limitations. J Sci Med Sport. 2008; 11(1):20–32. doi: https://doi.org/10.1016/j.jsams.2007.07.003.
6. Brocherie F, Millet GP. Is the Wet-Bulb Globe Temperature (WBGT) Index Relevant for Exercise in the Heat? Sports Med. 2015; 45(11):1619–1621. doi: https://doi.org/10.1007/s40279-015-0386-8.
7. Bröde P, Fiala D, Błażejczyk K, Holmér I, Jendritzky G, Kampmann B, Tinz B, Havenith G. Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). Int J Biometeorol. 2011; 56(3):481–494. doi: https://doi.org/10.1007/s00484-011-0454-1.
8. Blazejczyk K, Epstein Y, Jendritzky G, Staiger H, Tinz B. Comparison of UTCI to selected thermal indices. Int J Biometeorol. 2011; 56(3):515–535. doi: https://doi.org/10.1007/s00484-011-0453-2.
9. Trewin J, Meylan C, Varley MC, Cronin J. The influence of situational and environmental factors on match-running in soccer: a systematic review. Sci Med Footb. 2017; 1(2):183–194. doi: https://doi.org/10.1080/24733938.2017.1329589.
10. Nassis GP, Brito J, Dvorak J, Chalabi H, Racinais S. The association of environmental heat stress with performance: analysis of the 2014 FIFA World Cup Brazil. Br J Sports Med. 2015; 49(9):609–613. doi: https://doi.org/10.1136/bjsports-2014-094449.
11. Grantham J, Cheung SS, Connes P, Febbraio MA, Gaoua N, Gonzalez-Alonso J, Hue O, Johnson JM, Maughan RJ, Meeusen R, Nybo L, Racinais S, Shirreffs SM, Dvorak J. Current knowledge on playing football in hot environments. Scand J Med Sci Sports. 2010; 20 Suppl 3:161–167. doi: https://doi.org/10.1111/j.1600-0838.2010.01216.x.
12. Maughan RJ, Otani H, Watson P. Influence of relative humidity on prolonged exercise capacity in a warm environment. Eur J Appl Physiol. 2012; 112(6):2313–2321. doi: https://doi.org/10.1007/s00421-011-2206-7.
13. Zhou C, Hopkins WG, Mao W, Calvo AL, Liu H. Match Performance of Soccer Teams in the Chinese Super League-Effects of Situational and Environmental Factors. Int J Environ Res Public Health. 2019; 16(21). doi: https://doi.org/10.3390/ijerph16214238.
14. Halladay SD. Using predictive analytics to improve decisionmaking. The Journal of Equipment Lease Financing. 2013; 31(2):B1–B6.
15. Muthukrishnan R, Rohini R. LASSO: A feature selection technique in predictive modeling for machine learning. 2016 IEEE international conference on advances in computer applications (ICACA). 2016; pp. 18–20. doi: 10.1109/ICACA.2016.7887916.
16. Liu H, Hopkins W, Gómez AM, Molinuevo SJ. Inter-operator reliability of live football match statistics from OPTA Sportsdata. Int J Perform Anal Sport. 2017; 13(3):803–821. doi: https://doi.org/10.1080/24748668.2013.11868690.
17. Liu H, Gomez MA, Lago-Penas C, Sampaio J. Match statistics related to winning in the group stage of 2014 Brazil FIFA World Cup. J Sports Sci. 2015; 33(12):1205–1213. doi: https://doi.org/10.1080/02640414.2015.1022578.
18. Han J, Pei J, Tong H. Data mining: concepts and techniques. Morgan Kaufmann. 2022.
19. Konefal M, Chmura P, Kowalczuk E, Figueiredo AJ, Sarmento H, Rokita A, Chmura J, Andrzejewski M. Modeling of relationships between physical and technical activities and match outcome in elite German soccer players. J Sports Med Phys Fitness. 2019; 59(5):752–759. doi: https://doi.org/10.23736/S0022-4707.18.08506-7.
20. Waldmann P, Meszaros G, Gredler B, Fuerst C, Solkner J. Evaluation of the lasso and the elastic net in genome-wide association studies. Front Genet. 2013; 4:270. doi: https://doi.org/10.3389/fgene.2013.00270.
21. Friedman J, Hastie T, Tibshirani R. Regularization Paths for Generalized Linear Models via Coordinate Descent. J Stat Softw. 2010; 33(1):1–22. doi: 10.1163/ej.9789004178922.i-328.7.
22. Zhu Q, Zhang Q, Zeng Q, Yu Z, Tao C, Yang W. Efficacy of mechanical bowel preparation with polyethylene glycol in prevention of postoperative complications in elective colorectal surgery: a meta-analysis. Int J Colorectal Dis. 2010; 25(2):267–275. doi: https://doi.org/10.1007/s00384-009-0834-8.
23. Higham DG, Hopkins WG, Pyne DB, Anson JM. Performance indicators related to points scoring and winning in international rugby sevens. J Sports Sci Med. 2014; 13(2):358–364.
24. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1):3–13. doi: https://doi.org/10.1249/MSS.0b013e31818cb278.
25. Lago-Ballesteros J, Lago-Peñas C. Performance in team sports: Identifying the keys to success in soccer. J Hum Kinet. 2010; 25(1):85–91.
26. Sarmento H, Figueiredo A, Lago-Penas C, Milanovic Z, Barbosa A, Tadeu P, Bradley PS. Influence of Tactical and Situational Variables on Offensive Sequences During Elite Football Matches. J Strength Cond Res. 2018; 32(8):2331–2339. doi: https://doi.org/10.1519/JSC.0000000000002147.
27. Forcher L, Forcher L, Wasche H, Jekauc D, Woll A, Gross T, Altmann S. Is ball-possession style more physically demanding than counter-attacking? The influence of playing style on match

performance in professional soccer. Front Psychol. 2023; 14:1197039. doi: https://doi.org/10.3389/fpsyg.2023.1197039.
28. Racinais S, Cocking S, Periard JD. Sports and environmental temperature: From warming-up to heating-up. Temperature (Austin). 2017; 4(3):227–257. doi: https://doi.org/10.1080/23328940.2017.1356427.
29. Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The evolution of physical and technical performance parameters in the English Premier League. Int J Sports Med. 2014; 35(13):1095–1100. doi: https://doi.org/10.1055/s-0034-1375695.
30. Cheung S, Robinson A. The influence of upper-body pre-cooling on repeated sprint performance in moderate ambient temperatures. J Sports Sci. 2004; 22(7):605–612. doi: https://doi.org/10.1080/02640410310001655813.
31. Mitrotasios M, Gonzalez-Rodenas J, Armatas V, Aranda R. The creation of goal scoring opportunities in professional soccer. Tactical differences between Spanish La Liga, English Premier League, German Bundesliga and Italian Serie A. Int J Perform Anal Sport 2019; 19(3):452–465. doi: https://doi.org/10.1080/24748668.2019.1618568.
32. Brewer J, Warren L. A Review of the Potential Implications of Hot and Humid Environmental Conditions on Soccer Match-Play Performance. Int J Sci Basic Appl Res 2014; 1:584–589.
33. Asai T, Seo K, Kobayashi O, Sakashita R. Fundamental aerodynamics of the soccer ball. Sports Engineering. 2007; 10:101–109. doi: https://doi.org/10.1007/BF02844207.
34. Goff JE, Hong S, Asai T. Influence of Surface Properties on Soccer Ball Trajectories. Proceedings. 2020; 49(1):143. doi: https://doi.org/10.3390/proceedings2020049143.
35. Keller MC, Fredrickson BL, Ybarra O, Côté S, Johnson K, Mikels J, Wager T. A warm heart and a clear head: The contingent effects of weather on mood and cognition. Psychol Sci. 2005; 16(9):724–731. doi: https://doi.org/10.1111/j.1467-9280.2005.0160.
36. Anderson CA. Temperature and aggression: ubiquitous effects of heat on occurrence of human violence. Psychol Bull 1989; 106(1):74. doi: https://doi.org/10.1037/0033-2909.106.1.74.
37. Baron RA, Bell PA. Aggression and heat: the influence of ambient temperature, negative affect, and a cooling drink on physical aggression. J Pers Soc Psychol. 1976; 33(3):245. doi: https://doi.org/10.1037/0022-3514.33.3.245.
38. Pavlov KI, Syrtsev AV, Mukhin VN, Archimuk AN, Mikheeva EA, Nikolaeva SV, Andieva NM, Kamenskaya VG, Petrenko MI. The Effect of Environmental Factors on the Cognitive Functions of Cadets at a Military Institute. Izvestiya, Atmospheric and Oceanic Physics. 2020; 55(10):1465–1487. doi: https://doi.org/10.1134/s0001433819100086.
39. Houssein M, Lopes P, Fagnoni B, Ahmaidi S, Yonis SM, Lepretre PM. Hydration: The New FIFA World Cup's Challenge for Referee Decision Making? J Athl Train. 2016; 51(3):264–266. doi: https://doi.org/10.4085/1062-6050-51.3.04.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.139071
© Institute of Sport – National Research Institute

Balancing the load: A narrative review with methodological implications of compensatory training strategies for non-starting soccer players

AUTHORS: Filipe Manuel Clemente[1,2,3], Guglielmo Pillitteri[4,5], Luiz H. Palucci Vieira[6], Alireza Rabbani[7,8], Piotr Zmijewski[9], Marco Beato[10]

[1] Escola Superior Desporto e Lazer, Instituto Politécnico de Viana do Castelo, Rua Escola Industrial e Comercial de Nun'Álvares, 4900-347 Viana do Castelo, Portugal
[2] Sport Physical Activity and Health Research & Innovation Center, 4960-320 Viana do Castelo, Portugal
[3] Gdansk University of Physical Education and Sport, 80-336 Gdańsk, Poland
[4] Sport and Exercise Sciences Research Unit, Department of Psychology, Educational Science and Human Movement, University of Palermo, Palermo, Italy
[5] PhD Program in Health Promotion and Cognitive Sciences, University of Palermo, Palermo, Italy
[6] Universidad César Vallejo (UCV), Facultad de Ingeniería y Arquitectura, Escuela Profesional de Ingeniería Industrial, Grupo de investigación en Tecnología aplicada a Seguridad ocupacional, Desempeño y Calidad de vida (GiTaSyC), Campus Callao, 07001 Lima, Perú
[7] Sport Science Department, Ittihad Kalba F.C, UAE
[8] Sport Science Department, OFI Crete F.C, Crete, Greece
[9] Jozef Pilsudski University of Physical Education in Warsaw, Warsaw, Poland
[10] School of Health and Sports Sciences, University of Suffolk, Ipswich, UK

Corresponding author:
Filipe Manuel Clemente
Escola Superior Desporto e Lazer
Instituto Politécnico de Viana do Castelo, Rua Escola Industrial e Comercial de Nun'Álvares
4900-347 Viana do Castelo
Portugal
E-mail: filipe.clemente5@gmail.com

ORCID:
Filipe Manuel Clemente
0000-0001-9813-2842
Guglielmo Pillitteri
0000-0002-0905-6401
Luiz Palucci Vieira
0000-0001-6981-756X
Alireza Rabbani
0000-0002-1500-0447
Piotr Zmijewski
0000-0002-5570-9573
Marco Beato
0000-0001-5373-2211

ABSTRACT: New training approaches have emerged advocating for the implementation of compensatory physical training. This approach aims to provide additional training that balances the load typically experienced by non-starters during a match. This may help maintain their readiness and ensures that their physical fitness is not compromised by the reduced exposure to match loads. Thus, this narrative review aims to describe the differences in external loads between starting and non-starting players and describe the studies conducted in compensatory training. Studies examining external load metrics such as total distances covered, high-speed running, and sprinting suggest that, adjusted for playing time, values are often higher in non-starting players. Although not standardized, there is an obvious decrease in exposure for these critical variables in non-starters. Additionally, internal load parameters such as perceived exertion and heart rate tend to be higher in starting players. Regarding the physical fitness impacts, evidence suggests differences observed between starters and non-starters in some aspects of physical performance, although the extent and significance of these differences can vary. The studies on compensatory training are limited, and the typical approach usually centres on running-based exercises and small-sided games, offering differing approaches to address the physical needs. The gap in research underscores the necessity for improved study designs that can shed light on the real impact of compensatory training. Presently, the practice of compensatory training has been adopted, yet a definitive understanding of its genuine influence, particularly in terms of enhancing physical fitness and mitigating injury risks, remains elusive.

CITATION: Clemente FM, Pillitteri G, Palucci Vieira LH et al. Balancing the load: A narrative review with methodological implications of compensatory training strategies for non-starting soccer players. Biol Sport. 2024;41(4):173–185.

Received: 2023-12-19; Reviewed: 2024-02-08; Re-submitted: 2024-02-09; Accepted: 2024-04-03; Published: 2024-04-25.

Key words:
Football
Top-up
Sports training
High-intensity interval training

INTRODUCTION

Research focusing on the disparities in training and match loads between non-starter players and starters has been steadily increasing over the years. A very basic search on PubMed using the terms ("non-starter*" AND (soccer OR "football*")) yielded results indicating that publications since 2021 constitute 48% of the evidence available on this topic as of February 9, 2024.

Non-starter players, including substitute players and those not utilized during an official game, typically comprise those who are not chosen to participate from the commencement of a soccer match [1, 2]. According to regulations, the number of substitutions permitted in official elite soccer matches ranges from a maximum of three to five, depending on the specific rules of the federation, as outlined in the Laws of the Game for the 2023/2024 season [3]. These limitations result in non-starter players having a limited number of opportunities to partake in matches [4].

This situation implies that within the overall duration of a standard match – consisting of 90 minutes of regular playtime augmented by any supplementary time contingent upon the match's unfolding (sometimes exceeding ten extra minutes) – certain players have little or no involvement [4, 5]. Match load denotes the combination of increased physical demands and intensity witnessed in soccer matches [6, 7]. Consequently, the absence of this relevant stimulus may lead to an inadequacy in load exposure for certain players [8]. Such a disparity may lead to an imbalance between those players who start matches and those who do not [2]. This could potentially result in a diminished capacity to conform to the anticipated chronic load [9] or to achieve the requisite physical fitness adaptation demanded at the level of competitive match play, especially in cases where non-starter players remain in such a role over a long period [10].

Given this unique circumstance, strength and conditioning coaches have begun to incorporate compensatory training methodologies [11]. These include running-based high-intensity interval training (HIIT) or small-sided games (SSG) [4, 12], intending to potentially rectify the load imbalance experienced by non-starting players. Consequently, soccer coaches and trainers, particularly in professional settings, have increasingly included supplementary 'top-up' conditioning sessions tailored for players who have remained unused or have only participated partially during official matches [4, 12].

Termed compensatory training or colloquially referred to as "top-up" training, these sessions are frequently administered within the post-match context – immediately following the conclusion of a match [13, 14]. Additionally, in alternative contexts, these supplementary sessions are scheduled for the day after the match (i.e., MD+1), synchronizing with the recovery phase of the players who started the match. In a survey encompassing 33 soccer coaches, it was revealed that 39% of respondents often devise training regimens and preparatory strategies tailored to non-match days for substitute players [4]. Meanwhile, 8% indicated that such strategies were occasionally employed, with an equivalent proportion employing them consistently [4].

Recognizing the paramount importance of ensuring equitable load exposure for non-starting players – akin to their counterparts who participate from the outset of a match – with the overarching goal of optimizing their ability to manage load and navigate diverse scenarios, the implementation of compensatory training emerges as a pivotal strategy [15, 16]. This strategy aims to equalize the chronic load of non-starting players, prevent detraining, and ensure the appropriate stimulus for enhancing physical performance improvements [17]. Additionally, it addresses the unique constraints imposed by soccer's limitation on multiple substitutions, which sets it apart from other sports.

Despite the increasing popularity of compensatory training in soccer strength and conditioning practices, existing research in this area has not yet been systematically reviewed. This often leads to sporadic selection of articles, failing to provide an overview and summarized evidence necessary for identifying gaps and aiding practitioners in refining their practices. Given the emergent nature of this topic in recent years, a narrative review can offer interpretation, critique, and significant contributions to deepening understanding [18]. Such an approach may shed light on the current state of the field and uncover underexplored topics for further investigation.

Considering this context and opportunity, the present narrative review aims to elucidate compensatory training studies while providing an overview of the current state of research regarding comparisons between starters and non-starters in terms of match load, training load, and physical fitness differences. In addition to describing existing studies, this review seeks to identify research gaps and offer a practical example of compensatory training implementation based on available literature findings.

Distinguishing factors between starting and non-starting players in soccer

When examining differences between starters and non-starters, the studies primarily focus on two main dimensions [5, 19, 20]. One dimension pertains to the exposure of both groups to regular match loads, which ultimately may affect the total weekly load accumulated [2, 19, 20]. As a potentially related factor, these disparities may influence physical fitness adaptations to some extent [21]. Therefore, both topics are worthy of description, with the aim of identifying what the literature describes regarding differences between starters and non-starters.

Match load disparities between starting and non-starting players in soccer

The total distance covered (TD) is a traditional metric of external load and was generally greater in starting as compared to non-starting players in studies including senior male [22–25], female [26, 27] or youth (male) athletes [28]. Divergent results were found only in a separate study combining data (sum) of replacement and replaced players [29] and another one using only friendly matches [30]. In these cases, male senior starting athletes showed lower in-game TD or no differences as compared to non-starting peers. In studies taking in-game TD standardized by playing time, contrasting results to those reported for total TD were observed; higher values of standardized TD were reported for non-starting male youth [31, 32] or senior players [23, 33–40], in a total of 11 studies, while two demonstrated no differences [22, 41]. In female seniors, the results are not yet conclusive, because the two existing studies reported conflicting evidence of no between-status differences [42] or higher values in non-starting athletes [43].

Concerning high-speed running (HSR) outputs, mixed results were identified for the total amount expressed in male senior players, i.e. starting [24, 25, 40] and non-starting [29, 30, 44] having superior distances covered to their peers in three studies each. On the other hand, in-game HSR distance standardized by playing time was consistently reported to be higher in non-starting athletes [33–39, 41, 45].

Similar findings were identified in youth, in which no between-status difference [28] or higher values in starters [46] occurred simultaneously when taking absolute HSR data while standardization by playing time revealed superior distances at HSR in non-starters [31, 32]. In female senior studies indicated higher TD at HSR in starters [26, 27]; when adjusting by playing time one study showed higher values in non-starters [43] and another no between-status differences [42].

In the sprinting domain, there is an equivalent number of studies which found higher total values in starters [23–25] and no between-status differences or higher values in non-starters [29, 30, 44]. Conversely, there was a general tendency for non-starting players to experience greater standardized – by playing time – sprinting activity, i.e. six studies [35, 37–39, 41, 45] versus two showing similar results among statuses [22, 34]. In male youth players, no consensus was reached regarding whether total sprinting is dependent on player status [28, 46] while no studies were found reporting standardized sprinting data. For female senior players, the results of sprinting activity (total and standardized) were in line with those of HSR mentioned in the previous paragraph.

Peak demands – or worst-case scenarios (WCS) – represent a type of metric that has gained popularity over recent years and was also appraised. In this sense, peak game speed (also known as in-game maximal sprinting speed) was demonstrated most frequently to be faster in starting male senior players as compared to non-starting peers [35, 37–39]. The exceptions showing no differences were the same as in the case of total TD [29, 30], in other words, derived from observations of only friendly events or official ones yet calculating peak speed as the highest value between players involved in a substitution (pooling the starting/replaced and non-starting/replacement players). Regarding the WCS for TD, mixed results of being greater [47] or lower [48] in starting players were simultaneously identified, with also only a trend towards differences between status in WCS for HSR and sprinting. However, additional studies are needed to draw firm conclusions.

From the perspective of internal load parameters, match-derived ratings of perceived exertion were consistently greater in starting as compared to non-starting male (youth/senior) and female players [27, 30–32, 49–51] and the same seems valid for heart rate indices [25, 46]. Finally, across the aforementioned studies reporting in-game internal and/or external load measures, exposure – playing time – of non-starting male and female senior players ranged respectively from 13 ± 6 [38] to 25 ± 7 minutes [36] and 22 ± 13 [43] to 36 ± 14 minutes [26]. In young male soccer players playing time ranged from 23 ± 13 [50] to 50 ± 7 minutes [28], while there were no reports for young female soccer players among studies examined here.

Physical fitness disparities between starting and non-starting players in soccer

A high fitness level can be considered an important condition to allow soccer players to withstand the match demand characterized by high intensity actions interposed by lower intensity activities. The unbalanced external load exposure during official matches between starter and non-starter players could determine less physical fitness conditioning for players with inadequate play time or adjustment in physical training such as compensatory training (e.g., intermittent running, sprint training or SSG).

Aerobic fitness has been considered one of the most important physical variables at a high soccer level [52, 53]. Different markers such as maximal oxygen consumption ($\dot{V}O_{2max}$), have been related to competitive ranking or team level [54]. Worth noting, in-season fixture congestion may reduce the opportunities for implementing physical training that could progressively lead to aerobic fitness deterioration in the long term.

Sporis and colleagues [55] found that official match play time was related to maintenance of physical fitness in professional soccer, while in another study [21] no individual negative change occurred for the non-starters in terms of $\dot{V}O_{2max}$ compared to starters who had a more pronounced aerobic decrement. Moreover, the same authors reported that the mean team velocity at maximal oxygen uptake was not statistically significantly different between July and December for both starter and non-starter elite male soccer players [21]. A study [56] carried out on collegiate female soccer players reported no significant differences in physical ability between non-starters and starters by assessing 30-m sprint time, pro-agility test, and Yo-Yo intermittent recovery test level 1 (YYIR1) scores. Similarly, a study [57] compared the physical features and performances of Japanese elite female soccer players and found no significant difference in physical performance between starters and non-starters.

Conversely, the authors observed a higher value in starters in terms of the maximum isokinetic concentric strength performed by fast contractions such as an angular velocity of 300°/s compared to non-starters [57]. This result indicates a greater power level for the players most involved in official matches. The ability to develop actions at high intensity is related to the ability to integrate speed and changes of direction, assessed by very high-intensity running and sprint distance [58]. For this reason, a study [19] that involved a Colombian youth women's soccer team analysed the relationship of the physical variables of the squat jump, counter movement jump, counter movement with arms, right leg-left leg asymmetry, hamstring strength, change of direction, and speed in 5, 10, and 15 m as an influence of being a starter and non-starter. The authors found no differences in strength capacities and change of direction between starters and non-starters [19]. These results show that the starting and non-starting players present a similar physical performance evaluated based on strength, asymmetries, hamstring strength, change of direction, and speed.

Given the limited amount of research on this matter as in the cases of Colombian females [19] and Japanese females [57] or in male soccer players [21], it appears that whether one is a starter or a non-starter does not significantly influence physical fitness levels. As a result, the hypothesis regarding the impact of this status remains

unsubstantiated, albeit due to constraints in research quantity and diversity. Moreover, the extent of evidence regarding its impact on other aspects such as tactical and technical abilities, as well as complementary factors like body composition, remains largely unknown and insufficiently explored.

However, several factors such as tactical requirements, players' response, playing position, fitness level and individual characteristics are related to physical performance [59]. The literature has also focused on body composition and its implications on physical performance [60]. Indeed, a study [60] examined the relationship between body composition and tests of speed, power, and cardiorespiratory fitness in male collegiate (Division I) starter and non-starter soccer players. The authors found that the difference between starters and non-starters for height was less than 1 cm and for body mass was less than 0.1 kg [60]. These results agree with other studies carried out in Norwegian championships (41) and England International players (< 16 years).

The significance of high-speed running and sprinting training for establishing robust conditioning in soccer players: concerns of underexposure for non-starting players

When comparing the differences in external loads between starters and non-starters, it is imperative to consider key variables such as HSR and sprinting [61]. These activities involve substantial mechanical loads that are crucial for physical resilience and the ability to endure the demands of a match [62]. Notably, HSR and sprinting are predominantly observed during matches rather than training sessions [63], with minimal occurrence in training [64]. Therefore, particular attention should be paid to exposing players to near-maximal efforts, as some research suggests that programming > 95% of maximal sprint speed exposures may help reduce the incidence of hamstring injuries during elite soccer matches [65]. Consequently, the absence of match exposure may result in a significant deficiency that cannot be adequately compensated for during regular on-field sessions, particularly without specific considerations for non-starting players.

During official matches, HSR and sprint running distances ranged from 618 to 1,001 m and 153 to 295 m, respectively, in professional male soccer players. This amount of high-intensity running is performed by starter players only while non-starters need to be subjected to a similar amount of training during the following micro-cycle to avoid possible physical decrements.

The role that HSR and sprinting training play in the development of physical capabilities, sport-specific performance and injury prevention among soccer players has been described in detail [62]. However, the monitoring and quantification of running intensities have been frequently debated without finding a definitive agreement. Specifically, Gualtieri et al. [61] stated that there is no consensus on the absolute thresholds defining HSR and sprint running in adult soccer players. Men's and women's soccer players use a range of speed thresholds that are frequently defined with the same term (e.g., HSR and sprinting distances) but correspond to different speeds, which complicates the comparison among teams and studies. Anyway, traditionally, absolute thresholds for HSR and sprinting distance have been set at 19.8 $km \cdot h^{-1}$ and 25.2 $km \cdot h^{-1}$, respectively [62]. Another approach used by practitioners consists of quantifying velocity thresholds using a relative approach, where the intensity is calculated as a percentage (e.g., 80 or 90%) of the peak speed [66, 67].

This approach allows for consideration of inter-individual players' differences during training load monitoring and can have important implications for specific training sessions whose goal is to reach near-maximal velocity exposure [61]. Furthermore, a recently published scoping review explored load quantification using both absolute and individualized running speed thresholds in team sports. The authors reported that thirty-four articles used individualized speed running thresholds based on physical fitness or performance assessments (e.g., 40-m linear sprint). However, some other physiological approaches (e.g., percentage of the maximum aerobic speed deriving from a physiological test – $\dot{V}O_{2max}$ test) can also be used to quantify training intensity [61]. However, the non-standardized use of intensity (speed) thresholds in soccer can create some issues for practitioners.

For instance, some of these thresholds derive from physiological tests that have been used in sports (e.g., endurance) that are drastically different from the physiological and energetic model of soccer [68], and therefore they could have limited relevance for it. Therefore, scientists and practitioners need to use individualized thresholds (deriving from physiological or performance assessments) that can help to more accurately quantify the training load of soccer players. This would facilitate the implementation of training protocols aiming to compensate the training load gap between starters and non-starters.

Based on such evidence, it is clear that practitioners need to put in place some strategies to "top up" the training load missed during the match by non-starter players (e.g., players who played < 30 min). Practitioners should design specific training drills that allow non-starters to recreate in training the same intensities (distance/minute) and training stimuli needed to improve or at least maintain their sport-specific fitness level [69]. Beato et al. [69] reported that sided games with different formats (i.e., SSG, possession games, large-sided games) can replicate and sometimes exceed some match-specific intensity parameters (e.g., number of accelerations and decelerations); however, HSR and sprinting distances were consistently lower compared to official matches.

Those findings were confirmed by another study that found that some sided game formats are more suitable for specific load-specific parameters than others; for instance, distance per minute, HSR, and sprinting exposure were greater during large-sided games compared to other, smaller formats, while the number of accelerations and decelerations was greater in medium-sided games compared to other formats [70]. The use of large-sided game formats to expose players to HSR demands is also supported by another recent systematic

review [61]. The authors found that game-based drills designed in formats using relative areas per player greater than 225 m^2 and 300 m^2 appear to be adequate for achieving HSR and sprinting exposure, respectively [61]. Another valid training approach is based on soccer circuit-based drills, which offer some specific advantages to sided games (e.g., high load profiles and good reliability scores for both internal and external load parameters) [71], or on more traditional sprint running drills (without the use of the ball) [62]. Therefore, it seems that the combination of game-based, running exercises and soccer circuit-based drills is advisable to ensure adequate HSR and sprint running exposure at both a team and an individual level.

Current research on compensatory training for non-starters: for whom, when, and how is it applied?

In recent years, strength and conditioning practices have undergone significant changes, incorporating compensatory training for non-starters [4]. The rationale behind this shift is based on the belief that it provides the advantage of introducing a targeted level of training load [72]. This aids in sustaining the chronic load [2] while preventing imbalances during matches from exacerbating differences among starters. This increase in such practices has also sparked research interest in the field. Therefore, this section analyses how compensatory training has been implemented and explores potential findings related to this topic.

Contextualizing compensatory training for non-starters: exploring the research landscape and addressing current challenges

Recently, researchers have increasingly shown interest in exploring compensatory training for non-starters, as evidenced by the growing number of scholarly publications on the topicAn initial inquiry, conducted on PubMed and utilizing search terms such as "compensatory training," "top up," or "topup," in combination with the keywords "football" or "soccer," as of August 29, 2023, yielded a total of 10 relevant titles. Among these, 7 were published in the year 2022, while the remaining 3 were released within the current year of 2023. These statistics underscore the emergence of this subject as a burgeoning field of study, actively capturing the attention of sports researchers and practitioners alike.

At present, the majority of research related to compensatory training is concentrated on administering targeted external loads, predominantly focused on HSR distances. This specific external load measure is touted as integral in rendering players resilient to manage match intensities and loads, while concurrently bolstering their capacity to mitigate injury risks.

One of the challenges inherent in compensatory training is determining the appropriate dosage. For instance, depending on the extent of a substitute's participation in a match, the dosage of a prescribed HIIT regimen would need to be adjusted accordingly. Furthermore, challenges arise when compensatory training is not immediately introduced after a match, but rather during the preparation for the next match.

An optimal window for such training might be the training session immediately following the match day, as this typically coincides with a restorative training routine for the starting players [73]. However, integrating compensatory training on days beyond match day +1 proves to be more complex. The structural adjustments necessary for such sessions, coupled with the logistical issues arising from individualized comparisons to starting players, present formidable challenges for coaches. Additionally, introducing an additional training dose on such days could also impact the overall adaptation to the training load for the week, potentially adversely affecting player physical performance over that period.

The considerations surrounding tailored physical training for non-starting players remain an ongoing discourse. As revealed in a recent survey [4], 39% of coaches frequently devise specialized training for non-starters on non-match days, while 31% reported occasional implementation, and 15% acknowledged that such preparation is virtually absent. Among the factors contributing to the infrequent implementation of such training programmes are uncertainties stemming from unknown substitute playtime during matches and logistical intricacies concerning training session structuring or squad announcements within a timely manner [4].

If these preceding responses pertain to the planning of compensatory training for the day after a match, the immediate training session following a match also presents its challenges. One such challenge arises from the compressed schedule of matches, which leaves little leeway for additional training, especially considering the team's return travel commitments. Moreover, crafting an individualized training stimulus becomes imperative to ensure effectiveness. This implies the need for a streamlined process that accommodates the player who commenced the second half as a substitute in contrast to the player who entered the game during its final three minutes.

Furthermore, regulating the dosage of training, particularly in terms of metrics such as HSR, or sprint distance, poses its own set of complexities. The absence of a consensus or conclusive evidence delineating the precise extent of training a player should undergo relative to their typical in-game demands adds to the challenge.

Characterizing acute responses to compensatory training in non-starter players

In an endeavour to elucidate the post-match compensatory strategies for substitute players, a comprehensive study encompassing 37 matches and involving 31 professional United Kingdom premier league soccer players was undertaken [12]. The findings of this study revealed that the average duration of compensatory training was 17.13 ± 7.44 minutes, enabling an approximate coverage of 1.7 ± 6.2 km and 0.4 ± 1.7 km in distance covered and HSR distance, respectively [12]. The variability in the imposed workload was contingent upon a multitude of contextual factors. These factors encompassed the player's role as unused or substitute, the duration of their time on the field, the match's location, outcome, time of day, stage of the season, and scheduling [12].

In another study focusing on post-match compensatory training, an exploration into the training regimen of the day following the match revealed distinct findings [74]. Specifically, the study on professional players participating in the Spanish premier league investigated the extent of HSR (although under different speed thresholds: 21–24 km/h compared to the regular range of 19.8 to 24.9 km/h) [74]. The analysis indicated that substitutes who played 5 to 15 minutes recorded an average of 0.49 ± 0.31 km in HSR (running between 12 and 24 km/h). For those substitutes who participated for 15 to 30 minutes, the HSR distance averaged 0.96 ± 0.46 km. Similarly, substitutes engaged on the field for 30 to 45 minutes had an average HSR distance of 1.3 ± 0.54 km [74].

Upon analysis, it becomes evident that the observed average HSR distance falls considerably short of the typical range covered in a standard match, which typically ranges from 0.8 to 1.0 km over the course of a full 90-minute match [75, 76]. Taking into account that substitutes may cover approximately 0.1 km upon their entry into the match (naturally dependent on the match duration) [77], it becomes apparent that compensatory training still offers a lesser dosage than what would be expected to align with a typical full-match scenario.

Naturally, a concern arises regarding the pattern of dose application. While the HSR distance of 0.8–1.0 km is distributed over the span of 90 minutes during regular matches, for example the 0.4 km is accumulated within 17 minutes during the post-match compensatory training [12]. This pattern creates a pronounced peak in exposure for substitute players undergoing compensatory training, surpassing the regular range of 4.8 to 10.1 m per minute of HSR experienced in matches, with a significantly higher 28.1 m per minute covered in compensatory training. This aligns with the most demanding scenarios encountered during matches [78].

The implications stemming from load density remain incompletely studied, leaving various questions unanswered. For instance, should a 1-km HSR distance be executed with a high density of 30 m per minute? Should we consider the intensity (e.g., distance per minute)? Further research is warranted to investigate in more detail the intricacies of translating peak performance demands into meticulously tailored training prescriptions. This entails a specific focus on incorporating considerations of load density to facilitate more informed and effective training strategies.

The same query extends to another pivotal metric, namely sprinting distance. In the context of soccer, players often cover a sprinting distance (e.g., speed > 25.2 km/h) of up to 0.3 km throughout a full match [6, 79]. However, insights from a profiling study undertaken in the English Premier League revealed a notable contrast when it comes to compensatory training immediately after a match [12]. Specifically, these sessions led to a sprinting distance of only around 0.03 km, with the peak speed of approximately 7.0 m per second [12]. A parallel investigation conducted in Spain similarly noted that compensatory training conducted on the day after a match translated to an approximate sprinting distance of 0.04 km [74]. This indicates that sprinting in the context of compensatory training accumulates to roughly 10% of the TD covered during a full match.

Exploring compensatory training strategies and their applications for non-starter players

While the predominant application of compensatory training has been embedded in running-based regimes, which brings forth inherent advantages such as customization, controlled load management, and swift dose administration (density), there exist alternative approaches worth considering. For instance, the incorporation of SSG – a subset of drill-based exercises that mirror simplified game scenarios while incorporating specific constraints to highlight targeted behaviours – has emerged as a prospective avenue to administer compensatory stimuli for non-starters.

In a noteworthy pilot study conducted among female professional soccer players from the Spanish first league who assumed non-starter roles [11], a comparative examination of three distinct modes of compensatory training was undertaken. These encompassed running-based exercises, SSG, and a hybrid approach integrating both methods. The participants' external loads were meticulously monitored, yielding insightful findings. Notably, when subjected to SSG or the hybrid regimen, non-starter players covered markedly shorter distances relative to the running-based exposure [11].

Furthermore, under the running-based intervention, the players exhibited notably increased high-intensity running and sprinting distances [11]. Regardless of the specific form of compensatory training adopted, the non-starter players consistently covered significantly fewer TDs compared to their starting counterparts during the match [11]. It is worth highlighting that non-starters who underwent the running-based intervention achieved non-significant values in terms of high-intensity running and sprinting – an interesting observation [11].

Identifying gaps and proposing future research in compensatory training for non-starters

Considering the distinct nature of the research topic, there exists a limited body of knowledge concerning the potential effects of compensatory training on fostering adaptations in players who assume non-starter roles. This gap in research underscores the necessity for innovative study designs that can shed light on the tangible impact of compensatory training. Presently, the practice of compensatory training has been adopted, yet a definitive understanding of its genuine influence, particularly in terms of enhancing physical fitness and mitigating injury risks, remains elusive.

The causality and effectiveness of compensatory training are yet to be substantiated. At this juncture, its recommendation is largely rooted in observational studies and associated hypotheses regarding the correlations between training load, sustained fitness, and injury resilience.

Hence, the avenues for investigating compensatory training for non-starters diverge significantly and hold the potential to yield more

comprehensive insights. For instance, evaluating the contrast between generalized and individualized compensatory training protocols is imperative. Equally important are determining the optimal dosage required, delineating the criteria guiding its formulation, and identifying the pivotal variables governing its prescription.

A thorough examination of the actual ramifications of implementing compensatory training for player readiness, performance sustainment or enhancement, and the potential for fostering resilience against injury risk is essential. These investigative pathways can be effectively bolstered through the exploration of dose-response relationships and tailored approaches. Parallel study designs that incorporate control groups allow meaningful comparisons to be drawn.

Such research holds the potential to expand our understanding of compensatory training's true impact on non-starters and cultivating evidence-based recommendations to guide its practical application.

Furthermore, when considering the comparison between starters and non-starters, it presents a significant opportunity for exploration. For instance, most studies are descriptive and tend to focus on a small number of teams. Additionally, there is inconsistency in describing the relationships between training and match loads, as well as in understanding the proportion of load volume across both situations. It would be valuable to conduct studies that integrate individualized training, incorporating the volume that non-starters miss from matches into compensatory training, and comparing this approach with those not exposed to such conditions. By integrating descriptive analyses of load differences between starters and non-starters and applying these findings to practice in both the short and long term, a more comprehensive understanding can be achieved (Figure 1).

Practical approaches to implementing compensatory training for non-starter soccer players

Optimizing compensatory training is one of the most challenging tasks of sports science staff in soccer. However, in practice, it is more efficient to implement it via close collaboration with technical staff to ensure players train with the philosophy of the manager and achieve all possible physical, technical and tactical aspects simultaneously (Figure 2).

Indeed, in modern soccer fitness coaching, each manager has a game model and ideally all training details should be designed

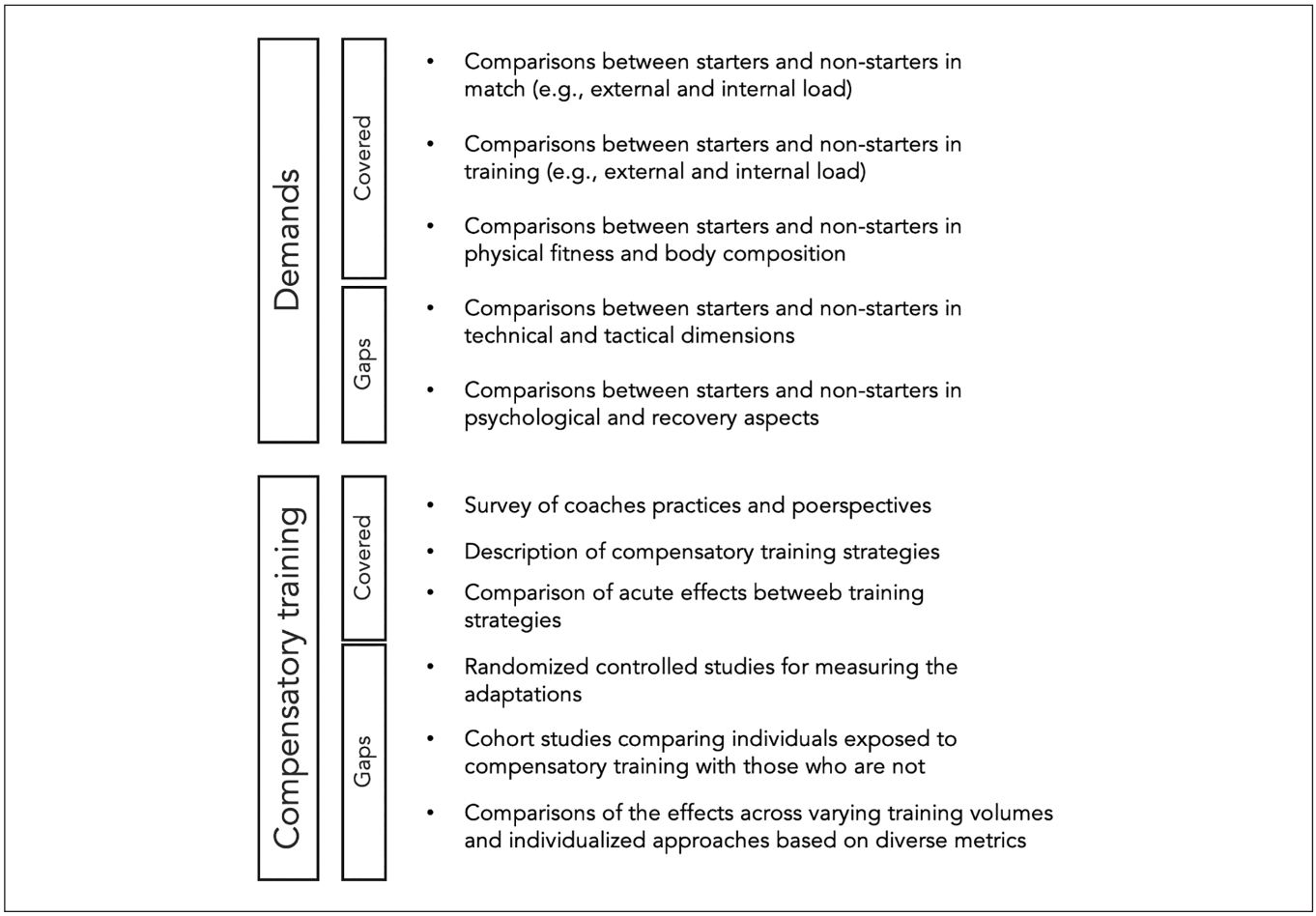


FIG. 1. Overview of the topics addressed in the current state-of-the-art research on starter versus non-starter players and research gaps demanding further research.

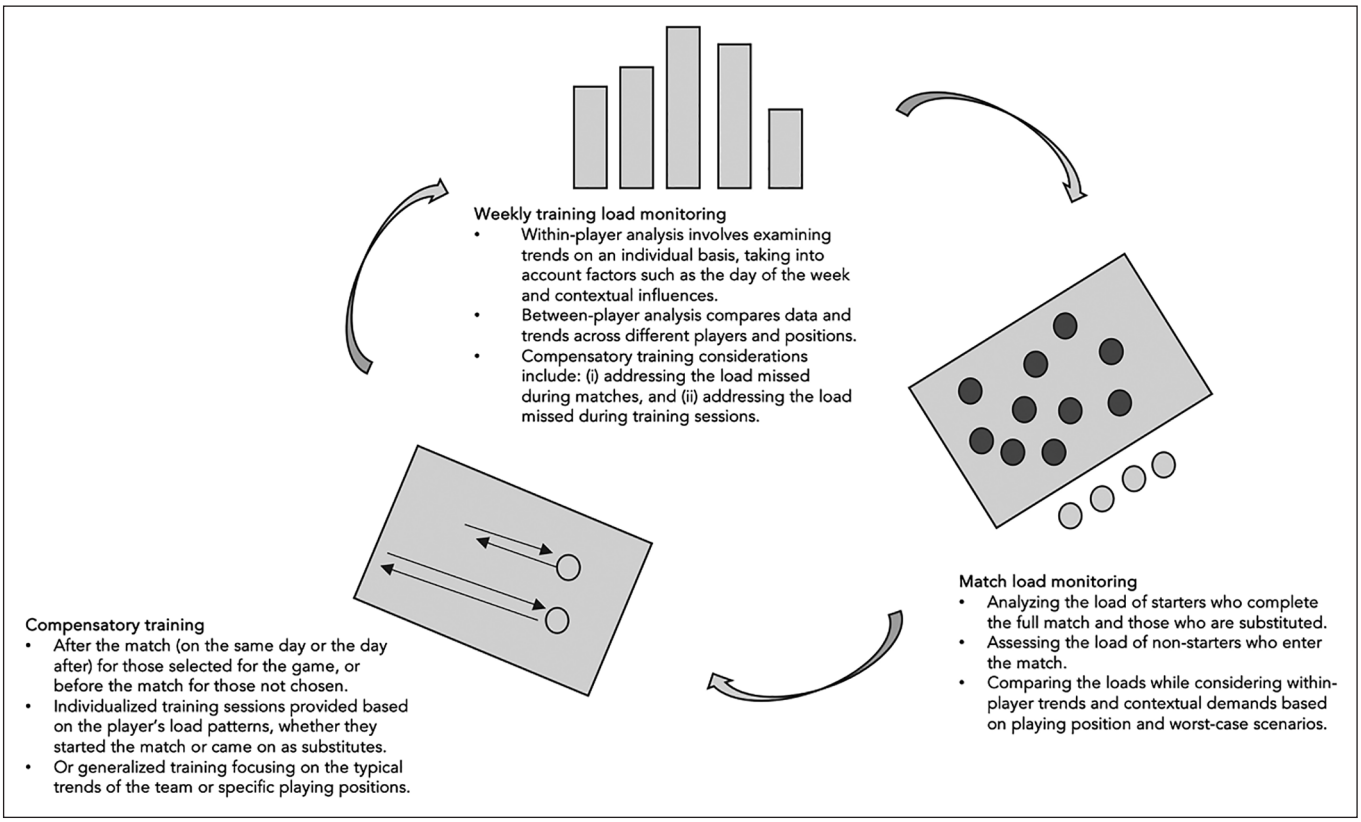


FIG. 2. Potential aspects to explore when comparing starters versus non-starters.

accordingly although with respect to the main principles of strength and conditioning [80, 81]. When designing compensatory training, the first factor to consider is the scenario or the weekly microcycle that players are approaching. For instance, compensatory training when implemented on MD+1 (match day +1) while MD+2 is off and the next match is after 5–6 days is completely different from when it is MD+2 (MD+1 is off) while it is also MD-2 for the next match. As there is a myriad of factors influencing such scenarios including match schedules, logistics, and manager preference to give a day off on MD+1 or MD+2, the first task of the strength and conditioning coach is to study the scenario and then try to design and implement the ideal possible compensatory session. As a logical rule, the closer the compensatory training is to the next match, the lower is the training level to prevent accumulated residual fatigue for the upcoming match as each non-starter player may be selected to play.

Although there is limited research in the area of compensatory training [11] and regardless of its complexity there is still no consensus agreement about its details, it seems that the main target should be to compensate external loads such as TD, HSR, sprinting, mechanical work and internal loads such as Edwards' TRIMP and time spent in the red zone (> 85–90% of maximal heart rate) as much as possible considering the context [12]. It seems that the second target needs to be placed on special demands of the game (e.g., peak external or internal intensity, maximal velocity). However, due to a smaller number of players (typically < 10 outfield players) in compensatory training, achieving such a high amount of load in all factors is almost impossible and the ideal solution is to organize a friendly game with other teams or at least with younger teams in the same club. Research has shown that the smaller format of the game such as SSG (less than 4v4 + goalkeepers (Gks)) entails fewer external demands of the game especially in some important factors such as HSR distance [82, 83]. Organizing friendly games in compensatory training not only helps to achieve high and more balanced loads in all categories but also simulates the real scenario that players are being prepared for (i.e., the 10v10+Gk game) [84]

If organizing friendly games even with less volume (e.g., 2 × 30 minutes) is not possible due to logistics or a congested schedule in the weekly microcycle (e.g., MD+1 = MD-3), the strength and conditioning coach must first study the current manager style of the compensation training, the current typical load achieved, and the peak intensity and demands of the session to supplement it with special top-up solutions within or at the end of the session. For instance, if the priority of the manager is aggressivity and he implements man-to-man rules, which research has shown to increases the intensity [85], the strength and conditioning coach needs to know what current peak intensity might be achieved within the typical training session and then he needs to target/adjust more volume of

external load measures to complement it. The other factors also include the number of players available and their individual fitness profiles. For instance, in one scenario there might be only four outfield players available due to other non-starters playing in the MD+1 for U21 or 2nd team of the club and a strength and conditioning coach who normally uses 3v3+Gk or 4v4+Gks in compensatory training needs to find another solution to achieve his targets.

The use of medium-sided games (MSG) (5V5+Gks to 7v7+Gks) or particularly SSG in compensatory training is widespread thanks to their popularity and coaches' interest in finishing the session with games. However, research has shown that implementing these formats although it inherently increases the intensity does not accumulate special and important demands of the real game (10v10+Gk) such as HSR distance [86]. The lower doses of these load-specific measures, in the long term, not only attenuate the fitness of players but also expose them to a higher risk of injury (e.g., HSR) due to the concept of acute to chronic load ratio [13]. To solve this problem, research suggests combining SSG and running-based HIIT [86] and many coaches supplement this MSG/SSG with analytical running exercises to top up and achieve higher doses of external loads [87]. In recent years, Bucchheit has developed an interesting method of supplementing training with running-based HIIT to address these issues [13]. Designing these HIIT methods via manipulating different influencing factors including the number of sets and series, straight running or running with the change of direction, the intensity and duration of work and rest periods, and the reference of defining the running intensity accordingly (e.g., V_{IFT}, the maximum velocity achieved during the 30–15 Intermittent Fitness Test) can help to target not only external load demands (e.g., HSR vs. mechanical works) but also internal metabolic (aerobic vs. anaerobic) conditions [88]. However, strength and conditioning coaches need to be cautious and design/select special HIIT formats considering their special context and depending on other exercises of the compensatory training to avoid overload and increased risk of injury.

For instance, when compensatory training includes a high volume of an intense format of SSG (e.g., 2v2+Gk) which has already a high percentage of anaerobic metabolic contribution and the internal load is very high [89], it is more logical to supplement it with a neuromuscular format of HIIT (e.g., 8 reps of 10 s running with 110% of V_{IFT} with enough rest period between reps, 30 s) to avoid overload in the anaerobic metabolic part [90]. In contrast, when there is a congested schedule and MD is also MD-3 for the upcoming match and the player has not played, such a HIIT format can be adjusted with more volume of the work and greater contribution of anaerobic metabolic condition (e.g., 2×8 reps of 10 s running with 110% of V_{IFT} with 20-s rest in between reps and 1.5 min rest between sets).

To design these special HIIT formats, considering the training background, position and profile of the player is also important. For example, the volume of accumulated HSR distance is different for a winger vs. central back with profiles of almost 1000 m and 400 m of HSR distance, respectively [91]. Therefore, due to the complexity of designing compensatory training and supplementing it with different HIIT formats depending on a myriad of factors, here we present three scenarios with some examples to highlight the importance of first studying the context for strength and conditioning coaches (Table 1).

As presented in Table 1, there are three main contextual factors when organizing compensatory training including match schedules, the number of players available and the manager game model and/or philosophy. In the first scenario (scenario A), the match schedule is a normal weekly microcycle which has a day off on the second day (MD+2) and MD+1 is a good opportunity to train players with a very high load. In this scenario, the manager philosophy is playing deep with a striker and for this reason, the dimension of SSG is more longitudinal to create more chances for players to play with a striker. The other important point in this scenario is that one player played 30 minutes and it was his first match after a grade 2 hamstring muscle injury and logically the training needs to be modified for him not to overload hamstring muscles that cannot recover fast. In this example, if a young player with a good training background and high fitness level has played 30 minutes, he could finish training with all its items. At the end of this session, the volume of HSR in HIIT can be adjusted and individualized according to each player's position or match profile by manipulating the repetitions.

In scenario B (Table 1), there is a congested schedule and the match day is MD-3 for the next match. As it is not logical to supplement MD+1 (which is also MD-2) with HIIT, in the end, to avoid accumulated fatigue close to the next match, the best way is to split HIIT and SSG across two days. In this scenario (B) the HIIT encompasses two parts: one more aerobic type including 1×8 reps of 15"-15" with 90% of V_{IFT} and then another type of neuromuscular HIIT including 1×8 reps of 10"-20" with 110% of V_{IFT}. The important point here is that a player who has played 40 minutes has done a high number of sprints and accumulated about 50% of his individual match profile in HSR and there is no need to overstress his hamstring muscles further with running-based HIIT. In this scenario the manager's philosophy is fast playing and quick transitions and the strength and conditioning coach will use two rules to increase the intensity of 3v3+Gk in MD-2. One is the touching limitation (maximum three touches) that pushes players to make fast decisions and the other rule is that they must pass the middle line to verify their scored goals, which causes a fast transition from defence to attack.

In Scenario C (Table 1), MD+1 is off (decision of the manager) and the game is at home, so post-match training in the stadium is possible. In this scenario because the players do not have a game at the end of the session and the day after is off, the type of HIIT is not split into two sets and players complete one long set of 6 min (12 reps) of 10"-20" with 110% of V_{IFT}. Of course, in MD+2 they will train more (mostly with the ball) than starters to achieve a greater load to

TABLE 1. Example scenarios of compensatory training sessions.

	Scenario A	**Scenario B**	**Scenario C**
Match Day	Sunday	Wednesday	Saturday
Next match	Sunday	Saturday	Thursday
Day off, if any	Tuesday MD+2	No day off	Sunday, MD+1
Compensatory session	Monday MD+1	Post-match & Thursday MD+1	Post-match & Monday MD+2
Available players for compensatory training	9 outfield player and 2 Gks are available. One player has played 30 minutes in the match and it was his first match after return to play from a hamstring injury, grade 2	7 outfield player and 2 Gks are available. One player (striker) has played 40 min but is young and very fit (he recovers fast)	7 outfield players are available from the bench and 3 players will join from out list players. The match is at home.
Manager Philosophy	Aggressivity and priority to play in deep with striker	Fast decision making and quick transitions (attack to defence and defence to attack) behaviour	Possession of the ball and play wide with wingers
Compensatory training	-Jogging 10 min -Warm-up with passing drill 2×6 min -Ball possession 3v3+3 3×2 min + 30 s rest -4 reps of 30-m sprint with > 90% of maximal velocity with 45 s recovery in between reps -Game, 4v4+1 joker +Gks [20×40 m] Man to man, free touch -Running-based HIIT 1–2×8 reps of 10''-20'' with 110% of V_{IFT} (the number of reps depending on player HSR profile)	-Post-match except the player who played 40 min other will do 1×8 reps of 15''-15'' with 90% of V_{IFT} and 1×8 reps of 10''-20'' with 90% of V_{IFT}. -In MD+1, -5 min jogging -Warmup with passing drill 2×3 min -Ball possession 3v3+1 joker 3×1.5 min + 1 min rest -2 reps of 30-m sprint with > 90% of maximal velocity with 45 s recovery in between reps -Game, 3v3+Gk [18×25 m] 6×2 min + 1.5 min rest	-After match will be short post-match training. This includes 10 min jogging, 5v5 ball possession for 4×3 min and 1.5 min rest in between, and finishing it with HIIT with the format of 12 reps of 10''-20'' with 110% of V_{IFT}. -In MD+2, the compensatory training which is also MD-3 includes -5 min jogging -Warmup in with passing drill 2×4 min -Ball possession 3v3+1J+3 wall players 3×2 min (each 5 passes are counted as one point in possession) -2 reps of 30-m sprint with > 90% of maximal velocity with 45 s recovery in between reps -Game, 5v5+Gk [40 m $\times$ 32 m] 5×4 min with 1.5 min rest
Notes	In this example, the player returning from injury will have a modified session and plays as joker and does not do HIIT in the end as he is returning from injury and hamstrings are sore and not recovered well to expose to HSR. The coach philosophy is to play in deep and aggressively and therefore the length of SSG is double that of its width (40 vs. 20) and in order to increase intensity instead of touch limitation, the man to man rule is implemented.	-In this scenario to avoid accumulated fatigue in the next match which is very close, the load is split into two days to do running-based HIIT after the match and training with ball on MD+1 -The player who has played 40 min will train only until the end of ball possession and 10 min jogging at the end of the session -The rules in SSG include three touches maximum and middle line to pass condition for the goals being scored (vertical shift).	-In this scenario as the game is at home and MD+1 is off based on decision of manager, there is the possibility of training in stadium after the match and on MD+2. To address the philosophy of the manager the number of passes is counted with one coach for encouragement and the game is played in width pitch to play wider with wingers. Running-based HIIT also is in one long set (6 min) as there is one day rest following the game and enough time to recover for the next session (MD+2).

Gk: goalkeeper; MD: match day; HIIT: high-intensity interval training

compensate. In this scenario (C, Table 1), the philosophy of the coach is to have more ball possession and play with wingers and the strength and conditioning coach uses the rules of points for the number of passes and organizes the pitch with more width (double box, 40×33 m) to create more chances to play with wingers in MSG (5V5+Gk). In this scenario as players accumulated a high volume of HSR on MD with HIIT and MD+2 is also MD-3, there is no need to supplement the training of MD+2 with running-based HIIT.

CONCLUSIONS

The current narrative review aimed to summarize studies covering compensatory training in soccer, as well as those addressing differences in training and match demands between starters and non-starters. While evidence suggests that non-starters experience significantly lower loads in critical aspects such as total distance, high-speed running, or sprinting, the impact of being a starter or non-starter on physical fitness parameters is not clearly observable. Research on compensatory training for non-starters is predominantly descriptive, focusing on practices and acute effects. There is a visible gap in experimental studies examining the effects of compensatory training in soccer players, and comparative approaches (e.g., training stimulus, volume, individualization vs. generalization) are lacking, hindering practitioners' ability to make informed decisions.

Although compensatory training has been established in strength and conditioning practices in soccer, the research gap prevents definitive support for decisions in this area. Therefore, substantial investment in both research and practice is necessary, as current approaches rely on trial and error. Caution is advised, and making definitive statements or recommendations is not advisable. Individualized intervention and careful consideration are recommended for compensatory training, while the scientific community should prioritize the development of research initiatives to inform future decisions in this field.

Conflict of interest

The authors declare no conflict of interest.

REFERENCES

1. Hills SP, Barwood MJ, Radcliffe JN, Cooke CB, Kilduff LP, Cook CJ, et al. Profiling the Responses of Soccer Substitutes: A Review of Current Literature. Sports Med. 2018; 48:2255–69.
2. Romero-Moraleda B, González-García J, Morencos E, Giráldez-Costas V, Moya J, Ramirez-Campillo R. Internal workload in elite female football players during the whole in-season: starters vs non-starters. Biol Sport. 2023; 40(4):1107–1115. doi: 10.5114/biolsport.2023.124849
3. The International Football Association Board. Laws of the game 23/24. Zurich, Switzerland: 2023.
4. Hills SP, Radcliffe JN, Barwood MJ, Arent SM, Cooke CB, Russell M. Practitioner perceptions regarding the practices of soccer substitutes. PLoS One. 2020; 15:e0228790.
5. Furtado Mesa M, Stout JR, Redd MJ, Fukuda DH. Accumulated Workload Differences in Collegiate Women's Soccer: Starters versus Substitutes. J Funct Morphol Kinesiol. 2023; 8:78.
6. Anderson L, Orme P, Michele R Di, Close GL, Drust B, Morton JP, et al. Quantification of training load during one-, two- and three-game week schedules in professional soccer players from the English Premier League: implications for carbohydrate periodisation. J Sports Sci. 2016; 34:1250–9.
7. Malone JJJJ, Di Michele R, Morgans R, Burgess D, Morton JP, Drust B. Seasonal Training-Load Quanti-fication in Elite English Premier League Soccer Players. Int J Sports Physiol Perform. 2015; 10:489–97.
8. Hills SP, Barrett S, Thoseby B, Kilduff LP, Barwood MJ, Radcliffe JN, et al. Quantifying the Peak Phys-ical Match-Play Demands of Professional Soccer Substitutes Following Pitch-Entry: Assessing Contex-tual Influences. Res Q Exerc Sport. 2022; 93:270–81.
9. Clemente FM, Silva R, Arslan E, Aquino R, Castillo D, Mendes B. The effects of congested fixture peri-ods on distance-based workload indices: A full-season study in professional soccer players. Biol Sport 2021; 38:37–44.
10. Silva JRJR, Magalhães JF, Ascensão AA, Oliveira EM, Seabra AFAF, Rebelo ANAN, et al. Individual match playing time during the season affects fitness-related parameters of male professional soccer play-ers. J. Strength Cond. Res. 2011; 25:2729–39.
11. Díaz-Serradilla E, Castillo D, Rodríguez-Marroyo JA, Raya González J, Villa Vicente JG, Rodríguez-Fernández A. Effect of Different Nonstarter Compensatory Strategies on Training Load in Female Soc-cer Players: A Pilot Study. Sports Health. 2023:19417381231176556.
12. Hills SP, Barrett S, Busby M, Kilduff LP, Barwood MJ, Radcliffe JN, et al. Profiling the Post-match Top-up Conditioning Practices of Professional Soccer Substitutes: An Analysis of Contextual Influences. J Strength Cond Res. 2020; 34:2805–14.
13. Buchheit M. Managing high-speed running load in professional soccer players: The benefit of high-intensity interval training supplementation. Sport Perf Sci Rep. 2019; 53:1–5.
14. Buckthorpe M, Wright S, Bruce-Low S, Nanni G, Sturdy T, Gross AS, et al. Recommendations for ham-string injury prevention in elite football: translating research into practice. Br J Sports Med. 2019; 53:449–56.
15. Bowen L, Gross AS, Gimpel M, Li FX. Accumulated workloads and the acute: Chronic workload ratio relate to injury risk in elite youth football players. Br J Sports Med 2017; 51:452–9. https://doi.org/10.1136/bjsports -2015-095820.
16. Gabbett TJ. The training—injury prevention paradox: should athletes be training smarter and harder? Br J Sports Med. 2016; 50:273–80.
17. Calderón-Pellegrino G, Gallardo L, Garcia-Unanue J, Felipe JL, Hernandez-Martin A, Paredes-Hernández V, et al. Physical Demands during the Game and Compensatory Training Session (MD+1) in Elite Football Players Using Global Positioning System Device. Sensors. 2022; 22:3872.
18. Greenhalgh T, Thorne S, Malterud K. Time to challenge the spurious hierarchy of systematic over narra-tive reviews? Eur J Clin Invest. 2018; 48.
19. Becerra Patiño BA, Paucar-Uribe JD, Martínez-Benitez CF, Ávila Martínez JD, Sarria-Lozano JC. Analy-sis of physical variables as an indicator of performance in a sample of Colombian women's soccer players: influence of being a starter and a non-starter. J Physical Edu Sport. 2023; 23:1–7.
20. Castillo-Rodríguez A, González-Téllez JL, Figueiredo A, Chinchilla-Minguet JL, Onetti-Onetti W. Start-ers and non-starters soccer players in competition: is physical performance increased by the substitutions? BMC Sports Sci Med. Rehabil 2023; 15:33.
21. Paraskevas G, Hadjicharalambous M. Aerobic fitness of starter and non-starter soccer players in the Champion's League. J Hum Kinet. 2018; 61:99–108.

22. Castillo-Rodríguez A, González-Téllez JL, Figueiredo A, Chinchilla-Minguet JL, Onetti-Onetti W. Start-ers and non-starters soccer players in competition: is physical performance increased by the substitutions? BMC Sports Sci Med Rehabil. 2023; 15:33.
23. Ayabe M, Sunami S, Kumahara H, Ishizaki S. Effects of substitute allowance on match activity character-istics in Japanese professional football across 2019, 2020, and 2021 seasons. J Sports Sci. 2022; 40:2654–60.
24. Jennifer Fields, Justin Merrigan, Mary Kate Feit, Jones M. Practice versus Game External Load Measures in Starters and Non-Starters of a Men's Collegiate Soccer Team. Int J Strength Con. 2021; 1.
25. Curtis RM, Huggins RA, Benjamin CL, Sekiguchi Y, M. Arent S, C. Armwald B, et al. Seasonal Accumu-lated Workloads in Collegiate Men's Soccer: A Comparison of Starters and Reserves. J Strength Cond Res. 2021; 35:3184–9.
26. Furtado Mesa M, Stout JR, Redd MJ, Fukuda DH. Accumulated Workload Differences in Collegiate Women's Soccer: Starters versus Substitutes. J Funct Morphol Kinesiol. 2023; 8.
27. Jagim AR, Askow AT, Carvalho V, Murphy J, Luedke JA, Erickson JL. Seasonal Accumulated Work-loads in Collegiate Women's Soccer: A Comparison of Starters and Reserves. J Funct Morphol Kinesiol. 2022; 7.
28. Barreira J, Nakamura FY, Ferreira R, Pereira J, Aquino R, Figueiredo P. Season Match Loads of a Portu-guese Under-23 Soccer Team: Differences between Different Starting Statuses throughout the Season and Specific Periods within the Season Using Global Positioning Systems. Sensors. 2022; 22.
29. García-Aliaga A, Martín-Castellanos A, Marquina Nieto M, Muriarte Solana D, Resta R, López del Cam-po R, et al. Effect of Increasing the Number of Substitutions on Physical Performance during Periods of Congested Fixtures in Football. Sports. 2023; 11.
30. Giménez J V., Leicht AS, Gomez MA. Physical performance differences between starter and non-starter players during professional soccer friendly matches. J Hum Kinet. 2019; 69:283–91.
31. Sydney MG, Wollin M, Chapman D, Ball N, Mara JK. Substitute running outputs in elite youth male soccer players: less peak but greater relative running outputs. Biol Sport. 2023; 40:241–8.
32. Titton A. Competitive evaluation in male elite junior soccer players: entire match, replaced, and substitute players. J Exerc Rehabil. 2020; 16:286–92.
33. Kubayi A. Work rate and technical performance analyses of substitute players during the UEFA Euro 2016. Med Dello Sport. 2020; 73:626–34.
34. Bradley PS, Noakes TD. Match running performance fluctuations in elite soccer: Indicative of fatigue, pacing or situational influences? J Sports Sci. 2013; 31:1627–38.
35. Calderón-pellegrino G, Gallardo L, Garcia-unanue J, Felipe JL, Hernandez-martin A, Paredes-hernández V, et al. Physical Demands during the Game and Compensatory Training Session (MD+1) in Elite Foot-ball Players Using Global Positioning System Device. Sensors. 2022; 22.
36. Carling C, Espié V, Le Gall F, Bloomfield J, Jullien H. Work-rate of substitutes in elite soccer: A prelimi-nary study. J Sci Med Sport. 2010; 13:253–5.
37. Bradley PS, Lago-Peñas C, Rey E. Evaluation of the match performances of substitution players in elite soccer. Int J Sports Physiol Perform. 2014; 9:415–24.
38. Liu H, Wang L, Huang G, Zhang H, Mao W. Activity profiles of full-match and substitution players in the 2018 FIFA World Cup. Eur J Sport Sci. 2020; 20:599–605.
39. Padrón-Cabo A, Rey E, Vidal B, García-Nuñez J. Work-rate analysis of substitute players in professional soccer: Analysis of seasonal variations. J Hum Kinet. 2018; 65:165–74.
40. Reche-Soto P, Rojas-Valverde D, Bastida-Castillo A, Gómez-Carmona CD, Rico-González M, Palucci Vieira LH, et al. Using Ultra-Wide Band to Analyze Soccer Performance through Load Indicators during a Full Season: A Comparison between Starters and Non-Starters. Appl Sci. 2022; 12.
41. Fransson D, Krustrup P, Mohr M. Running intensity fluctuations indicate temporary performance decre-ment in top-class football. Sci Med Football. 2017; 1:10–7.
42. Vescovi JD, Favero TG. Motion characteristics of women's college soccer matches: Female athletes in motion (faim) study. Int J Sports Physiol Perform. 2014; 9:405–14.
43. Lorenzo-Martínez M, Padrón-Cabo A, Rey E, Memmert D. Analysis of Physical and Technical Perfor-mance of Substitute Players in Professional Soccer. Res Q Exerc Sport. 2021; 92:599–606.
44. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special refer-ence to development of fatigue. J Sports Sci. 2003; 21:519–28.
45. Gai Y, Volossovitch A, Leicht AS, Gómez MÁ. Technical and physical performances of Chinese Super League soccer players differ according to their playing status and position. Int J Perform Anal Sport. 2019; 19:878–92.
46. Dalen T, Lorås H. Monitoring training and match physical load in junior soccer players: Starters versus substitutes. Sports. 2019; 7.
47. Fereday K, Hills SP, Russell M, Smith J, Cunningham DJ, Shearer D, et al. A comparison of rolling aver-ages versus discrete time epochs for assessing the worst-case scenario locomotor demands of professional soccer match-play. J Sci Med Sport. 2020; 23:764–9.
48. Novak AR, Impellizzeri FM, Trivedi A, Coutts AJ, McCall A. Analysis of the worst-case scenarios in an elite football team: Towards a better understanding and application. J Sports Sci. 2021; 39:1850–9.
49. Marqués-Jiménez D, Sampaio J, Calleja-González J, Echeazarra I. A random forest approach to explore how situational variables affect perceived exertion of elite youth soccer players. Psychol Sport Exerc. 2023; 67.
50. Raya-González J, Castillo D, Yanci J, Arcos AL. Assessing the perceived exertion in elite soccer players during official matches according to situational factors. Int J Environ Res Public Health 2020; 17. https://doi.org/10.3390/ijerph17020410.
51. Los Arcos A, Mendez-Villanueva A, Martínez-Santos R. In-season training periodization of professional soccer players. Biol Sport. 2017; 34:149–55.
52. Stolen T, Chamari K, Castagna C, Wisloff U. Physiology of soccer: an update. Sports Med. 2005; 35:501–536.
53. Impellizzeri FM, Rampinini E, Marcora SM. Physiological assessment of aerobic training in soccer. J Sports Sci. 2005; 23:583–92.
54. Impellizzeri FM, Marcora SM, Castagna C, Reilly T, Sassi A, Iaia FM, et al. Physiological and perfor-mance effects of generic versus specific aerobic training in soccer players. Int J Sports Med. 2006; 27:483–92.
55. Sporis G, Jovanovic M, Omrcen D, Matkovic B. Can the official soccer game be considered the most important contribution to player's physical fitness level? J Sports Med Physical Fit. 2011; 51:374–80.
56. Risso FG, Jalilvand F, Orjalo AJ, Moreno MR, Davis DL, Birmingham-Babauta SA, et al. Physiological Characteristics of Projected Starters and Non-Starters in the Field Positions from a Division I Women's Soccer Team. Int J Exerc Sci. 2017; 10:568–79.
57. Yamaguchi S, Inami T, Yamashita D, Nakamura M, Kohtake N. Physical Characteristics and Perfor-mance of Starters and Non-Starters in Elite-Level Female Soccer Players in College: A Case Study of Japanese Athletes. Football Sci. 2022; 19:49–58.

58. Rampinini E, Sassi A, Morelli A, Mazzoni S, Fanchini M, Coutts AJ. Repeated-sprint ability in profession-al and amateur soccer players. App. Phys. Nut. Metabolism. 2009; 34:1048–54.
59. Jaspers A, Brink MS, Probst SGM, Frencken WGP, Helsen WF. Relationships Between Training Load Indicators and Training Outcomes in Professional Soccer. Sports Med. 2017; 47:533–44.
60. Silvestre R, West C, Maresh CM, Kraemer WJ. Body composition and physical performance in men's soccer: A study of a National Collegiate Athletic Association Division I team. J Strength Cond Res. 2006; 20:177–83.
61. Gualtieri A, Rampinini E, Dello Iacono A, Beato M. High-speed running and sprinting in professional adult soccer: Current thresholds definition, match demands and training strategies. A systematic review. Front Sports Act Living 2023; 5.
62. Beato M, Drust B, Iacono AD. Implementing High-speed Running and Sprinting Training in Professional Soccer. Int J Sports Med. 2021; 42:295–9.
63. Clemente FM, Rabbani A, Conte D, Castillo D, Afonso J, Truman Clark CC, et al. Training/Match Exter-nal Load Ratios in Professional Soccer Players: A Full-Season Study. Int J Environ Res Public Health. 2019; 16:3057.
64. Buchheit M, Simpson BM, Hader K, Lacome M. Occurrences of near-to-maximal speed-running bouts in elite soccer: insights for training prescription and injury mitigation. Sci Med Football. 2021; 5:105–10.
65. Buchheit M, Settembre M, Hader K, McHugh D. Exposures to near-to-maximal speed running bouts during different turnarounds in elite football: association with match hamstring injuries. Biol Sport. 2023; 40:1057–67.
66. Clemente F, Ramirez-Campillo R, Beato M, Moran J, Kawczynski A, Makar P, et al. Arbitrary absolute vs. individualized running speed thresholds in team sports: A scoping review with evidence gap map. Biol Sport. 2023; 40:919–43.
67. Gualtieri A, Rampinini E, Sassi R, Beato M. Workload Monitoring in Top-level Soccer Players During Congested Fixture Periods. Int J Sports Med. 2020; 41:677–81.
68. Mohr M, Krustrup P, Bangsbo J. Fatigue in soccer: a brief review. J Sports Sci. 2005; 23:593–9.
69. Beato M, de Keijzer KL, Costin AJ. External and internal training load comparison between sided-game drills in professional soccer. Front Sports Act Living. 2023; 5.
70. Beato M, Vicens-Bordas J, Peña J, Costin A. Training load comparison between small, medium, and large-sided games in professional football. Front Sports Act Living. 2023; 5.
71. Dello Iacono A, Unnithan V, Shushan T, King M, Beato M. Training load responses to football game profile-based training (GPBT) formats: effects of locomotive demands manipulation. Biol Sport. 2022; 39:145–55.
72. Varjan M, Hank M, Kalata M, Chmura P, Mala L, Zahalka F. Weekly Training Load Differences between Starting and Non-Starting Soccer Players. J Hum Kinet. 2024; 90:125–135.
73. Walker GJ, Hawkins R. Structuring a Program in Elite Professional Soccer. Strength Cond J. 2018; 40:72–82.
74. Calderón-Pellegrino G, Gallardo L, Garcia-Unanue J, Felipe JL, Hernandez-Martin A, Paredes-Hernández V, et al. Physical Demands during the Game and Compensatory Training Session (MD+1) in Elite Football Players Using Global Positioning System Device. Sensors. 2022; 22:3872.
75. Bradley PS, Sheldon W, Wooster B, Olsen P, Boanas P, Krustrup P. High-intensity running in English FA Premier League soccer matches. J Sports Sci. 2009; 27:159–68.
76. Gualtieri A, Rampinini E, Dello Iacono A, Beato M. High-speed running and sprinting in professional adult soccer: Current thresholds definition, match demands and training strategies. A systematic review. Front Sports Act Living. 2023; 5.
77. Hills SP, Barrett S, Hobbs M, Barwood MJ, Radcliffe JN, Cooke CB, et al. Modifying the pre-pitch entry practices of professional soccer substitutes may contribute towards improved movement-related perfor-mance indicators on match-day: A case study. PLoS One. 2020; 15:e0232611.
78. Rico-González M, Oliveira R, Palucci Vieira LH, Pino-Ortega J, Clemente F. Players' performance during worst-case scenarios in professional soccer matches: a systematic review. Biol Sport. 2022; 39:695–713.
79. Bradley PS, Archer DT, Hogg B, Schuth G, Bush M, Carling C, et al. Tier-specific evolution of match performance characteristics in the English Premier League: it's getting tougher at the top. J Sports Sci. 2016; 34:980–7.
80. Jeffreys I, Cscs D. Movement Training for Field Sports: Soccer 2017.
81. Loturco I, T. Freitas T, E. Alcaraz P, Kobal R, Hartmann Nunes RF, Weldon A, et al. Practices of strength and conditioning coaches in Brazilian elite soccer. Biol Sport. 2022; 39:779–91.
82. Clemente FM, Sarmento H, Rabbani A, Van Der Linden CMIN, Kargarfard M, Costa IT. Variations of external load variables between medium- and large-sided soccer games in professional players. Res. Sports Med. 2019; 27:50–9.
83. Clemente FM. The Threats of Small-Sided Soccer Games: A Discussion About Their Differences With the Match External Load Demands and Their Variability Levels. Strength Cond J. 2020; 42:100–5.
84. Lacome M, Simpson BM, Cholley Y, Lambert P, Buchheit M. Small-Sided Games in Elite Soccer: Does One Size Fit All? Int J Sports Physiol Perform. 2018; 13:568–76.
85. Ngo JK, Tsui MC, Smith AW, Carling C, Chan GS, Wong del P. The effects of man-marking on work intensity in small-sided soccer games. J Sports Sci Med. 2012; 11:109–14.
86. Rabbani A, Clemente FM, Kargarfard M, Jahangiri S. Combined small-sided game and high-intensity interval training in soccer players: The effect of exercise order. J Hum Kinet. 2019; 69:249–57.
87. Clemente FM, Sarmento H. Combining small-sided soccer games and running-based methods: A system-atic review. Biol Sport. 2021; 38:617–27.
88. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: Part I: cardiopulmonary emphasis. Sports Med. 2013; 43:313–38.
89. Clemente FM, Martins FML, Mendes RS. Developing Aerobic and Anaerobic Fitness Using Small-Sided Soccer Games: Methodological Proposals. Strength Cond J. 2014; 36:76–87.
90. Laursen P, Buchheit M. Science and application of high-intensity interval training: solutions to the pro-gramming puzzle. Champaign IL, USA: Human Kinetics; 2019.
91. Martín-García A, Gómez Díaz A, Bradley PS, Morera F, Casamichana D. Quantification of a Professional Football Team's External Load Using a Microcycle Structure. J Strength Cond Res. 2018; 32:3511–8.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.135415
© Institute of Sport – National Research Institute

The influence of light and heavy training weeks on the cortisol and testosterone awakening responses of elite male judokas: is skeletal muscle damage a mediating factor?

AUTHORS: Blair T. Crewther[1,2,3], Benjamin G. Serpell[1,4], Christian J. Cook[1,5], Zbigniew Obmiński[2]

[1] School of Science and Technology, University of New England, Armidale, Australia
[2] Institute of Sport – National Research Institute, Warsaw, Poland
[3] School of Electrical Engineering and Robotics, Queensland University of Technology, Brisbane, Australia
[4] Geelong Cats Football Club, Geelong, Victoria, Australia
[5] Hamlyn Centre, Imperial College, London, UK

ABSTRACT: In sport, the awakening responses of cortisol (CAR) and testosterone (TAR) have been used as evaluative tools. Research findings are, however, inconsistent and the mechanisms involved are unclear. This study investigated the CAR and TAR in male athletes across light and heavy training weeks, focusing on skeletal muscle damage as a mediating factor. Twenty elite male judokas were assessed across consecutive weeks of light and heavy training (i.e., 6 days, 9–10 weekly sessions). Plasma cortisol and testosterone concentrations were measured post-awakening (+3, +30, +60 mins), along with creatine kinase (CK) at +3 mins. The CAR and TAR were indexed by baseline-corrected change scores (Δb30, Δb60) and area under the curve (AUCb30, AUCb60). The early-morning surge in plasma cortisol concentration ($CAR_{\Delta b30}$, $CAR_{\Delta b60}$, CAR_{AUCb30}, CAR_{AUCb60}) was significantly larger after light versus heavy training with effect-size differences of 2.14–2.64. The post-awakening decline in plasma testosterone ($TAR_{\Delta b30}$, TAR_{AUCb30}, TAR_{AUCb60}) was found to be significantly less pronounced, whilst CK level was elevated, after heavy than light training with effect-size differences of 0.95–1.04 and 4.70, respectively. Causal mediation analysis confirmed that CK mediated, in part, the training effect on the CAR, but not TAR, measures. In summary, male judokas, upon rising after a light training block, displayed a rising CAR (36%, 22%) and declining TAR (-11%, -15%) at +30 and +60 mins. A high-intensity training block suppressed the CAR (21%, 8%) and attenuated the TAR (-7%, -13%) with accompanying muscle damage offering one mechanism to partly explain the CAR differences.

CITATION: Crewther BT, Serpell BG, Cook CJ, Obmiński Z. The influence of light and heavy training weeks on the cortisol and testosterone awakening responses of elite male judokas: is skeletal muscle damage a mediating factor? Biol Sport. 2024;41(4):187–195.

Received: 2023-10-06; Reviewed: 2023-12-05; Re-submitted: 2024-01-09; Accepted: 2024-02-07; Published: 2024-04-25.

Corresponding author:
Blair Crewther
Biomedical Science – School of Science and Technology
University of New England
Armidale, NSW 2351
Australia
E-mail: bblair.crewther@gmail.com

ORCID:
Blair Crewther
0000-0003-4929-9456

Ben Serpell
0000-0002-9067-2948

Christian J Cook
0000-0001-9677-0306

Zbigniew Obmiński
0000-0002-3754-9748

Key words:
Stress
Adaptability
Recovery
Combat Sport
Physical Performance
HPG
HPA

INTRODUCTION

In sport, the cortisol awakening response (CAR) has garnered interest to evaluate the physical and/or psychological effects of training and competition [1]. The CAR is a distinct and reliable feature of hypothalamic-pituitary-adrenal (HPA) activity, characterized by a cortisol surge that peaks around 30–45 mins after awakening [2]. Contemporary viewpoints position the CAR as a proxy for baseline stress [3], reflecting both prior stress experienced and stress anticipation. As supporting evidence, a larger CAR emerged on the morning of shooting competition (vs. training) [4], archery elimination (vs. qualification) [5], and the pre-ascent phase of climbing (vs. resting day) [6]. Others have reported no CAR changes across a sporting competition [7, 8]. Further discrepancies were documented in a review of exercise and CAR studies with training factors (e.g., load acclimatization, intensity thresholds) identified as confounders [1].

Skeletal muscle damage offers an alternative explanation for divergent sport results. Support comes from research comparing athletes with the overtraining syndrome (OTS) and healthy athletes [9]. Upon initial diagnosis, the OTS group presented a flatter CAR and a higher creatine kinase (CK) level than the healthy group, indicating greater muscle trauma and damage. After three months recovery, the OTS group presented a CAR and CK profile that was comparable to healthy athletes. Similarly, triathletes (N = 2) diagnosed with the OTS had a lower CAR at the end of the season, relative to the season start [10]. Conversely, non-overtrained athletes showed a progressive rise in the CAR across the season [10]. Such findings suggest a link between the inflammatory response to excessive training loads, among other factors (e.g., insufficient recovery), and post-awakening cortisol secretion.

Cortisol regulation of human inflammation is well recognized [11, 12] and offers a theoretical model to explain CK and CAR dynamics in sport. As a glucocorticoid, cortisol exerts both pro- and anti-inflammatory effects on immune and inflammatory reactions following

a systemic stimulus [11, 12]. The bi-directional flow of information between the immune and neuroendocrine systems to repair damaged tissue and maintain homeostasis [12] could involve shifts in early-morning cortisol secretion. Regeneration of damaged muscle tissue might also promote secondary changes in cortisol secretion, due to metabolic factors related to control and recovery [13, 14]. To our knowledge, the impact of training on the CAR and muscle damage, as a mediating factor representing exercise-induced inflammation, has yet to be explored. A comparison of CAR and CK adaptations across training blocks that differ in load intensity (i.e., heavy vs. light) would be a logical first step.

The hypothalamic-pituitary-gonadal (HPG) axis, and its end product in male's testosterone, also adapts to training and competition stress [13]. Like cortisol, testosterone exhibits an awakening response (TAR) but is typified by a concentration decline over the same post-awakening period [15, 16]. Studies on rugby players and climbers report equivocal TAR results in terms of activity profiles and training adaptation [6, 17, 18]. Such inconsistencies could reflect more complex HPA- and HPG-axes interplay, whereby cortisol and testosterone reciprocally interact with upstream regulatory centers at each axis level [19, 20]. Partial support comes from positive CAR and TAR associations in healthy men [15, 16] and suggests that individuals presenting a larger CAR also tend to possess a flatter TAR. It remains unclear if, and how, muscle damage directly affects the TAR or whether sport-related TAR changes are driven by cortisol. Experimental testing of both hormonal features, and ensuing relationships with each other and CK, would help answer these questions.

This study investigated the CAR, TAR, and muscle damage in elite male judokas following light and heavy training weeks. Judo is a sport linked to varying degrees of muscle damage and hormonal change with different exercise and training configurations [21, 22, 23, 24, 25, 26]. Therefore, the targeting of male judokas would provide an ideal model for this training-based study. Our aims were to; (1) examine the impact of training at different intensities on reactive- and volume-based CAR and TAR metrics, as well as CK, and (2) evaluate CK as a causal mediator of training differences in the CAR and TAR. As a secondary aim, we explored our dataset for positive CAR and TAR associations. In relation to these aims, we first hypothesized that heavy training would suppress the CAR and TAR, and elicit more muscle damage (i.e., higher CK level) versus light training. Our second hypothesis was that the CAR and TAR differences would be mediated by CK activity. Finally, we anticipated that positive CAR-TAR linkages would emerge.

MATERIALS AND METHODS

Participants

Twenty elite male judokas (mean age = 24.4, SD = 2.0 years, mean weight = 80.4, SD = 10.5 kg) were recruited for this study. The participants had no current injuries, nor any medical or health conditions, that would affect their ability to complete the research procedures. Written informed consent was given before the study commenced, with approval from the ethics committee at the Institute of Sport – National Research Institute, Warsaw. This research was implemented in a preparatory training camp held at the Central Sport Centre, Zakopane.

Study design

A quasi-experimental, single-group, post-only design was used to address the study hypotheses. In our cohort of elite male judokas, CAR, TAR, and CK measures were taken after two consecutive training weeks that differed in session intensity and subsequently compared. In week one, lighter sessions were prescribed over six consecutive days of judo training (Monday to Saturday), followed by a recovery day (Sunday) before testing (Monday). The delayed assessment (~2 days after the last training session) removed the effect of acute exercise on next-day CAR [27, 28]. These procedures were replicated in week two, but a heavier workload was prescribed in each training session, as described in more detail below. The participants were housed together at the Central Sport Centre throughout this study. This ensured that dietary selection, meal timing, training activities, bedtime and time of awakening were consistent across athletes.

Training protocols

The participants completed 9–10 training sessions (60–90 mins each) each week aimed at enhancing technical performance, whilst developing general and sport-specific fitness. These goals were achieved via different exercising configurations; (1) sessions focusing on judo throwing and grappling techniques (e.g., ippon seoi nage, katame waza), (2) simulated judo bouts (i.e., randori) between opponents of a similar size and experience, each lasting 5 mins with a 5-min rest interval between bouts; (3) circuit training consisting of repeated bouts of 30-sec efforts (e.g., skipping, push-ups, sit-ups, jump squats, 20 m shuttle runs, burpees), and (4) fitness examinations using the Special Judo Fitness test [29], which lasts 75 sec and produces an elevated heart rate (up to 190 bpm) and blood lactate (up to 15 mmol/L) response. Heavy training was differentiated from light training in that more throws and grappling activities per technical session, randori per session (4 vs. 2), repeated efforts (3–4 vs. 2) during circuit training, and fitness tests (2 vs. 1) were performed. Rest intervals between sets and exercises were consistent throughout both training blocks. All sessions began with a standard warm-up comprising of basic throws (i.e., uchikomi) and dynamic stretching.

Morning assessment

Following an overnight (> 8 hours) fast, capillary blood samples were collected at three post-awakening points (+3, +30, +60 mins) for CAR and TAR determination. This 3-point protocol was chosen to capture the peak awakening surge (~30–45 mins) in cortisol [2, 30]. Additionally, the frequency and duration of sampling was deemed achievable in a field setting, without over-burdening the athletes involved. Creatine kinase was measured only once (+3 mins). The

participants reporting waking under alarm conditions in each weekly assessment, between the hours of 6.20 am and 7.00 am. To remove the effect of dietary intake [30], no food or drinks were taken until all blood samples were collected. Participants were instructed to rest (in a seated position) during the 60-min sampling period, thereby eliminating any hormonal bias due to physical movement.

Capillary blood samples (~300 μL at each time point) were collected by trained technicians into heparinized tubes. After sample centrifugation, the plasma portion was transferred into polypropylene tubes for storage at -80 °C. The recruited athletes were routinely tested for capillary blood biomarkers and thus, were less likely to exhibit a stress response due to the sampling procedure. Anecdotally, there is much less discomfort with capillary blood collections as opposed to venipuncture [31]. Cortisol measured in capillary blood also tracks well, and correlates strongly (r = 0.89) with, venous blood during acute stress induction [31]. As a further benefit for CAR research, capillary or venous blood measures can better capture the timing of cortisol peaks due to blood-saliva lag delays [27, 31, 32]. The same reasoning applies to TAR measurements.

Plasma cortisol and testosterone concentrations were determined using enzyme-linked immunoassay kits (DRG, Germany). The cortisol and testosterone kits had a sensitivity limit of 1.3 ng/mL and 0.083 ng/mL, respectively. Inter-assay variability on kit-supplied controls, expressed as a coefficient of variation, did not exceed 4%. All participants' samples were assayed in the same plate to eliminate inter-assay variation in the studied hormones. Plasma CK level, expressed in U/L, was determined spectrophotometrically using a biochemical analyzer (Biotecnica Instruments, Rome, Italy) and reagents provided by the manufacturer.

CAR and TAR features

Two complementary metrics were chosen to index the CAR and TAR; (1) change scores that reflect hormone reactivity and (2) area under the curve (AUC) measurements representing hormone secretory volume. To overcome interpretive issues arising from basal hormonal differences (e.g., due to sports training), both metrics were corrected for baseline values. Change scores were calculated as the raw difference at the 30-min (i.e., T2 [+30 mins] – T1 [+3 mins]) and 60-min (i.e., T3 [+60 mins] – T1 [+3 mins]) time points and expressed using the following notation: $CAR_{\Delta b30}$, $CAR_{\Delta b60}$, $TAR_{\Delta b30}$, and $TAR_{\Delta b60}$. The AUC for the 30-min and 60-min sampling periods was determined using a trapezoidal method [4, 27, 33] and expressed as follows: CAR_{AUCb30}, CAR_{AUCb60}, TAR_{AUCb30}, and TAR_{AUCb60}.

In the absence of a control group, reference blood cortisol and testosterone data were obtained from healthy men (N = 14–16) participating in a CAR study [34] and sleep research [35]. Study means were extracted from the article figures using WebPlotDigitizer (https://apps.automeris.io/wpd/). Reference values for blood CK were extracted from research on male judokas [23, 24] and collapsed into a single dataset (N = 23). The extracted means only served as a reference point and were not analyzed statistically.

Data analyses

The study data were analyzed using R software [36]. As a preliminary step to detect any post-awakening trends, the original cortisol and testosterone time series were plotted using local polynomial regression with a 95% confidence interval (CI). The reference datasets were also plotted, but no CI was estimated as individual data points were not available. Next, bivariate relationships between the CAR, TAR, and CK measures were explored using Pearson correlations (r). These correlations, computed after pooling data across both study weeks, were classified using the standard conventions of a weak (r = 0.20 to < 0.40), moderate (r = 0.40 to < 0.60), strong (r = 0.60 to < 0.80) or very strong ($r \geq 0.80$) effect.

To identify any training effect on the studied variables, each CAR, TAR, and CK metric was tested using a one-way, repeated measures analysis of variance. Models were constructed in the lmerTest package [37] using the linear mixed-effects procedure. Our specifications included training condition (light, heavy), as a within-subjects factor, and random intercepts for each participant. Checks of model residuals revealed that all normality assumptions were met. Results are plotted as estimated marginal means with a 95% CI. As an effect-size statistic, Cohen's d score was computed for each comparison and classified as a small (d = 0.20 to < 0.50), medium (d = 0.50 to < 0.80), large (d = 0.80 to < 1.20) or very large (d = 1.20+) effect.

To test whether CK acts as an intervening factor between training condition and the CAR or TAR, a series of causal mediation models were performed [38]. After standardizing all continuous variables, we first defined two effects using linear regression (i.e., training → mediator, training → outcome). Both outputs were entered into the mediation package [38] to estimate three pathways: (1) *direct effect* of training condition on each dependent variable (absent the mediator), (2) *indirect effect* of training condition on each dependent variable (going through the mediator), and (3) *total effect* representing the sum of direct and indirect effects. Estimates are provided with a bootstrapped 95% CI using a Quasi-Bayesian method (N = 5000 simulations). Statistical significance was set at an alpha level of $p \leq 0.05$.

RESULTS

All the plasma CAR parameters were strongly, and positively, interrelated with each other (p < 0.001, Table 1). The most prominent relationships, ranging from very strong to perfect (r = 0.96–1.00), emerged between the $CAR_{\Delta b30}$, CAR_{AUCb30}, and CAR_{AUCb60}. Likewise, the plasma TAR measures were strongly and positively related (p < 0.001), especially the $TAR_{\Delta b30}$, TAR_{AUCb30}, and TAR_{AUCb60} (r = 0.95–1.00). The plasma CAR and TAR metrics were all unrelated to each other (p > 0.154). Some trending (p = 0.062–0.063) negative, but weak, relationships were seen between plasma CK concentration and several CAR measures (i.e., $CAR_{\Delta b30}$, CAR_{AUCb30}, CAR_{AUCb60}). The plasma $CAR_{\Delta b60}$ and all TAR metric associations with CK concentration were found to be non-significant (p > 0.146).

Analysis of baseline (+3 mins) cortisol revealed no significant (p = 0.087) difference between light (marginal mean = 574 nmol/L)

TABLE 1. Pearson correlations between the plasma reactive changes and area under the curve measures of cortisol and testosterone, and creatine kinase (CK) concentration. Correlations are presented with a 95% CI in brackets.

Parameter	$CAR_{\Delta b60}$	CAR_{AUCb30}	CAR_{AUCb60}	$TAR_{\Delta b30}$	$TAR_{\Delta b60}$	TAR_{AUCb30}	TAR_{AUCb60}	CK
$CAR_{\Delta b30}$	0.68#	1.00#	0.96#	-0.19	-0.18	-0.19	-0.21	-0.30
	(0.47, 0.82)	(1.00, 1.00)	(0.92, 0.98)	(-0.47, 0.13)	(-0.47, 0.13)	(-0.47, 0.13)	(-0.49, 0.11)	(-0.56, 0.02)
$CAR_{\Delta b60}$		0.68#	0.87#	-0.19	-0.22	-0.19	-0.22	-0.23
		(0.47, 0.82)	(0.76, 0.93)	(-0.47, 0.13)	(-0.50, 0.10)	(-0.47, 0.13)	(-0.50, 0.10)	(-0.51, 0.08)
CAR_{AUCb30}			0.96#	-0.19	-0.18	-0.19	-0.21	-0.30
				(-0.47, 0.13)	(-0.47, 0.13)	(-0.47, 0.13)	(-0.49, 0.11)	(-0.56, 0.02)
CAR_{AUCb60}				-0.20	-0.22	-0.20	-0.23	-0.30
				(-0.48, 0.12)	(-0.49, 0.10)	(-0.48, 0.12)	(-0.50, 0.09)	(-0.56, 0.02)
$TAR_{\Delta b30}$					0.60#	1.00#	0.95#	0.13
					(0.35, 0.76)	(1.00, 1.00)	(0.91, 0.97)	(-0.19, 0.42)
$TAR_{\Delta b60}$						0.60#	0.81#	0.14
						(0.35, 0.76)	(0.67, 90)	(-0.18, 0.44)
TAR_{AUCb30}							0.95#	0.13
							(0.91, 0.97)	(-0.19, 0.42)
TAR_{AUCb60}								0.15
								(-0.17, 0.44)

Significant correlation at #$p < 0.001$.

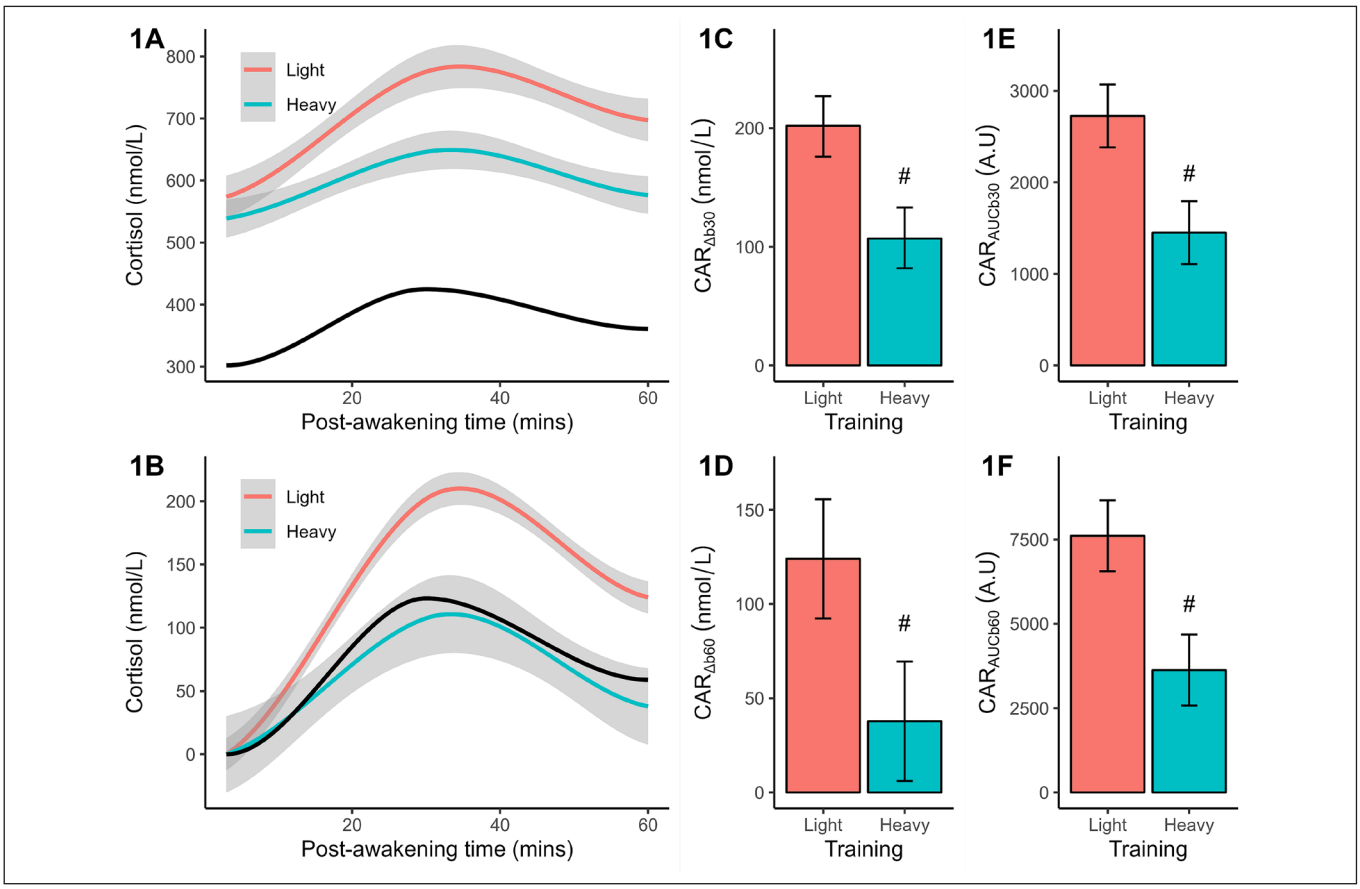


FIG. 1. Plasma measures of cortisol concentration (original, baseline-corrected), reactive changes ($CAR_{\Delta b30}$, $CAR_{\Delta b60}$), and area under the curve (CAR_{AUCb30}, CAR_{AUCb60}) following light and heavy training weeks. The smoothed concentration data are presented with a 95% CI. The solid black line indicates the smoothed reference data (means only). All CAR results are shown as marginal means with a 95% CI. Significant from light training #$p < 0.001$.

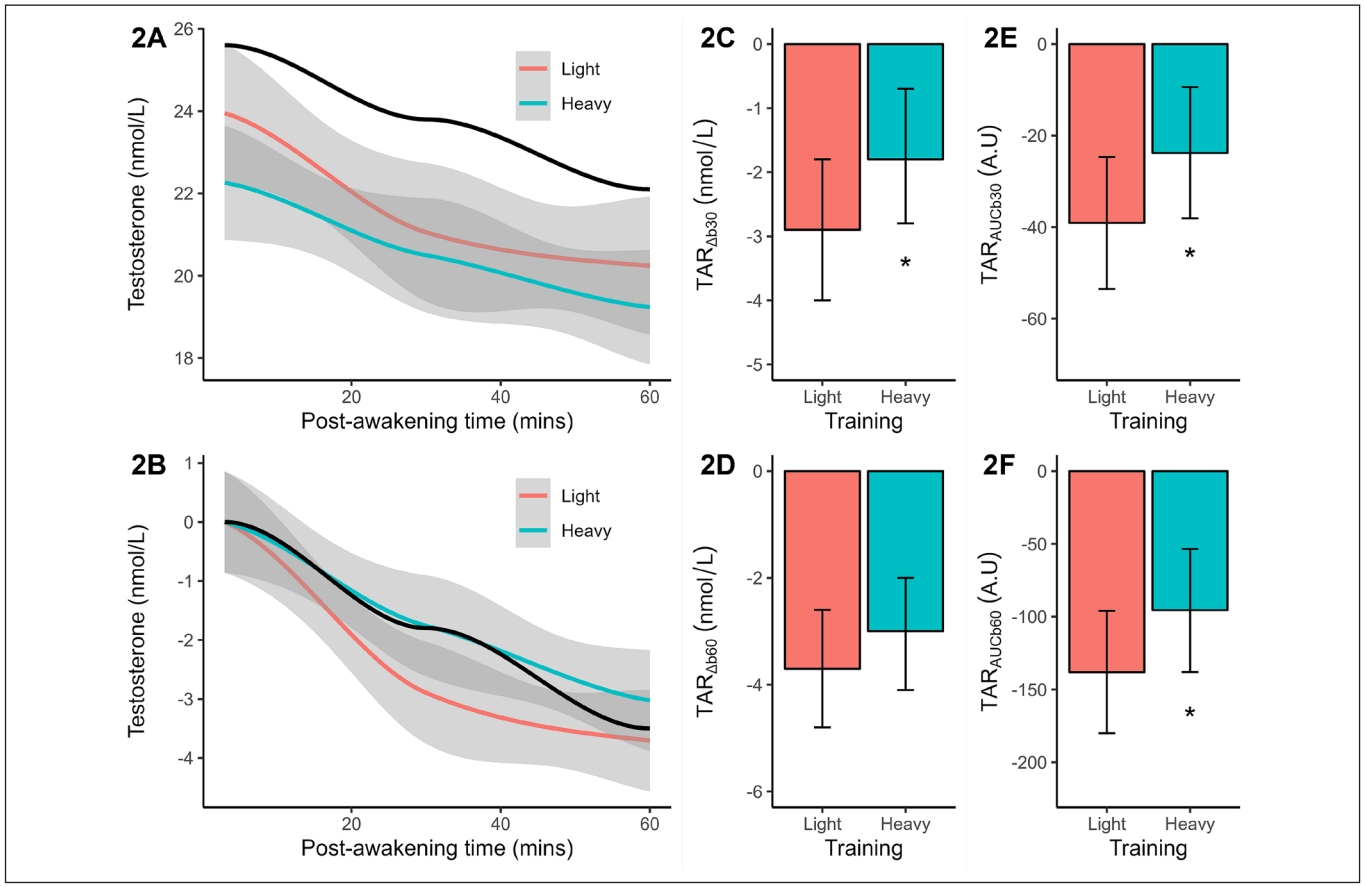


FIG. 2. Plasma measures of testosterone concentration (original, baseline-corrected), reactive changes ($TAR_{\Delta b30}$, $TAR_{\Delta b60}$), and area under the curve (TAR_{AUCb30}, TAR_{AUCb60}) following light and heavy training weeks. The smoothed concentration data are presented with a 95% CI. The solid black line indicates the smoothed reference data (means only). All TAR results are shown as marginal means with a 95% CI. Significant from light training *$p \leq 0.05$.

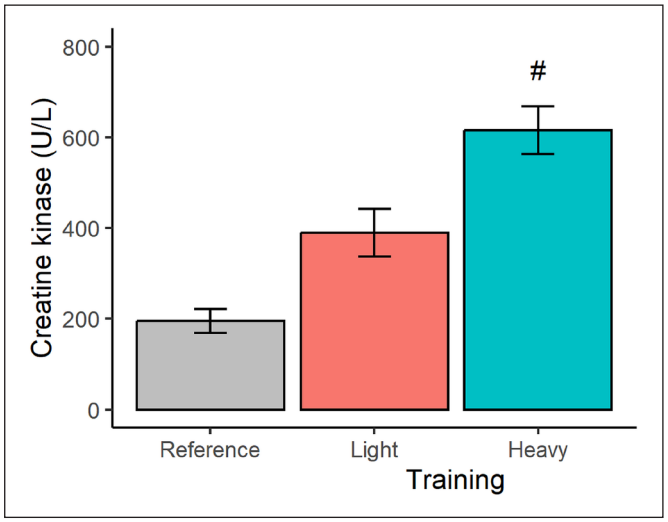


FIG. 3. Plasma creatine kinase concentration in male judokas following light and heavy training weeks. Results are presented as marginal means with a 95% CI. Reference data are shown as a descriptive mean with a 95% CI. Significant from light training #$p < 0.001$.

and heavy (marginal mean = 539 nmol/L) training, but the effect-size difference was large ($d = 0.83$) and potential meaningful. Qualitatively, both responses exceeded the reference group mean of 302 nmol/L. In the light training condition (Figure 1A), cortisol increased after waking and peaked after ~30 mins before declining; a pattern mirrored by heavy training and reference data, but at lower concentrations across most (or all) time points. The CAR shape remained once plotted after baseline corrections (Figure 1B), but training and reference differences were magnified. Statistical comparisons between training conditions verified a larger ($p < 0.001$) $CAR_{\Delta b30}$ (Figure 1C), $CAR_{\Delta b60}$ (Figure 1D), CAR_{AUCb30} (Figure 1E), and CAR_{AUCb60} (Figure 1F) after light than heavy training. The effect-size differences ranged from 2.14 to 2.64 or very large effects.

Baseline testosterone concentration differed significantly ($p = 0.038$, $d = 1.02$ or large effect) between light (marginal mean = 23.9 nmol/L) and heavy training (marginal mean = 22.3 nmol/L). Both results were slightly lower than the reference mean of 25.6 nmol/L. Post-awakening testosterone decreased with similar slopes in both training weeks and reference data (Figure 2A). After

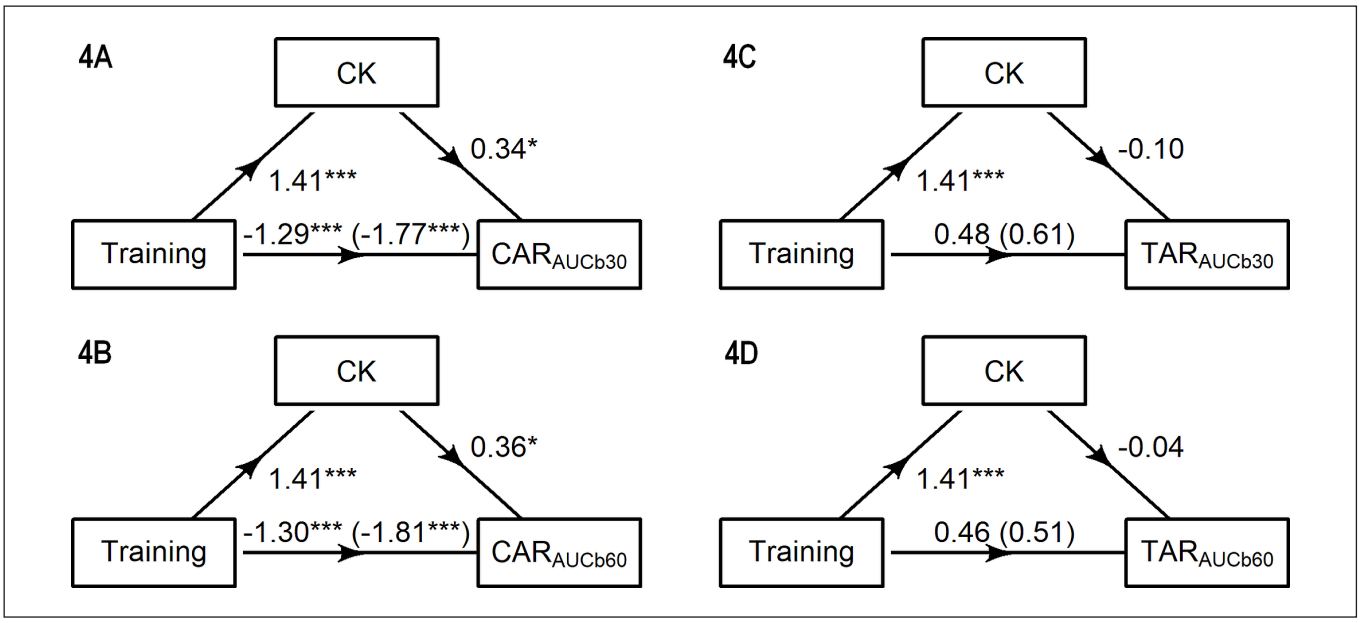


FIG. 4. Path models showing the effect of training condition on the CAR and TAR measures, as mediated by creatine kinase (CK). Total effect (path c) represents the effect of training on CAR_{AUCb30}, CAR_{AUCb60}, TAR_{AUCb30} and TAR_{AUCb60} with no mediator. Direct effect (path c') represents the effect of training on each outcome when the mediator is included in the model. Indirect effects (paths a*b) represent the effect of training on CAR_{AUCb30}, CAR_{AUCb60}, TAR_{AUCb30} and TAR_{AUCb60} through CK. Each figure shows the standardized regression coefficients (*$p < 0.05$, ***$p < 0.001$).

baseline corrections, the post-awakening decline in testosterone concentration was found to be less pronounced after heavy (vs. light) training (Figure 2B). Significance testing of the $TAR_{\Delta b30}$ ($p = 0.051$, Figure 2C), TAR_{AUCb30} ($p = 0.051$, Figure 2E), and TAR_{AUCb60} ($p = 0.035$, Figure 2F) confirmed a flatter early-morning trajectory after heavy training, compared to light training, with large effect-size differences (d = -0.95 to -1.04). No significant training effect on the $TAR_{\Delta b60}$ was identified (Figure 2D).

In terms of muscle damage (Figure 3), a higher ($p < 0.001$) CK concentration was seen after the heavy (vs. light) training condition, representing a very large effect-size difference of 4.70. The CK marginal means after the light and heavy training weeks also exceeded, at least qualitatively, the CK reference data by 100% and 216%, respectively.

The mediation results are plotted in Figure 4. Only the AUC outputs are presented to eliminate redundancies arising from strongly or perfectly correlated variables. Mediation analyses yielded a total and direct effect of training condition ($p < 0.001$) on the CAR_{AUCb30} (Figure 4A) and CAR_{AUCb60} (Figure 4B). The indirect CK-mediated effect of training on the CAR_{AUCb30} (estimate = 0.48, 95% CI 0.06, 0.17) and CAR_{AUCb60} (estimate = 0.50, 95% CI 0.03, 1.06) were also significant ($p \leq 0.040$). The total and direct effects of training on the TAR_{AUCb30} (Figure 4C) and TAR_{AUCb60} (Figure 4D) were non-significant. Likewise, the indirect effects of CK activity on the TAR_{AUCb30} (estimate = -0.14, 95% CI -0.63, 0.64) and TAR_{AUCb60} (estimate = -0.06, 95% CI -0.53, 0.64) were not significant. In summary, the CAR to training was partly mediated by CK, whilst no mediation effect on the TAR emerged.

DISCUSSION

This study investigated the impact of short training blocks at different intensities on plasma CAR, TAR and skeletal muscle damage (indexed by CK) in elite male judokas, and the intervening effect of muscle damage on the CAR and TAR. As hypothesized, the early-morning surge in cortisol concentration was reduced after a heavy (vs. light) training week. Heavy training also attenuated the post-awakening decline in testosterone concentration, and enhanced CK release, compared to light training. Aligning to our second hypothesis, the CK training response partly mediated the CAR, but not TAR, differences.

After the light training block, plasma cortisol values rose by 36% (+30 mins) and 22% (+60 mins) over waking levels, whilst plasma testosterone values decreased by -11% and -15% at these time points, consistent with general findings in athletic [4, 5, 7, 8, 17, 18, 33] and non-athletic men [2, 15, 16, 34, 39]. Training intensity appears to play a regulatory role with a heavy training block suppressing the CAR (21% and 8% increases) and attenuating the TAR (-7% and -13% decreases), respectively. Parallel results come from male rugby players, who displayed a smaller CAR and/or a flatter TAR across a short training camp [17, 18] that could reflect higher workloads and physiological stress. It is notable that the plasma CAR to training, and reference data, are smaller in magnitude than

saliva-based hormone research, where CAR increases of up to 50–120% have been described [2, 15, 27, 34]. Comparative studies show that the salivary CAR (as a %) is more than double the blood CAR [27, 34].

The training-induced CAR seen in male rugby players [17, 18] and male judokas differs from other sporting groups. For instance, a higher training load was linked to a larger CAR (delta and % change) in recreational runners, but no association was identified for cortisol AUC measurements [40]. Similarly, a 7-day period of intensified training in male footballers increased awakening and AUC cortisol concentrations, but the rate of cortisol increases and peaks did not change [33]. The physicality and physiology of each sport could explain these differences. Both judo and rugby are contact sports with high anaerobic demands, whilst running and football are non-contact sports with high aerobic (at least for running) demands. This lack of consistency across studies underscores the need for a mechanistic approach that targets key drivers and intervening factors, which might help contextualize any reported discrepancies.

In judokas, different exercise and training session configurations can elicit muscle damage of varying degrees [21, 22, 23, 24]. Here, a short block of heavy training promoted a dramatic rise in morning CK level from light training and both responses exceeded reference CK in a dose-response manner (light by 100%, heavy by 216%). The time course of muscle damage has implications for this study. For instance, three days of judo-specific training increased CK level, from a resting value of 211 U/L up to 795 U/L immediately post the last training session, before declining to 648 U/L some 12 hours later [23]. This pattern suggests an underestimation of muscle injury in this work, since CK was assessed nearly two days after the preceding workout. Nonetheless, the inflammatory response to muscle injury is a complex process, activating a myriad of pro- and anti-inflammatory cytokines, proteins, and oxidative stress markers on different time scales [22, 23, 24]. Hence, for a more detailed inspection of this process, a broader battery of biochemical markers with more frequent post-exercise or post-training sampling is recommended.

Our principal finding was that muscle damage mediated, in part, differences in the plasma CAR. Parallel results come from research on OTS athletes, who presented a lower CAR and higher CK level than healthy athletes at initial testing, but similar CAR and CK profiles after three months recovery [9]. Other descriptive and experimental work in sport suggest a CAR link to muscle damage [10, 17, 41]. Speculatively, the mechanism/s behind these linkages exist in the anti- and pro-inflammatory effects of cortisol [11, 12], which coexist and are imbedded in complex dynamics with the ascending and descending circadian phases [12]. As cortisol moves towards its ascending early-morning peak, suppressive effects rise and dominate over permissive effects [12]. Accordingly, when recovering from a prior inflammatory stimulus (e.g., heavy training), a smaller CAR might be adaptive by ensuring that permissive effects dominate to mount an efficient defensive response to imminent stressors. By this logic, a larger CAR seen under normal (e.g., light training) conditions could be more suppressive, but still adaptive, to meet homeostatic needs. These ideas await experimental testing in sport, as does a potential metabolic role for the CAR [13, 14].

The induction of muscle damage did not, however, mediate the plasma TAR. As one explanation, much smaller standardized effects on the TAR (< 1.1) than CAR (> 2.1) materialized. Baseline testosterone secretion also exhibits greater sensitivity to sports training than cortisol [13], as we illustrated, and is a major determinant of testosterone's post-awakening trajectory. Supporting this, initial (+3 min) testosterone concentration was strongly, and negatively, related to all TAR metrics (r = -0.75 to -0.83, $p < 0.001$) corrected for baseline differences. Other potential explanations exist, given that intra-individual variability in the daily rate of testosterone change is primarily due to individual-specific environmental factors [39]. This may include, but not limited to, speculated TAR roles to help partition testosterone's primary functions and target tissues to muscle anabolism while asleep, and to catabolism, behavior and social interaction while awake [16].

Contrary to initial expectations, we did not find any positive CAR and TAR associations. These null findings do come with important caveats. First, only between-subject CAR and TAR relationships were tested, not within-person associations where cortisol and testosterone linkages across the day often reside [20, 42, 43]. Second, stronger time-lagged associations (up to 60 mins) between cortisol and testosterone have been reported [20, 42] that could not be evaluated under the current sampling regime. Third, CAR modulation appears to be partly dependent on nocturnal HPA activity [34], driven by regulatory inputs (e.g., adrenocorticotropin hormone) beyond those psychophysiological processes specific to the sleep-wake transition. The same principle applies to those HPG signals (e.g., luteinizing hormone) that govern testosterone production. Therefore, a dedicated analysis of these HPA and HPG signals, across the late nocturnal and post-awakening periods, is needed to explicate interaxes coordination at this critical junction.

Several practical applications emanate from this work. Conceptualizing muscle damage as an intervening variable could explain the lack of CAR shifts in some competitive sports [7, 8], due to existing injuries and inflammation. It also offers a mechanism to explain a depressed CAR following a late evening exercise session [27] and rising CAR prior to challenging events [4, 6], since prior exercise intensity and/or volume is typically reduced. Awareness of impending muscle damage (e.g., after intensified training) might also guide novel interventional strategies. One being early-morning light exposure to boost the CAR [44] until inflammation subsides. The observed CAR and TAR adaptations could further assist study planning. Training intensity, for instance, can be adjusted to manipulate post-awakening hormones and test other hypotheses. From a measurement perspective, we discovered that some CAR and TAR metrics (i.e., Δb30, AUCb30, AUCb60) are interchangeable, due to very

strong or perfect *r* values. Likewise, the emergence of different effect sizes (CK > CAR > TAR) and thus, sensitivities to the same training stimuli, can inform instrument selection in sports research and practice.

The study strengths include the ecological design, collection of blood samples, and extended (up to 60 mins) post-awakening sampling period. Nevertheless, this work does have inherent limitations. Statistical power was compromised by the small sample and post-only assessment design. The targeting of male judokas also limits the generalizability of our findings to non-combat sport athletes and sedentary populations. Furthermore, we were unable to counterbalance the training interventions, due to practical constraints when working with elite athletes. On the other hand, any cross-over effect is minimized by the scheduling of light training first. Finally, we did not quantify individual workloads at each training intensity, although the CK results infer different physiological and physical demands, as does training and non-training (i.e., reference) comparisons. Still, this information would be a useful adjunct in future work to establish load thresholds for the CAR and TAR, and to investigate individual dose-response variability in these outcomes [1, 5, 40].

CONCLUSIONS

The CAR and TAR are distinct hormonal features with emerging focus in sport, but lacking a strong mechanistic understanding. This study on elite male judokas revealed a suppressed CAR, and attenuated TAR, following a short block of heavy versus light training. Differential CK release patterns (heavy > light training), as a proxy for skeletal muscle damage, partly explained the CAR differences. Viewing muscle damage as an intervening factor could therefore inform the design and interpretation of hormone-awakening research.

Acknowledgements

We wish to thank the study participants and coaching staff who contributed to this research. No external research funds were sought for this project. During manuscript preparation, the lead author (BTC) received a post-doctoral fellowship on the Performance Patch project, which was financially supported by the Defence Science & Technology (DST) Group's Next Generation Technology Fund. Financial support by the DST Group or the Department of Defence does not constitute an expressed or implied endorsement of the results or conclusions of the project.

Data availability

The research data collected are unavailable due to confidentiality agreements.

Conflict of interest

The authors report that there are no competing interests to declare.

REFERENCES

1. Anderson T, Wideman L. Exercise and the Cortisol Awakening Response: A Systematic Review. Sports Med Open. 2017; 3(37). doi: 10.1186/s40798-017-0102-3.
2. Pruessner JC, Wolf OT, Hellhammer DH, Buske-Kirschbaum A, von Auer K, Jobst S, et al. Free cortisol levels after awakening: a reliable biological marker for the assessment of adrenocortical activity. Life Sci. 1997; 61(26):2539–49.
3. Serpell BG, Colomer CM, Pickering MR, Cook CJ. Team Behavior and Performance: An Exploration in the Context of Professional Rugby Union. Int J Sports Physiol Perform. 2023; 18(9):996–1003
4. Lee JK, Park JK, Kim H, Kang JY, Park JY, Do SH, et al. Association of the HPA axis response to upcoming competition and shooting outcomes in elite junior shooting players. Stress. 2020; 23(2):153–61.
5. Kayacan Y, Derebasi DG, Ucar C, Ozgocer T, Yildiz S. The hypothalamic-pituitary-adrenal axis activity in archers: cortisol release, stress, anxiety and success. J Sports Med Phys Fit. 2022; 62(1):139–48.
6. Aguilar R, Martínez C, Alvero-Cruz JR. Cortisol awakening response and emotion at extreme altitudes on Mount Kangchenjunga. Int J Psychophysiol. 2018; 131:81–8.
7. Díaz MM, Bocanegra OL, Teixeira RR, Tavares M, Soares SS, Espindola FS. The relationship between the cortisol awakening response, mood states, and performance. J Strength Cond Res. 2013; 27(5):1340–8.
8. Strahler K, Ehrlenspiel F, Heene M, Brand R. Competitive anxiety and cortisol awakening response in the week leading up to a competition. Psychol Sport Exerc. 2010; 11(2):148–54.
9. Cadegiani FA, Silva PHL, Abrao TCP, Kater CE. Novel Markers of Recovery From Overtraining Syndrome: The EROS-LONGITUDINAL Study. Int J Sports Physiol Perform. 2021; 16(8):1175–84.
10. Gouarné C, Groussard C, Gratas-Delamarche A, P D, Duclos M. Overnight urinary cortisol and cortisone add new insights into adaptation to training. Med Sci Sports Exerc. 2005; 37(7):1157–67.
11. Yeager MP, Pioli PA, Guyre PM. Cortisol exerts bi-phasic regulation of inflammation in humans. Dose Response. 2011; 9(3):332–47.
12. Mavroudis PD, Corbett SA, Calvano SE, Androulakis IP. Circadian characteristics of permissive and suppressive effects of cortisol and their role in homeostasis and the acute inflammatory response. Math Biosci. 2015; 260:54–64.
13. Crewther BT, Cook C, Cardinale M, Weatherby RP, Lowe T. Two emerging concepts for elite athletes: The short-term effects of testosterone and cortisol on the neuromuscular system and the dose-response training role of these endogenous hormones. Sports Med. 2011; 41(2):103–23.
14. Viru A, Viru M. Cortisol--essential adaptation hormone in exercise. Int J Sports Med. 2004; 25(6):461–4.
15. Panizzon MS, Hauger RL, Xian H, Jacobson K, Lyons MJ, Franz CE, et al. Interactive effects of testosterone and cortisol on hippocampal volume and episodic memory in middle-aged men. Psychoneuroendocrinology. 2018; 91:115–22.
16. Kuzawa CW, Georgiev AV, McDade TW, Bechayda SA, Gettler LT. Is there a testosterone awakening response in humans? Adapt Hum Behav Physiol. 2016; 2(2):166–83.
17. Serpell BG, Horgan BG, Colomer CME, Field B, Halson SL, Cook CJ. Sleep and Salivary Testosterone and Cortisol During a Short Preseason Camp: A Study in Professional Rugby Union. Int J Sports Physiol Perform. 2019; 14(6):796–804.

18. Serpell BG, Larkham S, Cook CJ. Does stress affect nonverbal engagement in teams? A case study in professional team sport. Team Perform Manag. 2020; 26(3/4):197–210.
19. Oyola MG, Handa RJ. Hypothalamic-pituitary-adrenal and hypothalamic-pituitary-gonadal axes: sex differences in regulation of stress responsivity. Stress. 2017; 20(5):476–94.
20. Crewther BT, Hecht M, Cook CJ. Diurnal within-person coupling between testosterone and cortisol in healthy men: evidence of positive and bidirectional time-lagged associations using a continuous-time model. Adapt Hum Behav Physiol. 2021; 7(2):89–104.
21. Campos BT, Penna EM, Katsuragi AT, Porto L, Miyata FK, Albuquerque MR, et al. Neuromuscular and physiological responses to different training loads in Randori of elite judo athletes. Mot Rev de Educ Fis. 2020; 26(2):e10200203.
22. Gandouzi I, Turki M, Ayedi F, Souissi N. Comparison of muscle damage parameters between the training session and after a fight amongst judokas. J Phys Educ Sport. 2020; 20(1):71–8.
23. Laskowski R, Ziemann E, Olek RA, Zembron-Lacny A. The effect of three days of judo training sessions on the inflammatory response and oxidative stress markers. J Human Kinetic. 2011; 30:65–73.
24. Tartibian B, Nouri H, Azadpour N, Koşar Ş, Massart A, Filaire E. Eight weeks judo training increases oxidative stress biomarkers and creatine kinase in male judoka. Indian J Biochem Biophys. 2015; 52:281–8.
25. Parmigiani S, Bartolomucci A, Palanza P, Galli P, Rizzi N, Brain PF, et al. In judo, Randori (free fight) and Kata (highly ritualized fight) differentially change plasma cortisol, testosterone, and interleukin levels in male participants. Aggress Behav. 2006; 32:481–9.
26. Papacosta E, Gleeson M, Nassis GP. Salivary hormones, IgA, and performance during intense training and tapering in judo athletes. J Strength Cond Res. 2013; 27(9):2569–80.
27. Anderson T, Vrshek-Schallhorn S, Adams WM, Goldfarb AH, Wideman L. The effect of acute exercise on the cortisol awakening response. Eur J Appl Physiol. 2023; 123(5):1027–39.
28. Ogasawara Y, Kadooka S, Tsuchiya H, Sugo T. High cortisol awakening response measured on day following high-intensity exercise. J Phys Fit Sports Med. 2022; 11(2):59–66.
29. Sterkowicz S, Zuchowicz A, Kubica R. Levels of anaerobic and aerobic capacity indices and results for the Special Judo Fitness Test in judo competitors. J Human Kinetic. 1999; 2:115–35.
30. Stalder T, Kirschbaum C, Kudielka BM, Adam EK, Pruessner JC, S W, et al. Assessment of the cortisol awakening response: Expert consensus guidelines. Psychoneuroendocrinology. 2016; 63:414–32.
31. Fryer SM, Dickson T, Hillier S, Stoner L, Scarrott C, Draper N. A comparison of capillary, venous, and salivary cortisol sampling after intense exercise. Int J Sports Physiol Perform. 2014; 9(6):973–7.
32. Trifonova ST, Gantenbein M, Turner JD, Muller CP. The use of saliva for assessment of cortisol pulsatile secretion by deconvolution analysis. Psychoneuroendocrinology. 2013; 38(7):1090–101.
33. Minetto MA, Lanfranco F, Tibaudi A, Baldi M, Termine A, Ghigo E. Changes in awakening cortisol response and midnight salivary cortisol are sensitive markers of strenuous training-induced fatigue. J Endocrinol Invest. 2008; 31:16–24.
34. Wilhelm I, Born. J, Kudielka BM, Schlotz W, Wüst S. Is the cortisol awakening rise a response to awakening? Psychoneuroendocrinology. 2007; 32(4):358–66.
35. Axelsson J, Ingre M, Akerstedt T, Holmbäck U. Effects of acutely displaced sleep on testosterone. J Clin Endocrinol Metab. 2005; 90(8):4530–5.
36. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2023. https://www.R-project.org.
37. Kuznetsova A, Brockhoff PB, Christensen RHB. lmerTest Package: Tests in Linear Mixed Effects Models. J Stat Softw. 2017; 82(13):1–26.
38. Tingley D, Yamamoto T, Hirose K, Keele L, Imai K. mediation: R Package for Causal Mediation Analysis. J Stat Softw. 2014; 59(5):1–38.
39. Panizzon MS, Hauger R, Jacobson KC, Eaves LJ, York TP, Prom-Wormley E, et al. Genetic and environmental influences of daily and intra-individual variation in testosterone levels in middle-aged men. Psychoneuroendocrinology. 2013; 38(10):2163–72.
40. Anderson T, Lane AR, Hackney AC. The Cortisol Awakening Response: Association With Training Load in Endurance Runners. Int J Sports Physiol Perform. 2018; 13(9):1158–63.
41. Mousavi E, Sadeghi-Bahmani D, Khazaie H, Brühl AB, Stanga Z, Brand S. The Effect of a Modified Mindfulness--Based Stress Reduction (MBSR) Program on Symptoms of Stress and Depression and on Saliva Cortisol and Serum Creatine Kinase among Male Wrestlers. Healthcare. 2023; 11(11). https://doi.org/10.3390/healthcare11111643.
42. van der Spoel E, Roelfsema F, van Heemst D. Relationships Between 24-hour LH and Testosterone Concentrations and With Other Pituitary Hormones in Healthy Older Men. J Endocr Soc. 2021; 5(9):1–15.
43. Harden KP, Wrzus C, Luong G, Grotzinger A, Bajbouj M, Rauers A, et al. Diurnal coupling between testosterone and cortisol from adolescence to older adulthood. Psychoneuroendocrinology. 2016; 73:79–90.
44. Petrowski K, Schmalbach B, Niedling M, Stalder T. The effects of post-awakening light exposure on the cortisol awakening response in healthy male individuals. Psychoneuroendocrinology. 2019; 108:28–34.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.139072
© Institute of Sport – National Research Institute

Effects of a cardiopulmonary rehabilitation programme on submaximal exercise in Tunisian patients with long-COVID19: A randomized clinical trial

AUTHORS: Rania Kaddoussi[1], Hadhemi Rejeb[2], Amine Kalai[3], Eya Zaara[1], Naceur Rouetbi[1], Zohra Ben Salah Frih[3], Piotr Zmijewski[4], Helmi Ben Saad[5,6,7]

[1] Department of Pneumology, Fattouma Bourguiba Hospital, Monastir, Tunisia
[2] Ibn Nafiss department of Pneumology, Abdelrahman Mami hospital, Ariana, Tunisia
[3] Department of Physical Medicine and Rehabilitation, Fattouma Bourguiba Hospital, Monastir, Tunisia
[4] Jozef Pilsudski University of Physical Education in Warsaw, Warsaw, Poland
[5] Heart Failure (LR12SP09) Research Laboratory, Farhat HACHED Hospital, Sousse, Tunisia
[6] Laboratory of Physiology. Faculty of Medicine of Sousse. University of Sousse, Sousse Tunisia
[7] Department of Physiology and Functional Exploration. Farhat HACHED Hospital, Sousse, Tunisia

Corresponding author:
Helmi BEN SAAD
Laboratory of Physiology
Faculty of Medicine of Sousse
Street Mohamed KAROUI
Sousse 4000, Tunisia
Tel.: 0021698697024
E-mail: helmi.bensaad@rns.tn

ORCID:
Rania Kaddoussi
0000-0003-0287-1689
Hedhemi Rejeb
0000-0001-6292-0214
Amine Kalai
0000-0003-2964-892X
Eya Zaara
0009-0004-9219-3221
Naceur Rouetbi
0000-0002-2023-6294
Zohra Ben Salah Frih
0000-0003-4896-7897
Piotr Zmijewski
0000-0002-5570-9573
Helmi Ben Saad
0000-0002-7477-2965

ABSTRACT: There is a lack of randomized clinical trials (RCTs) exploring the outcomes of cardiopulmonary rehabilitation programmes (CPRPs) on submaximal aerobic capacity of long COVID-19 patients (LC19Ps). This RCT aimed to evaluate the effect of an ambulatory CPRP on the 6-min walk test (6MWT) data (main outcome: 6-min walk distance (6MWD)) of LC19Ps. Conducted as a single-blinded RCT, the study included Tunisian LC19Ps with persistent dyspnoea (i.e. modified medical research council (mMRC) level ≥2) at least three months post-diagnosis. LC19Ps were randomly assigned to the intervention (IG, n = 20) or control (CG, n = 10) groups. Pre- and post-CPRP evaluations included dyspnoea assessments (Borg and mMRC scales), anthropometric data, spirometry, and 6MWT. The CPRP (i.e. 18 sessions over six weeks) encompassed warm-up, aerobic training, resistance training, respiratory exercises, and therapeutic education. The CPRP significantly improved *i)* dyspnoea, i.e. IG exhibited larger reductions compared to the CG in Borg (-3.5 ± 2.0 vs. -1.3 ± 1.5) and mMRC (-1.5 ± 0.8 vs. -0.1 ± 0.3) scales, and *ii)* 6MWD, i.e. IG demonstrated larger improvements compared to the CG in 6MWD (m, %) (168 ± 99 vs. 5 ± 45 m, 28 ± 8 vs. 1 ± 8%, respectively), and resting heart rate (bpm, % maximal predicted heart rate) (-9 ± 9 vs. 1 ± 7 bpm; -5 ± 6 vs. 0 ± 4%, respectively), with small effect sizes. In the IG, the 1.5-point decrease in mMRC and the 168 m increase in 6MWD exceeded the recommended minimal clinical important differences of 1 point and 30 m, respectively. CPRP appears to be effective in enhancing the submaximal exercise capacity of LC19Ps, particularly in improving 6MWD, dyspnoea, and resting heart rate. RCT registration: www.pactr.org; PACTR202303849880222.

CITATION: Kaddoussi R, Rejeb H, Kalai A et al. Effects of a cardiopulmonary rehabilitation programme on submaximal exercise in Tunisian patients with long-COVID19: A randomized clinical trial. Biol Sport. 2024;41(4):197–217.

Received: 2024-01-27; Reviewed: 2024-02-17; Re-submitted: 2024-02-24; Accepted: 2024-03-11; Published: 2024-04-25.

Key words:
Ambulatory cardiopulmonary rehabilitation
Long-term COVID-19 effects
MCID
Persistent COVID-19 symptoms
Post-acute COVID-19
Randomized clinical trial
Submaximal exercise capacity
Therapeutic education

LIST OF ABBREVIATIONS

ANOVA: analysis of variance
ATS: American Thoracic Society
BMI: body mass index
CG: control group
COVID-19: coronavirus disease 2019
CPRPs: cardiopulmonary rehabilitation programmes
DBP: diastolic blood pressure
$_{End}$: after the walk
ERS: European Respiratory Society
FEV_1: forced expiratory volume in one second
FVC: Forced vital capacity
HR: heart rate
IG: intervention group
LC19: long COVID-19
LC19Ps: LC19 patients
LLN: lower limit of normal
MCID: minimal clinically important difference
MD: mean difference
mMRC: modified medical research council
PMHR: predicted maximal HR
RCTs: randomized clinical trials
$_{Rest}$: before the walk
RT-PCR: real-time reverse-transcription polymerase chain reaction
SARS-CoV-2: severe acute respiratory syndrome coronavirus-2 infection
SBP: systolic blood pressure
SpO_2: oxy-haemoglobin saturation
SD: standard deviation
SR: systematic review
6MWD: 6-min walk distance
6MWT: 6-min walk test
6MWW: 6-min walk work
ΔExercise: delta exercise change (= $6MWT_{End}$ value minus $6MWT_{Rest}$ value)

INTRODUCTION

The coronavirus disease 2019 (COVID-19) pandemic has had a profound global impact, causing widespread economic disruption and social upheaval [1]. As of February 19, 2024, there have been a staggering 70,3482,641 reported COVID-19 infections and 6,984,597 related deaths (0.9928%) worldwide (https://www.worldometers.info/coronavirus/). COVID-19, caused by severe acute respiratory syndrome coronavirus-2 infection (SARS-CoV-2), affects the respiratory system and various extra pulmonary organs [2]. Manifestations range from asymptomatic to critical illness [3]. Pneumonia resulting from COVID-19 infection can lead to permanent lung parenchyma structural damage, even with appropriate medical treatment [4]. Consequently, most COVID-19 patients continue to experience sequelae and medical complications lasting weeks to months after initial recovery [5]. In the post-acute phase of COVID-19, 40% to 90% of patients continue to manifest symptoms for months [5]. The term long COVID-19 (LC19) (also called "long-term COVID-19 effects", "post-acute COVID-19", and "persistent COVID-19 symptoms"), characterized by the continuation or development of new symptoms three months after the initial infection with SARS-CoV-2, refers to symptoms lasting at least two months with no other explanation [5, 6]. LC19 presents with diverse clinical manifestations affecting various systems, including respiratory, cardiovascular, muscular, nutritional status, and sleep [5, 7, 8]. First, studies on LC19 patients (LC19Ps) reported persistent reductions in forced expiratory volume in one second (FEV_1) and forced vital capacity (FVC), as well as exertional dyspnoea (modified medical research council (mMRC)) [9, 10]. Second, a 2023 systematic review (SR) and meta-analysis revealed significantly higher odds ratios for cardiovascular outcomes in LC19Ps compared to controls, including electrophysiological abnormalities, coronary vessel diseases, thromboembolic disorders, and diseases of cardiac tissue [11]. Third, musculoskeletal complaints were reported in 39% of LC19Ps [7]. Fourth, a study reported that 13.3% of COVID symptom study app users experienced at least one persistent symptom beyond four weeks of infection, with half believed to be cardiac in origin [12]. Finally, a reduced 6-min walk distance (6MWD) was reported by some authors [9], and it appears that approximately 33% [13] and 23% [14] of LC19Ps have a decreased peak oxygen consumption three and 12 months after hospital discharge, respectively. Given the significant compromises in daily functioning experienced by survivors of moderate to severe COVID-19 [13], cardiopulmonary rehabilitation programmes (CPRPs) have emerged as a crucial intervention for improving outcomes in LC19Ps and preventing further long-term damage [15–19].

CPRPs are pivotal in managing chronic cardiorespiratory conditions, with well-established benefits [20]. A 2022 American consensus specifically addressed post-acute persistent breathing discomfort and respiratory sequelae in LC19Ps, recommending CPRPs for those with dyspnoea, breathing abnormalities, fatigue, peripheral and respiratory muscle weakness, and reduced endurance [21]. The aim is to promote functional improvement and facilitate a return to daily activities [21]. CPRPs have demonstrated safety and effectiveness, even in severe LC19Ps [19]. Assessing submaximal exercise capacity through the 6-min walk test (6MWT) is recommended for patients with cardiorespiratory conditions [22]. The 6MWT is widely used in CPRPs, providing valuable insights into their impact on cardiorespiratory fitness [23]. A 2022 SR [24] concluded that CPRPs had inconsistent results in pulmonary function of LC19Ps. Nevertheless, the SR detected improvements in dyspnoea, muscle strength, 6MWD, and quality of life [24]. However, since this SR [24] included a limited number of randomized clinical trials (RCTs) (n = 5), with two having a low risk of bias and three in the "some concerns" category, additional RCTs are needed to confirm these preliminary findings. This was corroborated by a 2023 SR [25] assessing the impact of CPRPs on 6MWT outcomes in LC19Ps, which included six RCTs demonstrating "low" or "moderate" risk of bias [26–31]. The SR concluded that CPRPs show promise in improving submaximal exercise performance among LC19Ps, and further research is needed to refine these programmes [25]. As of December 30, 2023, 26 RCTs related to the effects of CPRPs on LC19Ps have been published in *PubMed* [i.e. research using the two keywords (pulmonary rehabilitation) AND (COVID-19)] (see all references in the Appendix), but only 11 have exclusively reported 6MWT and/or pulmonary function data, among others [26–36]. Among these 11 RCTs, two [27, 28] opted for CPRPs exclusively via telemedicine, three [26, 30, 32] opted for both hospital and telemedicine CPRPs, and six [29, 31, 33–36] opted for exclusively hospital CPRPs. In North Africa, it appears that only one Egyptian RCT has evaluated the effects of a CPRP on LC19Ps [29]. The authors determined whether the addition of manual diaphragm release to an inspiratory muscle-training programme is more effective than inspiratory muscle training alone in reducing blood pressure, dyspnoea, fatigue, and aerobic performance capacity in male LC19Ps [29]. In Tunisia, only one pilot observational study has evaluated the effects of a CPRP on submaximal exercise capacity [37] social disadvantage and physical activity data [38] of male LC19Ps.

The main objective of the present RCT conducted in Tunisia was to evaluate the impacts of an ambulatory CPRP on submaximal aerobic capacity, evaluated via 6MWT data (the main outcome is the 6MWD). The null hypothesize is that the two groups (i.e. intervention (IG) and control (CG) groups) will have comparable 6MWDs. The CPRP will be considered 'efficient' if the change in 6MWD exceeds the recommended minimal clinically important difference (MCID) of 30 m [39]. The secondary aim was to evaluate the effects of the CPRP on perceived dyspnoea and spirometric data. A decrease of more than one point for mMRC dyspnoea will signify a perceived clinical improvement [40, 41]. The last aim was

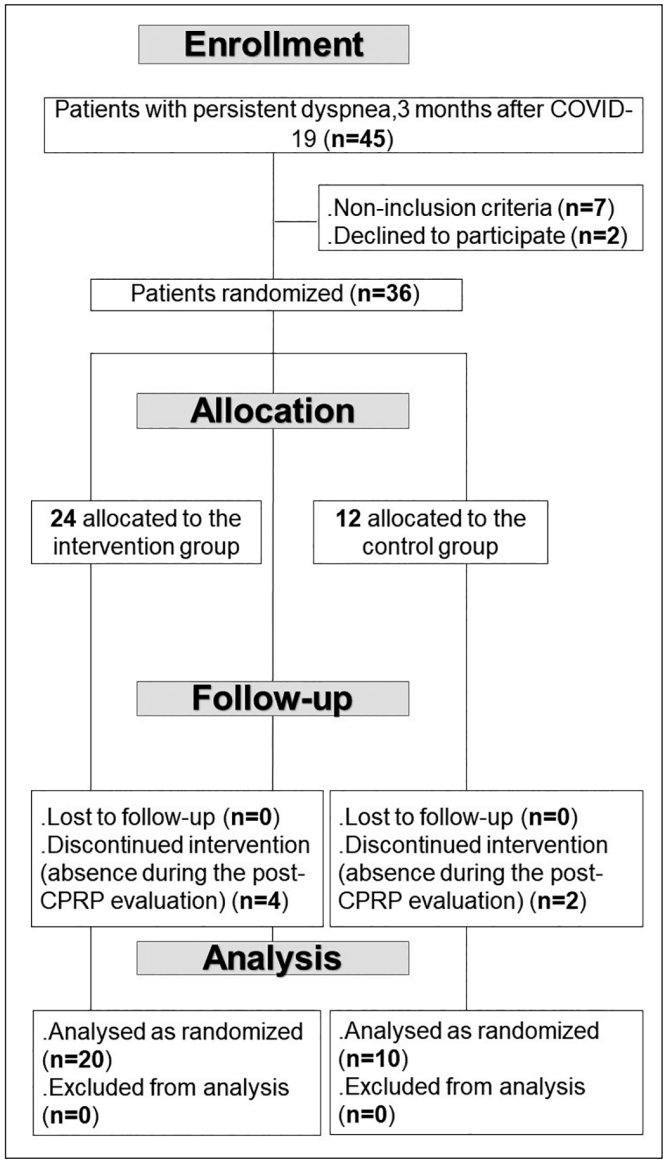


FIG. 1. Study protocol. COVID-19: coronavirus disease 2019. CPRP: cardiopulmonary rehabilitation programme

to perform a narrative review including exclusively RCTs aiming to determine the effectiveness of CPRPs on the submaximal exercise capacity of LC19Ps, specifically assessed through the 6MWT data.

MATERIALS AND METHODS

This study is one component of a broader project comprising two distinct parts. The first part constitutes the aim of this RCT. The second part will involve evaluating the effects of CPRP on social disadvantage, encompassing psychological data and health-related quality of life. Figure 1 details the flowchart of the current project.

Study design

This was a single-blinded RCT carried out by two Tunisian teams from the departments of pulmonology and physical medicine and rehabilitation (Fattouma Bourguiba hospital, Monastir, Tunisia). This study was approved by the medical and research ethics committee of the faculty of medicine of Sousse (Approval number CEFMS 162/2023). The study was registered at the Pan African Clinical Trial Registry (www.pactr.org; PACTR202303849880222). A written informed consent form was issued and signed by all patients before their inclusion in the study. Clear and appropriate information was communicated to each patient in French or in Arabic languages, including the description and the progress of the various examinations.

This study was performed during a period of 84 days (i.e. from April 1 to June 23, 2023 (Figure 2]). A ten-day period (i.e. from April 1 to 10) was reserved for the recruitment of LC19Ps (i.e. invitation to participate, explanation of the protocol and answering patients' questions). During a two-week period (i.e. April 11 to April 25, 2023), the pre-CPRP evaluations' tests were performed. A six-week period (i.e. April 27 to June 8, 2023) was reserved for the practice of the CPRP. During a two-week period (i.e. June 9 to 23, 2023), the post-CPRP evaluations' tests were performed.

Study population

The source population for this study comprised LC19Ps residing in Monastir (Tunisia), who sought care at the outpatient department of pulmonology in the mentioned hospital. Inclusion criteria encompassed patients with a confirmed diagnosis of COVID-19, aged over 18 years, experiencing persistent dyspnoea three months after the COVID-19 diagnosis, with dyspnoea scoring two or more on the mMRC scale [42]. LC19Ps with pre-existing chronic lung conditions such as asthma, chronic obstructive pulmonary disease, or lung cancer, those with moderate to advanced heart failure, patients with conditions affecting walking or limiting mobility (e.g. orthopaedic, rheumatologic, or muscular diseases), active cigarette or narghile smokers, and those having contraindications to the 6MWT [22, 39, 43] (e.g. signs of unstable angina or myocardial infarction within the previous month, resting ($_{Rest}$) heart rate (HR_{Rest}) ≥ 120 bpm, systolic blood pressure (SBP_{Rest}) ≥ 180 mmHg, diastolic blood pressure (DBP_{Rest}) ≥ 100 mmHg)) or to spirometry [44] were not included in the study. Files of patients who missed any session of the CPRP or did not attend the final evaluation were excluded from the final statistical analysis.

Random assignment and blinding

Patients were randomly assigned to either undergo the CPRP (i.e. IG) or not (i.e. CG). The random allocation sequence was generated using free software (http://www.randomized.org/; last visit: February 24, 2024). The principal investigator (*RK* in the authors' list) executed the randomization sequence to determine two groups identified as IG and CG. The evaluator who enrolled and assessed patients (*EZ* in the authors' list) had no access to the randomization sequence.

The investigators (*EZ* and *HR* in the authors' list) and patients in the study were blinded throughout the entire procedure. The

investigators were uninformed about the study aims and the randomized distribution of patients to study groups, and they did not have access to the randomization sequence. Meanwhile, although blinding for patients could not be achieved, patients were unaware of the other treatment modalities. They did not know if they belonged to the IG or CG.

Sample size estimation

The sample size was estimated using the predictive formula [45]: $N = [(r+1)(Z_{\alpha/2} + Z_{1-\beta})^2 \delta^2]/(r\, d^2)$, where

- *"N"* is equal to $n_1 + n_2$ (i.e.*;* sample sizes for the CG and IG);
- *"*$Z_{\alpha/2}$*"* is the normal deviate at a 5% level of significance (= 1.96);
- "$Z_{1-\beta}$*"* is the normal deviate at 90% statistical power with 10% type II error (= 1.28);
- *"r"* (equal to n_1/n_2*)* is the ratio of the sample size required for the two groups (here, r = 0.5 gives a sample size distribution of 0.5:1 for the CG and IG);
- "δ*"* and "*d"* are the pooled standard deviation (SD) and the difference of the main outcome (i.e. change in the 6MWD after CPRP).

Given the pioneering nature of this study at the time it was conducted, values of "δ" and "*d"* were obtained from a previous RCT [46] evaluating the feasibility and effectiveness of a CPRP through telerehabilitation tools in COVID-19 patients with mild to moderate symptomatology in the acute stage (18 in the IG and 18 in the CG). The 6MWD mean ± SD changes were 80 ± 126 and 0.05 ± 26 m, in the IG and CG, respectively [46]. Insertion of the aforementioned data into the formula resulted in a total sample of 28 patients (19 in the IG and 9 in the CG). Assuming a 20% absence during the CPRP or the post-CPRP evaluation session, the revised sample size was calculated to be 35 patients [35 = 28/(1–0.20)].

COVID-2019 diagnosis and extent evaluation

The diagnosis of COVID-19 was confirmed by the presence of a real-time reverse-transcription polymerase chain reaction (RT-PCR). Before commencing the CPRP, a chest scan was performed for all patients to determine the extent of parenchymal lung injury. The evaluation categorized patients into five groups based on the extent of lung involvement: absent or minimal (< 10%), moderate (10–25%), extensive (25–50%), severe (50–75%), and critical (> 75%) [47].

Phases of the study and applied protocol

Figure 2 summarizes the four phases of the study.

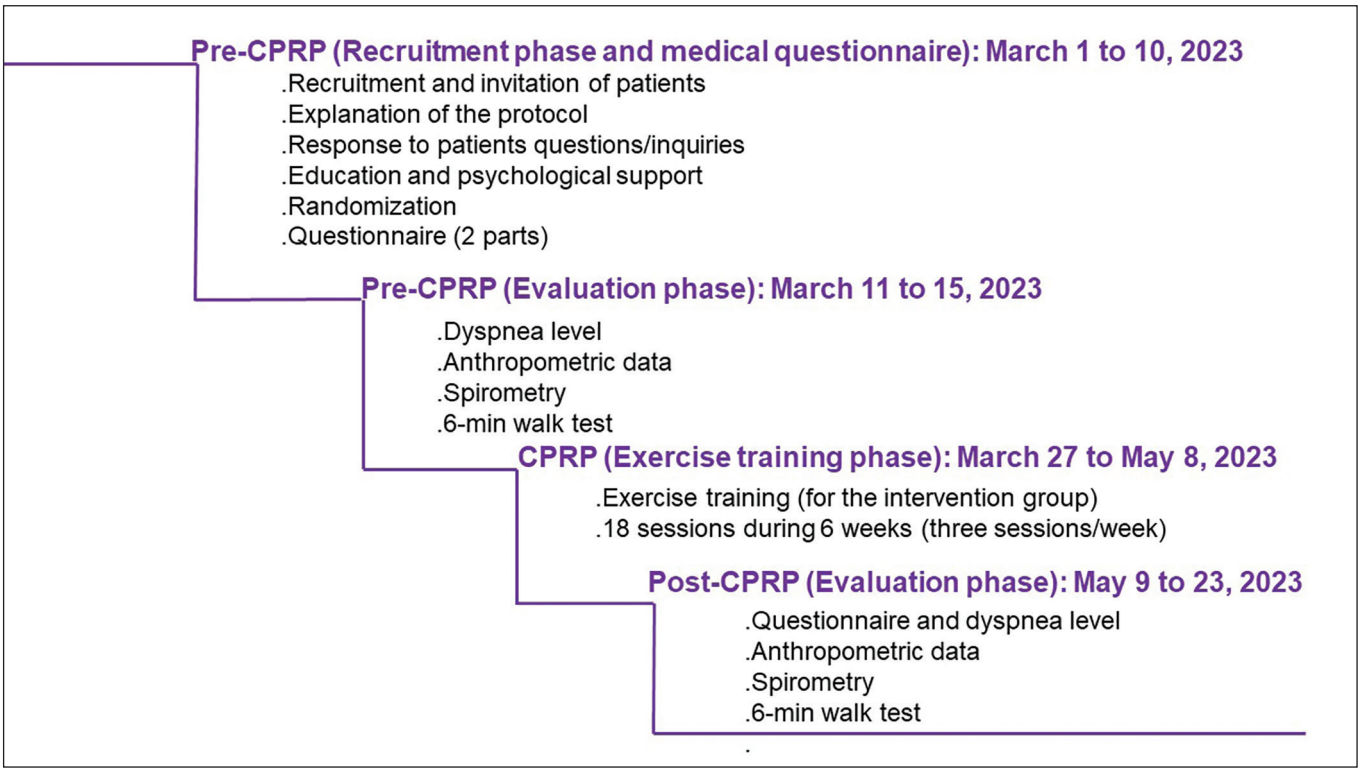


FIG. 2. Description of the 4 phases of the cardiopulmonary rehabilitation programme (CPRP).

First phase (10 days): Recruitment phase and medical questionnaire

This initial phase focused on recruiting LC19Ps during their consultations in the outpatient department of pulmonology. During the recruitment process (i.e. meeting), the investigators (RK and AK in the authors' list) explained the protocol's content, progression, and tasks to be carried out during different phases to the patients. They addressed patient questions regarding the project's aims, methods of data collection and usage, as well as participation modalities. The meeting also served to assess the patient's general aptitude, offer advice on managing comorbidities such as diabetes mellitus and arterial hypertension, and introduce psychological support (e.g. handling emotional distress, post-traumatic stress disorder, and strategies for coping with COVID-19) [48], along with nutritional counselling [49]. Following this, patients signed the consent form, and randomization was conducted. At the phase's conclusion, an interviewer (EZ in the authors' list), unaware of the patient's group allocation, completed a questionnaire for each patient. The questionnaire, with an average duration of approximately 30–40 minutes, was administered by the same interviewer before and after CPRP. In Tunisian dialect, the questionnaire comprised two parts. The first part, a general questionnaire, covered demographic (e.g. age, sex, socioeconomic level, smoking status), clinical (e.g. lifestyle habits, medical history), and COVID-19-related information (e.g. date of RT-PCR, hospitalization details, length of hospitalization, symptom duration, treatment such as corticosteroid or oxygen therapies, imaging, and extent of lesions). Low socioeconomic level was defined as unskilled worker, jobless, and high socioeconomic level as skilled worker, farmer and manager. History of cigarette smoking was evaluated in pack-years, and patients were classified into non-smoker, passive smoker, and ex-smoker. Narghile smoking was also assessed. The second part of the questionnaire was reserved to explore patients' health-related quality of life and psychological data. The data of this part will be examined in the second phase of the project.

Second phase (2 weeks): Pre-CPRP evaluations

During this phase, the interviewers (HR and EZ in the authors' list) received the LC19Ps in groups of four or five per day, and the following four evaluations/tests were performed on the same day in the morning, and in the following order: dyspnoea, anthropometric data, spirometry test, and 6MWT.

Dyspnoea was assessed before and after CPRP using two scales: mMRC [42] and Borg [50] scales. Questions were presented in Arabic language. The mMRC scale, a self-rating scale, measures the disability caused by breathlessness in daily activities, ranging from level 0 to level 4 [42] (details in the Appendix). The Borg scale was used to rate dyspnoea from 6 (i.e. no exertion at all) to 20 (i.e. maximal exertion) and to monitor patients' post-CPRP progress [50]. For the pre-CPRP evaluation phase, patients were asked to evaluate their mMRC dyspnoea level before and during the COVID-19, and whether their dyspnoea was subjectively worsened.

BOX 1. Description of the 5 types of exercises performed during the strength-training phase of the cardiopulmonary rehabilitation program (CPRP).

N	Type of exercise	Description
1.	**Leg extension exercise**	• The patient, while sitting on a chair, performed knee extension, and maintained the extension for 5 seconds and returned gradually to the resting position for each repetition. • During the first 2 weeks, the 2nd and 3rd weeks, and the 5th and 6th weeks of the CPRP, 1 series of 10 repetitions, 2-series of 10 repetitions, and 3-series of 10 repetitions for each side were performed, respectively.
2.	**Heel raises exercise**	• The patient, while standing up, performed gradual maximal plantar flexion, maintained the contraction for 5 seconds and gradually returned to the resting position. • During the 1st 2-weeks, 3rd week, and 5th and 6th weeks of the CPRP, 1 series of 10 repetitions, 2-series of 10 repetitions and 2-series of 10 repetitions for each side were performed, respectively.
3.	**Sit-stand-sit exercise**	• The patient started from the seated position and performed controlled stand-ups and returned to the seated position as slowly and as controlled as possible. • During the 1st two weeks, the 2nd and 3rd weeks, and the 5th and 6th weeks of the CPRP, 1 series of 10 repetitions, 2-series of 10 repetitions, and 3-series of 10 repetitions for each side were performed, respectively.
4.	**Overhead press exercise**	• The patient performed three-series of 10 repetitions of the movement for each side. • Progression in load was obtained through a gradual increase in dumbbell weight.
5.	**Biceps curls exercise**	• The patient performed 10 repetitions of alternated elbow flexions while carrying a dumbbell in each hand for three series. • Progression in load was obtained through a gradual increase in dumbbell weight.

Anthropometric data (e.g. age (year), height (cm), weight (kg), and body mass index (BMI, kg/m^2) were determined. Corpulence status (i.e. underweight (BMI < 18.5 kg/m^2), normal weight (BMI: 18.5–24.9 kg/m^2), overweight (BMI: 25.0–29.9 kg/m^2), and obesity (BMI ≥ 30.0 kg/m^2)) was noted [51].

The spirometry test was conducted by an experienced technician using a portable spirometer (MIR, Spirodoc, Italy) following international guidelines [44]. The collected spirometric data (i.e. FVC (L), FEV_1 (L), FEV_1/FVC ratio (absolute value)) were expressed as absolute values, percentages of predicted values, and as z-scores [52].

The 6MWT was conducted outdoors in the morning by one physician (*EZ* in the authors' list), following international guidelines [22, 39]. The test took place along a flat, straight corridor with a hard surface, rarely travelled by others (40 meters long, marked every meter with cones to specify turnaround points). Patients were instructed to walk as far as possible for 6 minutes, with the option to rest if necessary. Throughout the 6MWT, various parameters were determined at rest ($_{Rest}$) and at the end ($_{End}$) of the walk, including HR (bpm), oxy-haemoglobin saturation (SpO_2, %), 6MWD (m, % of predicted value), and the number of stops. Blood pressure was measured only at rest to verify the absence of 6MWT contraindication [22, 39, 43]. For some 6MWT parameters, delta exercise changes ($\Delta_{Exercise}$ = $6MWT_{End}$ value minus $6MWT_{Rest}$ value) were calculated (e.g. Δ_{SpO2}, Δ_{HR}). The instructions given to the patients during the test were in accordance with international guidelines [22, 39]. HR was expressed as absolute value and as a percentage of the predicted maximal HR (PMHR) (PMHR (bpm) = 208 – (0.7 × age)) [53]. HR and SpO_2 were measured using a finger pulse oximeter (Beurer PO 40, Shanghai, China). The HR_{End} (bpm) was considered as an HR target for lower limb exercise training [54]. The predicted 6MWD and its lower limit of normal (LLN) were calculated based on North African norms for adults aged 18–40 years [55] and more than 40 years [56]. An abnormal 6MWD was identified when the 6MWD was lower than the LLN [55, 56]. The 6-min walk work (6MWW) (i.e. the product of 6MWD and weight [57]), reflecting the work of walking, was calculated. Clinically significant desaturation was defined as Δ_{SpO2} greater than five points [58].

Third phase (6 weeks): Exercise training

The constituents of the CPRP were 'derived' from preceding national and international recommendations for COVID-19 patients [8, 49, 59–66].

Patients performed exercise training or sedentary activities (depending on randomized allocation to the study groups), and could not be combined with other physical therapy or sports physical activity. The exercise-training phase, exclusive to the IG, was

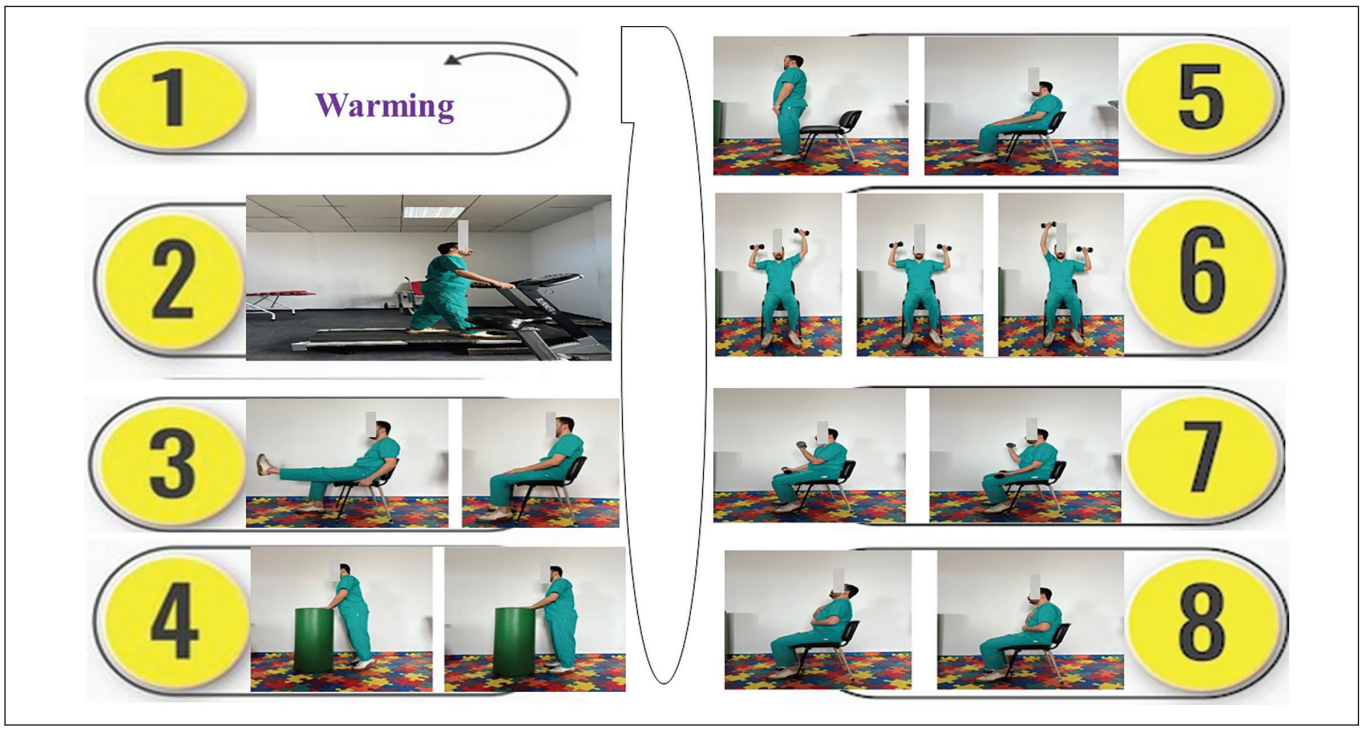


FIG. 3. Description of an exercise training session.
1: Warming (5 minutes); 2: Treadmill walking exercise; 3: Knee extension exercise; 4: Heel raises exercise; 5: Sit-stand-sit exercise; 6: Overhead press exercise; 7: Biceps curls exercise; 8: Controlled breathing exercise.

conducted in the morning in two groups of 10–12 patients. This phase comprised 18 sessions (i.e. three sessions/week for six weeks), with each session lasting 60–90 minutes [59]. Patients of the CG were asked to maintain their usual level of sedentary physical activities [26].

A typical exercise-training session included four parts (Figure 3): *i)* Warming-up for five minutes; *ii)* Aerobic training for 10–35 minutes; *iii)* Resistance training for 15–20 minutes; and *iv)* Respiratory exercises for 15 minutes. During the warm-up phase, light exercises were performed such as walking slowly, mobilization of cervical, lumbar spine, and peripheral joints. In the aerobic-training phase, patients engaged in treadmill walking exercise for a gradually increased duration (e.g. starting with 10 minutes in the first week and increasing by five minutes each week, reaching a total of 35 minutes in the sixth week). Patients were instructed to interrupt the walk if they experienced shortness of breath or dizziness. The walking intensity was personalized using a HR monitor, and the HR target was the $HR_{End} \pm 5$ bpm determined at the end of the 6MWT [37]. On days without aerobic training, patients were advised to perform outdoor walking exercise for the same duration. The strength-training phase involved five types of exercises (Box 1). During the respiratory exercises phase, patients performed controlled breathing and chest expansion exercises. In the sitting position, the patient put one hand on the chest and the other on the abdomen, and performed slow and ample inspiration followed by controlled and maximal expiration.

Throughout each exercise-training part, therapeutic education was provided to enhance patients' adherence to lifestyle counselling provided during the first phase of the CPRP. This included guidance on managing comorbidities (when applicable), psychological support, and nutritional counselling [49].

Fourth phase (2 weeks): Post-CPRP evaluations

In this phase, both groups underwent similar evaluations/tests to those conducted in the second phase. The results of the CPRP were communicated, and explained to the patients.

Data presentation and statistical analyses

Expression mode of data

Quantitative and categorical data were presented as mean ± SD (95% confidence interval) and number (%), respectively. For each set of quantitative data (i.e. dyspnoea (mMRC and Borg scales), weight, BMI, spirometric data, 6MWD, 6MWW, HR, SpO_2, and $\Delta_{Exercise}$), changes induced by the CPRP were calculated (Δ_{CPRP} = pre- minus post-CPRP).

Session effect: Pre- vs. post-CPRP

The Wilcoxon test and the two-sided chi-squared test were used to compare the quantitative and categorical data of the same group determined before and after CPRP, respectively.

Group effect: IG vs. CG

The Student's t-test and the two-sided chi-squared test were used to compare the quantitative and categorical data of the two groups before and after CPRP, respectively.

Group and session effect: Group (IG or CG) vs. session (pre- or post-CPRP)

Analysis of variance (ANOVA) was used to examine the intervention differences (i.e. groups vs. sessions) and to analyse the differences between and within the sessions study and groups. The partial eta-squared effect size was calculated, and Hedge's values were used for effect size measurement [67]. An effect size of ≤ 0.2 was described as a small effect, around 0.5 as a medium effect, around 0.8 as a large effect, and more than 1.30 as very large effect [67].

Clinical significant approach

The CPRP was considered 'efficient' if the mean Δ_{CPRP} for 6MWD exceeded the recommended MCID of 30 m for 6MWD [39]. A decrease of more than one point in the mean Δ_{CPRP} for mMRC dyspnoea signified a perceived clinical improvement [40, 41].

All statistical procedures were performed using statistical software (StatSoft, Inc. (2011). STATISTICA, version 12). The significance level was set at $p < 0.05$.

RESULTS

Among the 45 LC19Ps recruited, 36 agreed to participate in the study (Figure 1). However, only 30 (20 in the IG, 10 in the CG) completed the protocol.

Patients' characteristics

The two groups were matched for sex, anthropometric data, comorbidities, and dyspnoea levels before and during COVID-19, COVID-19 data, and computed tomography scan data (Table 1). The only difference was in the consumption of cigarettes (in pack-years): the CG had a higher consumption compared to the IG (Table 1).

Effect on weight, BMI, and corpulence status

ANOVA revealed that the CPRP did not influence weight or BMI. In the IG, the percentage of patients with overweight decreased significantly from 55% to 25% (Table 2).

Effect on dyspnoea

ANOVA revealed that the CPRP impacted dyspnoea evaluated via the Borg and mMRC scales (Table 2). Compared to the CG, the IG had larger decreases in Δ_{CPRP} for Borg and mMRC scales (-1.3 ± 1.5 vs. -3.5 ± 2.0; and -0.1 ± 0.3 vs. -1.5 ± 0.8; respectively). In the IG, the 1.5-point decrease in mMRC exceeded the recommended MCID of 1 point. The percentage of patients with dyspnoea mMRC level 3 in the IG decreased significantly from 75% to 5%.

TABLE 1. Characteristics of the 2 groups: Intervention group (IG, n = 20) and control group (CG, n = 10).

Data	Unit/Category	IG (n = 20)	CG (n = 10)	p-value
Sex and initial anthropometric data				
Sex	Male	10 (50)	4 (40)	0.604
Age	Year	53 ± 14	52 ± 14	0.922
Height	cm	167 ± 10	167 ± 6	0.919
Weight	kg	79 ± 15	85 ± 26	0.438
Body mass index	kg/m^2	28.5 ± 4.8	30.2 ± 7.6	0.477
Corpulence status	Underweight	1 (5)	0 (0)	0.472
	Normal weight	2 (10)	2 (20)	0.447
	Overweight	11 (55)	4 (40)	0.439
	Obesity	6 (30)	4 (40)	0.583
Smoking data and socioeconomic data				
Smoking cigarette status	Non-smoker	9 (45)	4 (40)	0.794
	Passive smoker	3 (15)	2 (20)	0.729
	Ex-smoker	8 (40)	4 (40)	-
	Pack-year	22 ± 8	34 ± 5	0.027*
Smoking narghile status	Ex-smoker	4 (20)	1 (10)	0.488
Socioeconomic level	Low	13 (65)	7 (70)	0.784
Comorbidities				
Diabetes mellitus	Yes	5 (25)	1 (10)	0.760
Arterial hypertension	Yes	4 (20)	2 (20)	-
Dyslipidemia	Yes	2 (10)	2 (20)	0.447
Dysthyroid	Yes	2 (10)	1 (10)	-
Dyspnea (mMRC) **level before and during the COVID-19**				
Before COVID-19	Yes	2 (10)	2 (20)	0.447
	Level-1	18 (90)	8 (80)	0.447
	Level-2	2 (10)	2 (20)	0.447
During COVID-19	Yes	20 (100)	10 (100)	-
	Level-2	3 (15)	2 (20)	0.729
	Level-3	15 (75)	8 (80)	0.760
	Level-4	2 (10)	0 (0)	0.301
Worsening of dyspnea	Yes	20 (100)	10 (100)	-
COVID-19 data				
Hospitalization	Yes	11 (55)	5 (50)	0.796
	IUC	5 (25)	1 (10)	0.333
Length of hospitalization	Days	14 ± 9	20 ± 7	0.206
Duration of symptoms	Days	25 ± 24	21 ± 8	0.635
Corticosteroid therapy	Yes	15 (75)	8 (80)	0.760
Oxygen therapy	Yes	14 (70)	6 (60)	0.583
Computed tomography (CT) scan data				
CT	Yes	11 (55)	8 (80)	0.180
Extent of lesions	0–10%	1 (5)	1 (10)	0.605
	10–25%	1 (5)	2 (20)	0.197
	25–50%	5 (25)	5 (50)	0.171
	50–75%	4 (20)	0 (0)	0.129

COVID-19: Coronavirus disease 2019. **mMRC**: Modified medical research council.
Quantitative and categorical data were mean ± standard deviation and number (%), respectively.
*p-value < 0.05 (Student T-test or two-sided chi-2 test): IG vs. CG.

TABLE 2. Impact of the cardiopulmonary rehabilitation program (CPRP) on weight, body mass index (BMI), and dyspnea of the 2 groups: Intervention group (IG, n = 20) and control group (CG, n = 10).

Data	Unit/category	IG (n = 20)			CG (n = 10)			Comparison between 2 groups: p-value			ANOVA: Group vs. Session	
		Pre	Post	Δ	Pre	Post	Δ	Pre- vs. Pre-	Post- vs. Post-	Δ vs. Δ	p-value	Partial eta-squared (effect size)
Weight	kg	79 ± 15	81 ± 16	2 ± 13	85 ± 26	85 ± 25	-1 ± 4	0.438	0.623	0.618	0.843	0.001
BMI	kg/m^2	28.5 ± 4.8	29.2 ± 6.1	0.7 ± 4.4	30.2 ± 7.6	30.0 ± 7.5	-0.2 ± 1.4	0.477	0.756	0.562	0.805	0.001
Corpulence status	Underweight	1 (5)	0 (0)	-1	0 (0)	0 (0)	0	0.472	-	-	-	-
	Normal weight	2 (10)	5 (25)	+3	2 (20)	3 (30)	-1	0.447	0.773	-	-	-
	Overweight	11 (55)	5 (25)	-6$^{\mu}$	4 (40)	3 (30)	-1	0.439	0.773	-	-	-
	Obesity	6 (30)	10 (50)	+4	4 (40)	4 (40)	0	0.583	0.605	-	-	-
Dyspnea (rest)	Borg scale	5.2 ± 2.0	1.8 ± 0.9	-3.5 ± 2.0*	5.1 ± 2.0	3.8 ± 1.0	-1.3 ± 1.5	0.896	0.001	0.005	0.010	0.105
	mMRC total	3.0 ± 0.5	1.5 ± 0.6	-1.5 ± 0.8*	2.7 ± 0.5	2.6 ± 0.7	-0.1 ± 0.3	0.208	0.001	0.001	0.007	0.248
mMRC dyspnea	Level-1	0 (0)	11 (55)	+11$^{\mu}$	0 (0)	1 (10)	+1	-	0.018	-	-	-
	Level-2	3 (15)	8 (40)	+5$^{\mu}$	3 (30)	2 (20)	-1	0.333	0.273	-	-	-
	Level-3	15 (75)	1 (5)	-14$^{\mu}$	7 (70)	7 (70)	0	0.770	0.001	-	-	-
	Level-4	2 (10)	0 (0)	-2	0 (0)	0 (0)	0	0.301	-	-	-	-

BMI: Body mass index. **mMRC**: Modified medical research council. **Post**: After CPRP. **Pre**: Before CPRP. **Δ**: Post minus Pre. Quantitative and categorical data were mean ± standard deviation, and number (%) respectively.
Session effect: Pre vs. Post; *p-value < 0.05 (Wilcoxon test): Quantitative data; $^{\mu}$p-value < 0.05 (One-sided chi-2 test): Corpulence status; **Group effect:** IG vs. CG; $^{\#}$p-value < 0.05 (Student test): Pre vs. Pre or Post vs. Post or Δ vs. Δ; $^{\theta}$p-value < 0.05 (Two-sided chi-2 test): Pre vs. Pre or Post vs. Post; **Session and group effect** $^{\Psi}$p-value < 0.05 (Analysis of variance: ANOVA)

Effect on spirometric data

ANOVA revealed that the CPRP had no impact on spirometric data. In the IG, from pre- to post- CPRP, FEV_1 and FVC increased by 200 ml (7%) and 180 ml (5%), respectively (Table 3).

Effect on submaximal exercise data

No patient stopped during the 6MWT, and no side effects were noted.

ANOVA revealed that the CPRP impacted the 6MWD (m, %) and the HR_{rest} (bmp, %), but did not impact the 6MWW and SpO_2 (Table 4). First, compared to the CG, the IG had a higher Δ_{CPRP} for 6MWD (m, %) (5 ± 45 vs.168 ± 99; and 1 ± 8 vs. 28 ± 8; respectively), with small effect sizes. In the IG, the 168 m Δ_{CPRP} for 6MWD greatly exceeded the recommended MCID of 30 m. Second, compared to the CG, the IG had a higher Δ_{CPRP} for HR_{rest} (bpm, %) (1 ± 7 vs. -9 ± 9; and 0 ± 4 vs. -5 ± 6; respectively). In the IG, the percentages of patients with abnormal 6MWD or desaturation during the 6MWT decreased from 100% to 75%, and from 30% to 10%, respectively.

DISCUSSION

Our Tunisian RCT, investigating the effects of a CPRP on submaximal aerobic capacity, dyspnoea and spirometric data in LC19Ps, revealed that compared to the CG, the IG demonstrated statistically significantly higher changes in *i)* 6MWD (m, %) (5 ± 45 vs. 168 ± 99; 1 ± 8 vs. 28 ± 8; respectively) and HR_{rest} (bpm, %) (1 ± 7 vs. -9 ± 9; 0 ± 4 vs. -5 ± 6; respectively), with small effect sizes. The IG's 168 m Δ_{CPRP} for 6MWD significantly exceeded the recommended MCID of 30 m; and *ii)* Borg and mMRC scales (-1.3 ± 1.5 vs. -3.5 ± 2.0; and -0.1 ± 0.3 vs. -1.5 ± 0.8, respectively). The IG's 1.5-point decrease in mMRC significantly exceeded the recommended MCID of 1 point. The two groups exhibited comparable changes in spirometric data.

Our results contribute valuable insights to the growing body of literature on the efficacy of CPRPs for LC19Ps, emphasizing improvements in aerobic capacity and dyspnoea. To the best of the authors' knowledge, up until December 30, 2023, only 11 RCTs had assessed the effects of a CPRP on the submaximal aerobic capacity of LC19Ps [26–36]. Tables 1S to 6S in the Appendix

provide insights into the methodological characteristics (Table 1S), recruitment methods, inclusion, non-inclusion and exclusion criteria (Table 2S), patient characteristics (Table 3S), 6MWT methodological aspects (Table 4S), CPRP details (Table 5S), and the effects of CPRPs on 6MWT (Table 6S) across these studies. This RCT stands out as the second North-African study in this domain, with the first being conducted in Egypt [29].

Rationale for choosing the 6MWD data as the main outcome

The assessment of exercise tolerance is traditionally conducted by measuring maximum oxygen consumption in a cardiorespiratory test [68]. However, this approach necessitates sophisticated and expensive equipment, along with personnel possessing advanced skills for its operation [68]. Consequently, the repeated use of such tests poses a substantial financial burden and is not practically feasible on a large scale [68]. Recognizing these challenges, simpler assessments such as the 6MWT have gained popularity [22, 39, 43]. The latter entails measuring the distance an individual can walk on a flat surface within a span of 6 minutes [22, 39, 43]. The 6MWT comes with various benefits, presented in detail in the Appendix. Its simplicity, ease of administration, and minimal resource requirements make it a practical choice for assessing exercise tolerance in various settings and populations [22, 39, 43]. In comparison to complex cardiorespiratory tests, the 6MWT strikes a balance between providing meaningful insights into functional exercise capacity and addressing the logistical constraints associated with assessments that are more sophisticated.

Effect on 6MWD

In our RCT, both statistical and clinical significance of the increase in the 6MWD were observed. Compared to the CG, the IG demonstrated a higher Δ_{CPRP} for 6MWD (m, %) (5 ± 45 vs. 168 ± 99; 1 ± 8 vs. 28 ± 8, respectively), albeit with small effect sizes.

Regarding the 6MWD expressed in absolute value (i.e., m), our results are consistent with findings from related two RCTs [29, 30]. A significant group-session effect (i.e. comparison of Δ_{CPRP}) was reported [29, 30], indicating a higher ΔCPRP for 6MWD in the IG compared to the CG (57 ± 48 vs. 17 ± 10 [29], 54 vs. 5 [30], respectively) (Table 6S). Among the remaining nine related RCTs (Table 6S), three failed to report the group-session effect [26–28], and six reported no group-session effect [31–36]. In contrast to our RCT, where the effect size for 6MWD was small, one RCT [30] reported a large effect size. Between two RCTs [34, 35] that reported no group-session effect, the effect sizes for 6MWD were small.

Regarding the 6MWD expressed as a percentage of predicted values (i.e. %), the only RCT that chose this expression mode [28] failed to report the group-session effect (Table 6S). However, in contrast to our findings (Table 4), this particular RCT [28] reported no group – or session – effects, as the 6MWD values measured before and after CPRP in both the CG and the IG were comparable (92 ± 14 vs. 96 ± 16%, and 86 ± 17 vs. 89 ± 13%, respectively (Table 6S)). In practice, it is crucial to interpret the 6MWD by comparing it to normal values [22, 39, 43]. The latter are essential to guide the diagnostic and prognostic use of the 6MWT [22, 43]. The success in medical decision-making depends as much on selecting and properly using norms and their limits [22, 43].

In our RCT, the Δ_{CPRP} for 6MWD in the IG and CG were 168 m (i.e. > 30 m MCID [39]) and 5 m (i.e. < 30 m MCID [39]), respectively (Table 4). First, two relevant RCTs [27, 32] adopted the MCID approach for 6MWD, setting it at 50 m (Table 4S). Consistent with our RCT, these two RCTs reported statistically significant effects, as the 6MWD in the IGs were 85 [27] and 95 [32] m (Table 6S). However, in one RCT [27], the 6MWD change in the CG was below the 50 m MCID (i.e. 15 m), while in the other RCT [32], it significantly exceeded the 50-m MCID (i.e., 72 m) (Table 6S). Second, the 6MWD change observed in the IG of the remaining RCTs surpassed the recommended MCID of 30 m [39] (63 [33], 57 [29, 34, 35], 54 [30] m) (Table 6S). Third, the 6MWD change observed in the CG of the remaining RCTs either exceeded the recommended MCID of 30 m [39] in three RCTs [57 [33], 39 [34, 35] m], or fell below the recommended MCID of 30 m [39] in two RCTs [5 [30], 17 [29] m)] (Table 6S). The considerable variation in 6MWD changes observed in our RCT and the 11 other RCTs highlights the necessity of establishing the 6MWD MCID in LC19Ps [25]. The aforementioned findings from our RCT and the 11 other RCTs (Table 6S) align with those reported by previous SRs [25, 69–74], confirming the effectiveness of CPRPs in improving various health outcomes, including physical health, in LC19Ps. The results of the aforementioned seven SRs [25, 69–74] are extensively detailed in the Appendix.

The percentage of patients exhibiting an abnormal 6MWD remained steady at 80% in the CG, while it decreased from 100% (pre-CPRP) to 75% (post-CPRP) in the IG (Table 4). First, no prior related RCT has compared the percentage of LC19Ps or cases with abnormal 6MWD before and after CPRP. Second, our results contrast with those reported in a German study [15], where 79% of mild/moderate COVID-19 patients exhibited an abnormal 6MWD after three weeks of inpatient CPRP. Third, a previous observational study indicated that the percentages of LC19Ps with abnormal 6MWD decreased from 21% to 0% [37].

The two groups in our RCT showed comparable changes in 6MWW, but in the IG, the 6MWW change increased by 14,153 mkg (Table 4). First, no previous related RCT has assessed the 6MWW, which may offer a more comprehensive estimation of the work required to perform the test compared to 6MWD alone [37]. Second, in agreement with our findings, a prior observational study indicated that the 6MWW change in LC19Ps increased by 2448 mkg [37]. Since weight directly influences the energy needed for completing the 6MWT [22, 39], future related RCTs should consider calculating and reporting the 6MWW, as it can provide valuable insights into patients' functional capacity [25].

TABLE 3. Impact of the cardiopulmonary rehabilitation program (CPRP) on spirometric data of the 2 groups: Intervention group (IG, n = 20) and control group (CG, n = 10).

Data	Unit/category	IG (n = 20)			CG (n = 10)			Comparison between 2 groups: p-value			ANOVA: Group vs. Session	
		Pre	Post	Δ	Pre	Post	Δ	Pre- vs. Pre-	Post- vs. Post-	Δ vs. Δ	p-value	Partial eta-squared (effect size)
FEV_1	l	2.56 ± 0.96	2.76 ± 1.01	0.20 ± 0.32*	2.33 ± 0.72	2.34 ± 0.67	0.01 ± 0.13	0.521	0.244	0.075	0.690	0.002
	% predicted	82 ± 24	89 ± 25	7 ± 12*	78 ± 25	78 ± 25	1 ± 4	0.626	0.272	0.119	0.651	0.003
	z-score	-1.23 ± 1.63	-0.77 ± 1.72	0.46 ± 0.74*	-1.56 ± 1.57	-1.52 ± 1.59	0.04 ± 0.28	0.597	0.258	0.099	0.644	0.003
FVC	l	3.13 ± 1.12	3.31 ± 1.08	0.18 ± 0.37*	2.96 ± 0.70	2.98 ± .0.74	0.01 ± 0.14	0.674	0.398	0.192	0.768	0.001
	% predicted	80 ± 21	85 ± 21	5 ± 11	79 ± 21	79 ± 23	1 ± 4	0.873	0.494	0.223	0.703	0.002
	z-score	-1.48 ± 1.55	-1.13 ± 1.50	0.35 ± 0.75	-1.60 ± 1.54	-1.54 ± 1.65	0.05 ± 0.30	0.846	0.492	0.236	0.725	0.002
FEV_1/FVC	Absolute value	0.82 ± 0.10	0.83 ± 0.07	0.01 ± 0.08	0.77 ± 0.13	0.78 ± 0.10	0.00 ± 0.07	0.305	0.117	0.847	0.915	0.001
	% predicted	102 ± 12	104 ± 9	1 ± 10	97 ± 17	97 ± 13	1 ± 8	0.297	0.124	0.867	0.925	0.001
	z-score	0.37 ± 1.45	0.51 ± 1.10	0.14 ± 1.2	-0.25 ± 1.60	-0.27 ± 1.42	-0.02 ± 0.90	0.297	0.112	0.726	0.837	0.001

FEV_1: Forced expiratory volume in one second. **FVC**: Forced vital capacity. **Post**: After CPRP. **Pre**: Before CPRP. Δ: Post minus Pre. Data were mean ± standard deviation.
Session effect: Pre vs. Post; *p-value < 0.05 (Wilcoxon test): Quantitative data. **Group effect:** IG vs. CG; #p-value < 0.05 (Student test): Pre vs. Pre or Post vs. Post or Δ vs. Δ. **Session and group effect:** Ψp-value < 0.05 (Analysis of variance: ANOVA)

Effect on dyspnoea

In comparison to the CG, the IG demonstrated higher changes in Borg and mMRC scales (-1.3 ± 1.5 vs. -3.5 ± 2.0; and -0.1 ± 0.3 vs. -1.5 ± 0.8, respectively). In related RCTs (Table 4S), conflicting dyspnoea values were reported in eight studies [27, 29–35]. On one hand, four related RCTs reported effects of CPRP on mMRC [29–31, 33], while two others [27, 32] reported no effects. For instance, in one RCT [29], the mean mMRC between-group differences decreased by 49%, from a score of 2.63 ± 0.60 to 1.38 ± 0.49. On the other hand, while one RCT reported significant effects of CPRP on the Borg scale [31], two others [34, 35] reported no effects. Some previous SRs [24, 69, 70, 72, 73], described in detail in the Appendix, reported conflicting findings related to the effects of CPRP on dyspnoea. Previous studies have indicated that CPRP improves perceived $dyspnoea_{Rest}$, regardless of the mode of evaluation (e.g. mMRC [15, 18], chronic obstructive pulmonary disease assessment test [16]), even in severe/critical COVID19 patients [15].

In our IG, the percentage of patients experiencing dyspnoea at mMRC level 3 decreased significantly from 75% to 5%, and the 1.5-point decrease in mMRC exceeded the recommended MCID of 1 point [40, 41]. This aligns with the findings of one observational study [37], where mMRC improvement surpassed than the 1-point MCID [40].

Dyspnoea is a crucial determinant of the 6MWD in patients with chronic respiratory disease, reflecting both the physiology of exercise limitation and the impact of exercise limitation on daily life [22, 39]. However, comparing dyspnoea data between studies with different assessment scales (Table 4S) is challenging due to the lack of standardization and potential scale-related variations in measurement [25]. The observed reduction in dyspnoea perception during CPRP might be attributed to physiological adaption to exercise training [75]. The reduction of dyspnoea, one of the most common symptoms among individuals with chronic respiratory disease, is an important target of CPRPs [76]. In LC19Ps, the improvement in perceived dyspnoea is crucial, as dyspnoea is significantly linked with a higher mortality [77], and serves as a predictive factor of reduced functional capacity [78].

Effect on HR

Regarding HR expressed in bpm, our RCT revealed that: *i)* compared to the CG, the IG had a larger change in HR_{rest} (1 ± 7 vs. -9 ± 9; respectively), with a small effect size; *ii)* compared to before CPRP, after CPRP both HR_{Rest} and HR_{End} of the IG decreased by 9 ± 9 and 10 ± 13, respectively; and *iii)* compared to before CPRP, after CPRP HR_{Rest} in the CG remained unchanged, but HR_{End} decreased by 10 ± 8 (Table 4). Concerning HR expressed as a percentage of PMHR, our RCT identified that: *i)* compared to the CG, the IG had

TABLE 4. Impact of the cardiopulmonary rehabilitation program (CPRP) on submaximal exercise data of the 2 groups: Intervention group (IG, n = 20) and control group (CG, n = 10).

Data	Unit/category	IG (n = 20)			CG (n = 10)			Comparison between 2 groups: p-value			ANOVA: Group vs. Session	
		Pre	Post	Δ	Pre	Post	Δ	Pre- vs. Pre-	Post- vs. Post-	Δ vs. Δ	p-value	Partial eta-squared (effect size)
6MWD	m	349 ± 137	517 ± 115	168 ± 99*	414 ± 106	419 ± 78	5 ± 45	0.194	0.023	0.001	0.013	0.104
	% predicted	53 ± 16	81 ± 14	28 ± 8*	67 ± 18	68 ± 14	1 ± 8	0.044	0.017	0.001	0.002	0.157
	< LLN	20 (100)	13 (75)	-7μ	8 (80)	8 (80)	0	0.038	0.760	-	-	-
6MWW	mkg	27383 ± 11455	41536 ± 10859	14153 ± 11096*	37226 ± 22018	36847 ± 18757	-379 ± 4577	0.116	0.391	0.001	0.078	0.054
HR (bpm)	Rest	84 ± 9	75 ± 4	-9 ± 9*	81 ± 7	82 ± 6	1 ± 7	0.367	0.001	0.007	0.014	0.102
	End	106 ± 10	96 ± 6	-10 ± 13*	105 ± 11	95 ± 7	-10 ± 8*	0.782	0.729	0.965	0.966	0.001
	Δ_{Walk}	21 ± 12	21 ± 8	-0 ± 15	23 ± 11	13 ± 9	-10 ± 10*	0.653	0.034	0.076	0.091	0.050
HR (%)	Rest	49 ± 6	44 ± 3	-5 ± 6*	48 ± 5	48 ± 5	0 ± 4	0.425	0.012	0.007	0.041	0.072
	End	62 ± 7	56 ± 6	-6 ± 8*	61 ± 8	56 ± 5	-6 ± 4*	0.781	0.738	0.983	0.987	0.001
	Δ_{Walk}	12 ± 7	12 ± 5	0 ± 9	14 ± 6	8 ± 5	-6 ± 6	0.662	0.032	0.069	0.087	0.051
SpO_2 (%)	Rest	96 ± 2	98 ± 1	2 ± 2*	97 ± 1	96 ± 1	-0 ± 1	0.635	0.005	0.007	0.056	0.063
	End	93 ± 3	96 ± 3	2 ± 3*	94 ± 2	94 ± 2	0 ± 3	0.523	0.141	0.112	0.153	0.036
	Δ_{Walk}	-3 ± 3	-2 ± 2	1 ± 3	-2 ± 2	-2 ± 2	0 ± 3	0.710	0.894	0.694	0.702	0.003
	Desaturation	6 (30)	2 (10)	-4 μ	1 (10)	2 (20)	+1	0.222	0.038	-	-	-

HR: Heart-rate. **LLN**: Lower limit of normal. **End**: End of walk. **Post**: After CPRP. **Pre**: Before CPRP. **Rest**: Before the walk. **SpO_2**: Oxy-hemoglobin saturation. **6MWD**: 6-min walk distance. **6MWW**: 6-min walk work. **Δ**: Post minus Pre. **Δ_{Walk}**: End minus Rest. Quantitative and categorical data were mean ± standard deviation (95% confidence interval) and number (%), respectively. **Session effect:** Pre vs. Post; *p-value < 0.05 (Wilcoxon test): Quantitative data; μp-value < 0.05 (One-sided chi-2 test): 6MWD < LLN or desaturation. **Groups effect: IG vs. CG** #p-value < 0.05 (Student test): Pre vs. Pre or Post vs. Post or Δ vs. Δ; θp-value < 0.05 (Two-sided chi-2 test): Pre vs. Pre or Post vs. Post. **Session and group effect:** Ψp-value < 0.05 (Analysis of variance: ANOVA)

a larger change in HR_{Rest} (0 ± 4 vs. -5 ± 6, respectively), with a small effect size, *ii)* compared to before CPRP, after CPRP both HR_{Rest} and HR_{End} of the IG decreased by 5 ± 6 and 6 ± 8, respectively; and *iii)* compared to before CPRP, after CPRP HR_{Rest} of the CG remained unchanged, but HR_{End} decreased significantly by 6 ± 4 (Table 4). During the CPRP, expressing HR as a percentage of PMHR accommodates individual variations in fitness levels and age, allowing for personalized exercise intensity assessment [37]. Among the related 11 RCTs (Table 4S), HR responses during the 6MWT were measured in three RCTs [26–28], but only one reported HR values in bpm and not as a percentage of PMHR [28]. This particular RCT identified that *i)* HR_{Rest} was comparable in IG and CG both pre- (84 ± 12 vs. 78 ± 14, respectively) and post- (82 ± 10 vs. 78 ± 14, respectively) CPRP; and *ii)* HR_{End} was higher in the IG than the CG both before (118 ± 18 vs. 100 ± 14, respectively) and after (118 ± 19 vs. 106 ± 14, respectively) CPRP [28].

An increased HR_{Rest}, even after adjustment for fitness, serves as an independent risk factor for all-cause mortality [79], and a 10-bpm increase in HR_{Rest} may elevate all-cause mortality by 17% [80]. An observational study [37] reported a post-CPRP decrease in HR_{Rest} by 7 ± 9 bpm (5 ± 5%). The authors suggested that their finding indicates a beneficial effect for endurance-based exercise training as well as combined exercise training [37]. In our RCT, the observed decrease in HR_{Rest} reflects the positive impact of endurance and combined exercises [81], and could be attributed to improvements in physical fitness [82], sleep quality [83] and diet [39]. Monitoring HR during the 6MWT proves valuable, offering insights into exercise performance and cardiovascular responses, and therefore, should be included in 6MWT assessments [22, 39]. HR responses may contribute to the performance of the 6MWT in patients with chronic respiratory disease, and HR patterns (e.g. HR_{Rest}, HR_{End}, maximum HR, increase in HR, and HR recovery at two minutes) can be among the factors explaining a part of the improvement in the 6MWD [22, 39].

Effect on SpO_2

Our CPRP did not influence SpO_2 (Table 4). First, among the 11 RCTs, SpO_2 responses during the 6MWT were measured in three RCTs [26–28], but only one [28] reported SpO_2 values. This particular RCT identified that both groups increased SpO_{2End} after CPRP, while pre-CPRP SpO_2 increased only in the IG [28]. Second, an observational study reported that CPRP had no effect on both SpO_{2Rest} and SpO_{2End} of LC19Ps [37]. The lowest SpO_2 recorded during a 6MWT, which may not align with SpO_{2End}, has emerged as an important marker of disease severity and prognosis [22, 39]. Moreover, oxygen desaturation during a 6MWT provides valuable information regarding exercise-induced desaturation, disease severity, and disease progression [22, 39].

In our IG, the percentage of patients experiencing desaturation during the 6MWT decreased from 30% to 10% (Table 4). Our result is consistent with a previous observational study reporting a decrease in the percentage of LC19Ps with desaturation during the 6MWT from 14% to 0% [37]. Exercise-induced desaturation is associated with impaired daily physical activity, a faster FEV_1 decline, and a worse prognosis, highlighting its clinical importance [22, 39].

Effect on spirometric data

ANOVA revealed that our CPRP had no effect on the spirometric data. In the IG, from before to after CPRP, FEV_1 and FVC increased by 200 ml (7%) and 180 ml (5%), respectively (Table 3). First, the findings of our RCT align with the conclusion of a 2023 SR and meta-analysis aiming to examine the efficacy of CPRP in LC19Ps [84]. The meta-analysis results of the included 10 RCTs reported no significant differences in lung function [84]. For example, the FVC pooled mean difference (MD) showed a non-significant overall effect of CPRP compared to the comparator groups (MD = 0.21). The results show heterogeneity, detecting a significant variability with I2 = 66%, not attributable to chance [84]. Second, the results observed in our IG are comparable to those reported in some studies indicating improvements in FEV_1 [15, 17, 26] and/or FVC [15, 17, 18, 26]. The 200-ml increase in FEV_1 observed in our IG is higher than, equal to, and lower than some values reported in the literature (e.g. 110 ml [37], 200 ml [17], 340 ml [26], respectively). On one hand, since there is a positive correlation between FEV_1 and/or FVC and 6MWD [56], the increases in FEV_1 and FVC could explain a part of the increase in the 6MWD. On the other hand, these increases are useful to improve risk stratification in patients with intermediate coronary heart disease [85]. The improvement in FVC and FEV_1 in the IG could be partly explained by the breathing exercises applied during CPRP [15, 17, 26]. However, some authors reported that there is presumably a spontaneous improvement over time of lung function in LC19Ps, and there is a natural upturn occurring without the influence of CPRP [86].

Effect on weight, BMI, and corpulence status

ANOVA revealed that the CPRP did not impact weight or BMI. In the IG, the percentage of patients with overweight decreased from 55% to 25% (Table 2). Our results contrast with those of one RCT [28], which reported a significant "group vs. session" effect of CPRP on weight. In this particular RCT [28], weight increased by 2.8 ± 0.6 kg in the CG (i.e. pre-CPRP = 89.0 ± 21.7 kg; post-CPRP = 90.5 ± 22.0 kg), whereas a tendency toward increase by 1.9 ± 0.5 kg occurred in the IG (i.e. pre-CPRP = 89.1 ± 14.4 kg; post-CPRP = 90.4 ± 14.1 kg). This difference may be explained by the higher BMI of their patients at baseline and the fact that they included only post-hospitalization patients who may experience an increase in dietary intake after their discharge [28].

Discussion of the methodology

The disparities observed between our results and those of some related RCTs (Tables 1S to 6S, Appendix) can be attributed to at least 12 factors related to differences in *(i)* recruitment methods,

(ii) applied questionnaires and tests, *(iii)* blinding technique and randomization method, *(iv)* primary and secondary outcomes, *(v)* time interval between the onset of COVID-19 and the initiation of the CPRP, *(vi)* applied inclusion, non-inclusion and exclusion criteria, *(vii)* sample size calculation, *(viii)* characteristics of LC19Ps and controls, *(ix)* methodological aspects of the 6MWT, *(x)* collected data during the 6MWT, *(xi)* methodological aspects of the CPRP, and *(xii)* statistical approaches. A discussion related to points *(i)* to *(vi)* is detailed in the Appendix, and a discussion related to points *(vii)* to *(xii)* is provided in the following sentences.

Sample size calculation

Similar to eight related RCTs [26, 27, 29, 30, 32–35] (Table 1S), we calculated the required sample size using a predictive equation [45]. Our sample size (n = 30) exceeded that of one RCT (n = 17) [32], was comparable to the samples of three RCTs (n = 32 [28, 34, 35]), and was smaller than the samples of seven RCTs (n = 42 [33], n = 52 [29, 30], n = 72 [26], n = 81 [36], n = 119 [27], and n = 392 [31]) (Table 3S). Determining the optimal sample size is crucial as it helps avoid inadequate power to detect statistical effects [87], and ensures a representative sample for detecting statistical significance [45]. A large sample size is expensive and exposes more participants to measures [87], but using an insufficient number of participants may result in lower precision in the results.

Characteristics of LC19Ps and controls

The characteristics of our patients and controls, including the ratio between the CG and IG, sex, age, corpulence status, comorbidities, COVID-19 data, and smoking status, fall within intermediate ranges compared to related similar studies (Table 3S). First, as in some related RCTs [34–36], our sample size distribution for the CG and IG was lower than one. In the remaining RCTs, the sample size distributions were either "equal" [26, 27, 29–33], or higher than [28] ours. Second, similar to some related RCTs [26–28, 30–35], we included both sexes. Third, the mean age of our patients (i.e. 52–53 years) was intermediate compared to that reported in the literature: higher than in some RCTs [29, 31], comparable to others [27, 28, 30, 32], and lower than in some RCTS [26, 33–36] (Table 3S). Fourth, the observed frequency of obesity in our RCT (i.e. 33%, Table 1) was lower than in one RCT (i.e. 65–67% [28]) and higher than in another RCT (i.e. 13–15% [27]). Fifth, the most frequent comorbidities in our RCT, diabetes mellitus, and arterial hypertension (each 20%, Table 1) were consistent with those reported in some related RCTs [26–28, 30, 33] (Table 3S). Sixth, the initial extent of COVID-19 lesions observed in our RCT (Table 1) was comparable to that reported in another related RCT [29] (Table 3S). Finally, the percentages of ex-smokers of cigarettes (40%) or narghile (17%) reported in our RCT (Table 1) are comparable to those reported in the literature, with frequencies varying from 10% [27] to 68% [33] (Table 3S).

Methodological aspects of the 6MWT

In alignment with four previous RCTs [27, 28, 34, 35], we conducted the 6MWT according to the most updated 6MWT guideline, specifically the European respiratory society (ERS)/American Thoracic Society (ATS)-2014 guideline [22, 39]) (Table 4S). It is noteworthy that five related RCTs [30–33, 36] applied an outdated guideline for the 6MWT (i.e. ATS-2002 guideline [43]), despite updated guidelines being available since 2014. Adhering to the most current guidelines is crucial for ensuring the accuracy and relevance of the test results [25].

We implemented the 6MWT along a 40 m-long corridor, while in related RCTs, corridor lengths varied between 30 [27, 28, 30, 33–36] and 35 [29] m (Table 4S). The length of the corridor can impact performance [22, 43], and guidelines suggest a walking course of at least 30 m [43]. Research indicated that there are no significant differences in outcomes when tracks of lengths ranging from 15 to 50 m are used [88]. Consistency in corridor length is essential for accurate comparisons of 6MWT results [25, 88].

In contrast to two related RCTs [29, 36] where the 6MWT was conducted indoors, we performed it outdoors. Other related RCTs implemented the 6MWT both indoors and outdoors [27, 32] (Table 4S). Guidelines recommend performing the 6MWT indoors [43], but it can also be conducted outdoors if weather conditions permit. Research suggested MDs in 6MWD (i.e. MD of 4 m) between indoor and outdoor courses [89]. This flexibility allows adaptation to different clinical settings and patient comfort [25].

Similar to two related RCTs [34, 35], our patients were allowed to move independently and rest if necessary. In contrast to one related RCT [27], our patients were not allowed to use walking aids during the 6MWT. The use of walking aids during the 6MWT can significantly influence the 6MWD [22, 39]. This information is important for interpreting and comparing results across different studies [25].

Collected data during the 6MWT

Before the initiation of the 6MWT (i.e., at rest), we assessed dyspnoea using two scales, namely the Borg and mMRC scales. Among the 11 related RCTs (Table 4S), dyspnoea was evaluated in nine [26, 27, 29–35] using the mMRC scale [27, 29, 30, 32], the Borg scale [26, 34, 35], or both mMRC and Borg scales [31, 33].

During the 6MWT, we determined the following parameters: 6MWD, 6MWW, HR, and SpO_2. First, while all related RCTs determined the 6MWD (Table 4S), only three determined HR and SpO_2 [26–28], and none reported the 6MWW. Second, in the related RCTs (Table 4S), some studies also measured additional parameters, including SBP and DBP [26–28], respiratory rate [26], fatigue [34, 35], and blood pressure, HR, and SpO_2 at recovery [28]. Third, akin to all related RCTs (Table 4S), we reported 6MWD as an absolute value, and as performed in one RCT [28], we also expressed it as a percentage of predicted norms. Fourth, mirroring one related RCT [28], we expressed HR in bpm, and as

a percentage of PMHR. Finally, in contrast to our study, where desaturation was defined as $\Delta_{SpO2} > 5$ points [58], in one related RCT [28], it was defined as $\Delta_{SpO2} \geq 4$ points. The latter definition is debatable, as in several studies [56, 58, 90], the most used definition for clinically significant desaturation is $\Delta_{SpO2} > 5$ points. Some studies recommended considering novel desaturation indices, such as the distance-saturation product, desaturation area, and desaturation-distance ratio, for a more comprehensive assessment in future RCTs [22, 39].

Methodological aspects of the CPRP

The design and execution of CPRPs can significantly impact their outcomes and benefits for patients with chronic respiratory conditions [25]. Four points related to the CPRP merit discussion.

First, our CPRP was conducted at the hospital, aligning with other related RCTs [29, 30, 34–36], and differing from others where CPRPs were administered at home [27, 28, 33] or both at home and at the hospital [26, 27, 32] (Table 5S). The choice of CPRP location, whether at home, at hospital, or a combination of both, substantially influences programme results [25, 91]. Hospital-based CPRPs offer several advantages, such as a structured and supervised environment, access to various exercise equipment, peer support, and expert guidance [25, 91]. In contrast, home-based CPRPs provide more flexibility, convenience, personalized plans, and opportunities for self-management [25, 91]. Decisions on CPRPs' location should consider patients' needs, preferences, and desired outcomes [25].

Second, our CPRP comprised three sessions per week for six weeks, with each session lasting 60–90 minutes. The frequency of sessions per week (e.g. one [30, 32], two [26], three [27–29, 32, 33], four [27, 32], five [28, 30, 33–35], six [36], seven [33], 21 [30]), the duration of the CPRP (e.g. two [31], three [34, 35], four [32], five [30], six [26, 27, 29, 36], eight [33], 12 [28] weeks), and session durations (in minutes) (e.g. less than 3–4 [29], 10 [26], 10–30 [28], 20–30 [33], and 40–60 [32]) varied among similar related RCTs (Table 5S). These variances can significantly affect CPRP outcomes [25, 91]. Higher session frequency (e.g. 3–5 sessions/week) improves conditioning, offering consistency and greater social interaction, while lower frequency (e.g., 1–2 sessions/week) provides flexibility, sustainability, and gradual progression [25, 91]. Regarding programme duration, shorter programmes (e.g. 4–8 weeks) focus intensively and suit acute needs, while longer programmes (e.g. ≥12–19 weeks) sustain benefits, induce behavioural changes, and instil patient confidence [25, 91]. The optimal number of sessions/week and CPRP duration should be individualized based on factors such as respiratory condition severity, patients' baseline fitness levels, goals, and their ability to commit to the programme [25, 91]. The American College of Sports Medicine recommends 16 weeks of supervised aerobic exercise training for inducing training adaptations [92].

Third, our typical exercise-training session included warming-up, aerobic training, resistance training, and respiratory exercises (Figure 3). In related RCTs (Table 5S), different CPRPs were applied in cases including respiratory muscle training [26, 27, 29, 30], breathing exercises [27, 29] [30, 31], bough exercise [26], stretching exercise [26], strength exercises [27], aerobic exercise [27, 28, 30], resistance training [28], and Baduanjin exercise [31]. Variations in CPRP content critically influence its outcomes [25]. A well-designed and comprehensive CPRP can significantly improve the health and well-being of individuals with chronic respiratory conditions [25, 91]. Regarding the CPRP content, a 2023 SR [25] extensively described key elements to be considered. In line with some related RCTs [26], our controls were instructed to maintain sedentary activities. In related RCTs (Table 5S), controls were recommended various activities, including short educational instructions [27], inspiratory muscle training [29], pursed lip breathing, diaphragmatic breathing exercise, and aerobic exercise training [30], and standard rehabilitation treatments such as lip and abdominal breathing training, and respiratory rhythm training [31]. The application of different approaches in controls complicates direct comparisons between RCTs, making it essential to consider CG characteristics when interpreting CPRP outcomes [25].

Fourth, in our RCT, CPRP local guidelines/recommendations and international recommendations [8, 49, 59–66] were applied. In related RCTs (Table 5S), one [27] followed the American College of Sports Medicine guideline [92], and five [30, 31, 34–36] followed guidelines developed based on previous studies. Numerous recommendations/guidelines related to managing LC19Ps exist in the literature [8, 49, 60–66]. These guidelines target specialist physicians such as pulmonologists, cardiologists, physical medicine and rehabilitation specialists, or a combination of different specialties [60, 61, 65, 66], or general practitioners [8, 49, 64]. When comparing RCT results that used different CPRP guidelines, the main challenge is the potential for inconsistency and variability in CPRP design and implementation [25]. This can complicate drawing meaningful conclusions and making direct comparisons between these RCTs [25]. Adherence to evidence-based guidelines can enhance CPRP quality and consistency, improving patient outcomes [25].

Applied statistical approaches

In our RCT, we employed both statistical and clinical significance approaches. The statistical significant approach, utilized in all related RCTs (Table 4S), typically emphasizes statistical significance to assess differences between groups (i.e. to compare the 6MWD between cases and controls), with a "p value" < 0.05 considered significant. Presently, this approach faces criticism [93]. The clinical significance approach, which was applied in four related RCTs [27, 32, 34, 35] determines whether the results influence medical exercise. It consists in calculating the effect size for some parameters or using the MCID for one specific parameter (e.g. MCID

for the 6MWD [27, 32] or dyspnoea). First, as done in two related RCTs [34, 35], we calculated the effect size, which measures the magnitude of the difference between groups or the effect of an intervention [94]. Second, the MCID approach is valuable for assessing whether observed changes in one parameter such as 6MWD or dyspnoea hold practical clinical relevance beyond statistical significance (e.g. the smallest change considered meaningful by patients or clinicians) [95]. In clinical practice, as the MCID for LC19Ps has not been established yet [75], one SR recommended deeming a CPRP 'efficient' if the mean changes for 6MWD and dyspnoea (mMRC) exceed recommended MCIDs (i.e. 30 m [39], and one point [40], respectively) [25]. While we set the 6MWD MCID at 30 m (i.e. as per ERS-ATS recommendations [39]), other authors [27, 32] have set it at 50 m. Moreover, following one SR's recommendation [25], we compared the percentage of LC19Ps or controls with an abnormal 6MWD (i.e. 6MWD < LLN) before and after CPRP. This analysis provides insights into the extent to which CPRPs help patients achieve values within a normal range [37].

Study strengths and limitations

Our RCT exhibits three notable strengths. First, it was conducted in an outpatient unit in a low-income country, specifically Tunisia. Second, the sample size was calculated, enhancing the study's statistical robustness [45]. Third, we applied the clinically significant approach, incorporating the MCID of 30 m for the 6MWD [39] and 1 point for mMRC [40].

The present RCT has five limitations. First, we did not measure blood pressure at the end of the 6MWT. Assessing $6MWT_{End}$ blood pressure is valuable for evaluating cardiovascular health, exercise responses, and overall patient safety [20, 56, 90]. This information can aid in diagnosis, risk assessment, exercise prescription, and patient care in cardiovascular conditions [20, 56, 90]. Notably, high blood pressure is one of the most critical modifiable risk factors for cardiovascular disease and mortality [96]. A related RCT [28] reported that SBP_{End} and DBP_{End} measured before and after CPRP remained unchanged in both cases (SBP (mmHg): 151 ± 24 vs. 158 ± 17, DBP: 90 ± 14 vs. 93 ± 11, respectively) and controls (SBP (mmHg): 147 ± 29 vs. 151 ± 25, DBP: 87 ± 18 vs. 88 ± 16, respectively). Another observational study [37] reported a decrease in post-CPRP DBP_{Rest}, with the mean DBP_{Rest} decreasing from 85 to 79 mmHg. This outcome is noteworthy, aligning with the 2018 European Society of Cardiology recommendation of an optimal DBP_{Rest} target between 70 and 80 mmHg for patients across all risk levels [96]. Second, we did not determine SpO_2 at recovery. Assessing SpO_2 at recovery provides insights into how effectively a patient's body returns to a stable SpO_2 level after exertion [97]. This parameter can reveal the functionality of the cardiovascular and respiratory systems in responding to exercise stress [97]. Third, bronchodilator tests were not performed for our patients. It has been suggested that the bronchodilator response could serve as a predictor of lung function improvement after CPRP in LC19Ps [98]. Fourth, a broader exploration of respiratory function using additional tests, such as plethysmography [17], diffusion capacity of the lungs for carbon monoxide [15, 17, 26], maximal inspiratory pressure [17], and cardiorespiratory tests to determine the ventilatory threshold exercise data using a cardiorespiratory test in order to determine the ventilatory threshold, would have been more comprehensive. In COVID-19 patients, altered diffusing capacity of the lungs for carbon monoxide is a frequent impairment (39%) [99]. Unfortunately, due to the unavailability of equipment in our public health hospital, these additional tests were not conducted. Finally, we did not assess waist circumferences of our patients. Evaluating waist circumference in LC19Ps during a CPRP is important for assessing cardiometabolic health, stratifying risk, monitoring progress, implementing lifestyle interventions, and delivering comprehensive patient care.

CONCLUSIONS

In summary, the outcomes of our Tunisian RCT demonstrate significant improvements within the IG compared to the CG. Particularly noteworthy are the statistically significant and clinically meaningful increases in the 6MWD and reductions in HR_{Rest} within the IG, surpassing the recommended MCID thresholds. Additionally, participants in the IG experienced significantly greater decreases in Borg and mMRC scales, with the latter achieving a reduction exceeding the MCID. While spirometric data remained comparable between the two groups, the observed positive outcomes in submaximal aerobic capacity and symptomatology underscore the potential efficacy of cardiopulmonary rehabilitation in enhancing the health status of LC19Ps. These findings contribute valuable insights to the evolving understanding of rehabilitation strategies for individuals recovering from lingering impacts of COVID-19.

Declaration

We used assistance from artificial intelligence (i.e. language model, ChatGPT 3.5) in the correction and improvement of our scientific paper [100].

Sources of financial support

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Name and location of the institution where the review was performed

Fattouma Bourguiba hospital Monastir, Tunisia.

Competing interest

The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

APPENDIX: link to appendix.

REFERENCES

1. Dergaa I, Ben Saad H, Zmijewski P, Farhat RA, Romdhani M, Souissi A, et al. Large-scale sporting events during the COVID-19 pandemic: insights from the FIFA World Cup 2022 in Qatar with an analysis of patterns of COVID-19 metrics. Biol Sport. 2023; 40(4):1249–58. Epub 20230907. doi: 10.5114/biolsport.2023.131109. PubMed PMID: 37867752; PubMed Central PMCID: PMC10588590.
2. Washif JA, Pyne DB, Sandbakk O, Trabelsi K, Aziz AR, Beaven CM, et al. Ramadan intermittent fasting induced poorer training practices during the COVID-19 lockdown: A global cross-sectional study with 5529 athletes from 110 countries. Biol Sport. 2022; 39(4):1103–15. Epub 20220627. doi: 10.5114/biolsport.2022.117576. PubMed PMID: 36247962; PubMed Central PMCID: PMC9536381.
3. Wu Z, McGoogan JM. Characteristics of and important lessons from the coronavirus disease 2019 (COVID-19) outbreak in China: Summary of a report of 72 314 cases from the Chinese center for disease control and prevention. JAMA. 2020; 323(13):1239–42. doi: 10.1001/jama.2020.2648. PubMed PMID: 32091533.
4. Cascella M, Rajnik M, Aleem A, Dulebohn SC, Di Napoli R. Features, evaluation, and treatment of coronavirus (COVID-19). StatPearls. Treasure Island (FL)2024.
5. Lopez-Leon S, Wegman-Ostrosky T, Perelman C, Sepulveda R, Rebolledo PA, Cuapio A, et al. More than 50 long-term effects of COVID-19: a systematic review and meta-analysis. Sci Rep. 2021; 11(1):16144. Epub 20210809. doi: 10.1038/s41598-021-95565-8. PubMed PMID: 34373540; PubMed Central PMCID: PMC8352980.
6. World health organisation. Post COVID-19 condition (Long COVID). Link: https://www.who.int/europe/news-room/fact-sheets/item/post-covid-19-condition (Last visit: February 24, 2024).
7. Ali M, Bonna AS, Sarkar AS, Islam A. Is coronavirus infection associated with musculoskeletal health complaints? Results from a comprehensive case-control study. J Prim Care Community Health. 2022; 13:21501319221114259. doi: 10.1177/21501319221114259. PubMed PMID: 35869693; PubMed Central PMCID: PMC9310274.
8. Guezguez F, Romdhani M, Boutaleb-Joutei A, Chamari K, Ben Saad H. Management of long-COVID-19 patients with sleep disorders: practical advice to general practitioners. Libyan J Med. 2023; 18(1):2182704. Epub 2023/02/27. doi: 10.1080/19932820.2023.2182704. PubMed PMID: 36842064; PubMed Central PMCID: PMC9970199.
9. Huang L, Yao Q, Gu X, Wang Q, Ren L, Wang Y, et al. 1-year outcomes in hospital survivors with COVID-19: a longitudinal cohort study. Lancet. 2021; 398(10302):747–58. doi: 10.1016/S0140-6736(21)01755-4. PubMed PMID: 34454673; PubMed Central PMCID: PMC8389999.
10. Zhao YM, Shang YM, Song WB, Li QQ, Xie H, Xu QF, et al. Follow-up study of the pulmonary function and related physiological characteristics of COVID-19 survivors three months after recovery. EClinicalMedicine. 2020; 25:100463. Epub 20200715. doi: 10.1016/j.eclinm.2020.100463. PubMed PMID: 32838236; PubMed Central PMCID: PMC7361108.
11. Shrestha AB, Mehta A, Pokharel P, Mishra A, Adhikari L, Shrestha S, et al. Long COVID syndrome and cardiovascular manifestations: A systematic review and meta-analysis. Diagnostics (Basel). 2023; 13(3). Epub 20230129. doi: 10.3390/diagnostics13030491. PubMed PMID: 36766599; PubMed Central PMCID: PMC9913936.
12. Sudre CH, Murray B, Varsavsky T, Graham MS, Penfold RS, Bowyer RC, et al. Attributes and predictors of long COVID. Nat Med. 2021; 27(4):626–31. Epub 20210310. doi: 10.1038/s41591-021-01292-y. PubMed PMID: 33692530; PubMed Central PMCID: PMC7611399.
13. Skjorten I, Ankerstjerne OAW, Trebinjac D, Bronstad E, Rasch-Halvorsen O, Einvik G, et al. Cardiopulmonary exercise capacity and limitations 3 months after COVID-19 hospitalisation. Eur Respir J. 2021; 58(2). Epub 20210826. doi: 10.1183/13993003.00996-2021. PubMed PMID: 34210791; PubMed Central PMCID: PMC8247555.
14. Ingul CB, Edvardsen A, Follestad T, Trebinjac D, Ankerstjerne OAW, Bronstad E, et al. Changes in cardiopulmonary exercise capacity and limitations 3–12 months after COVID-19. Eur Respir J. 2023; 61(2). Epub 20230202. doi: 10.1183/13993003.00745-2022. PubMed PMID: 36137587; PubMed Central PMCID: PMC9515478.
15. Gloeckl R, Leitl D, Jarosch I, Schneeberger T, Nell C, Stenzel N, et al. Benefits of pulmonary rehabilitation in COVID-19: a prospective observational cohort study. ERJ Open Res. 2021; 7(2). Epub 20210531. doi: 10.1183/23120541.00108-2021. PubMed PMID: 34095290; PubMed Central PMCID: PMC7957293.
16. Daynes E, Gerlis C, Chaplin E, Gardiner N, Singh SJ. Early experiences of rehabilitation for individuals post-COVID to improve fatigue, breathlessness exercise capacity and cognition – A cohort study. Chron Respir Dis. 2021; 18:14799731211015691. doi: 10.1177/14799731211015691. PubMed PMID: 33957805; PubMed Central PMCID: PMC8114752.
17. Puchner B, Sahanic S, Kirchmair R, Pizzini A, Sonnweber B, Woll E, et al. Beneficial effects of multi-disciplinary rehabilitation in postacute COVID-19: an observational cohort study. Eur J Phys Rehabil Med. 2021; 57(2):189–98. Epub 20210115. doi: 10.23736/S1973-9087.21.06549-7. PubMed PMID: 33448756.
18. Bouteleux B, Henrot P, Ernst R, Grassion L, Raherison-Semjen C, Beaufils F, et al. Respiratory rehabilitation for Covid-19 related persistent dyspnoea: A one-year experience. Respir Med. 2021; 189:106648. Epub 20211013. doi: 10.1016/j.rmed.2021.106648. PubMed PMID: 34689061; PubMed Central PMCID: PMC8511554.
19. Spielmanns M, Pekacka-Egli AM, Schoendorf S, Windisch W, Hermann M. Effects of a comprehensive pulmonary rehabilitation in severe post-COVID-19 patients. Int J Environ Res Public Health. 2021; 18(5):2695. Epub 20210307. doi: 10.3390/ijerph18052695. PubMed PMID: 33800094; PubMed Central PMCID: PMC7967422.
20. Ben Saad H, Hamadou R, Ben Cheikh I, Chouchene A, Rejeb N, Zbidi A, et al. Respiratory rehabilitation of chronic obstructive pulmonary disease patients: Preliminary data of Tunisian experience. Journal de Réadaptation Médicale. 2008; 28(4):138–47. doi: 10.1016/j.jmr.2008.09.001.
21. Maley JH, Alba GA, Barry JT, Bartels MN, Fleming TK, Oleson CV, et al. Multidisciplinary collaborative consensus guidance statement on the assessment and treatment of breathing discomfort and respiratory sequelae in patients with post-acute sequelae of SARS-CoV-2 infection (PASC). PM R. 2022; 14(1):77–95. Epub 2021/12/14. doi: 10.1002/pmrj.12744. PubMed PMID: 34902224.
22. Holland AE, Spruit MA, Troosters T, Puhan MA, Pepin V, Saey D, et al. An official European respiratory society/American thoracic society technical standard: field walking tests in chronic respiratory disease. Eur Respir J. 2014; 44(6):1428–46. Epub 20141030. doi: 10.1183/09031936.00150314. PubMed PMID: 25359355.

23. Jenkins S, Cecins NM. Six-minute walk test in pulmonary rehabilitation: do all patients need a practice test? Respirology. 2010; 15(8):1192–6. doi: 10.1111 /j.1440-1843.2010.01841.x. PubMed PMID: 20920121.
24. Fugazzaro S, Contri A, Esseroukh O, Kaleci S, Croci S, Massari M, et al. Rehabilitation interventions for post-acute COVID-19 syndrome: A systematic review. Int J Environ Res Public Health. 2022; 19(9). Epub 20220424. doi: 10.3390/ijerph19095185. PubMed PMID: 35564579; PubMed Central PMCID: PMC9104923.
25. Ghram A, Latiri I, Methnani J, Souissi A, Benzarti W, Toulgui E, et al. Effects of cardiorespiratory rehabilitation program on submaximal exercise in patients with long-COVID-19 conditions: a systematic review of randomized controlled trials and recommendations for future studies. Expert Rev Respir Med. 2023; 17(12):1095–124. Epub 20231214. doi: 10.1080/17476348.2023 .2293226. PubMed PMID: 38063359.
26. Liu K, Zhang W, Yang Y, Zhang J, Li Y, Chen Y. Respiratory rehabilitation in elderly patients with COVID-19: A randomized controlled study. Complement Ther Clin Pract. 2020; 39:101166. Epub 20200401. doi: 10.1016/j.ctcp.2020.101166. PubMed PMID: 32379637; PubMed Central PMCID: PMC7118596.
27. Li J, Xia W, Zhan C, Liu S, Yin Z, Wang J, et al. A telerehabilitation programme in post-discharge COVID-19 patients (TERECO): a randomised controlled trial. Thorax. 2022; 77(7):697–706. Epub 20210726. doi: 10.1136/thoraxjnl -2021-217382. PubMed PMID: 34312316; PubMed Central PMCID: PMC8318721.
28. Teixeira DOAV, Viana AA, Heubel AD, Linares SN, Martinelli B, Witzler PHC, et al. Cardiovascular, respiratory, and functional effects of home-based exercise training after COVID-19 hospitalization. Med Sci Sports Exerc. 2022; 54(11):1795–803. Epub 20220617. doi: 10.1249/MSS.000000000000 2977. PubMed PMID: 35714077.
29. Nagy EN, Elimy DA, Ali AY, Ezzelregal HG, Elsayed MM. Influence of manual diaphragm release technique combined with inspiratory muscle training on selected persistent symptoms in men with post-Covid-19 syndrome: A randomized controlled trial. J Rehabil Med. 2022; 54:jrm00330. Epub 20221020. doi: 10.2340/jrm. v54.3972. PubMed PMID: 36121338; PubMed Central PMCID: PMC9608026.
30. Okan F, Okan S, Duran Yucesoy F. Evaluating the efficiency of breathing exercises via telemedicine in post-Covid-19 patients: Randomized controlled study. Clin Nurs Res. 2022; 31(5):771–81. Epub 20220429. doi: 10.1177/10547738221097241. PubMed PMID: 35485738.
31. Pang W, Yang F, Zhao Y, Dai E, Feng J, Huang Y, et al. Qingjin Yiqi granules for post-COVID-19 condition: A randomized clinical trial. J Evid Based Med. 2022; 15(1):30–8. Epub 2022/04/14. doi: 10.1111/jebm.12465. PubMed PMID: 35416437; PubMed Central PMCID: PMC9114922.
32. Vallier JM, Simon C, Bronstein A, Dumont M, Jobic A, Paleiron N, et al. Randomized controlled trial of home-based vs. hospital-based pulmonary rehabilitation in post COVID-19 patients. Eur J Phys Rehabil Med. 2023; 59(1):103–10. Epub 20230126. doi: 10.23736/S1973 -9087.22.07702-4. PubMed PMID: 36700245; PubMed Central PMCID: PMC10035444.
33. Sahin H, Naz I, Karadeniz G, Sunecli O, Polat G, Ediboglu O. Effects of a home-based pulmonary rehabilitation program with and without telecoaching on health-related outcomes in COVID-19 survivors: a randomized controlled clinical study. J Bras Pneumol. 2023; 49(1):e20220107. Epub 20230123. doi: 10.36416/1806-3756/e202201 07. PubMed PMID: 36700571; PubMed Central PMCID: PMC9970366.
34. Rutkowski S, Bogacz K, Czech O, Rutkowska A, Szczegielniak J. Effectiveness of an inpatient virtual reality-based pulmonary rehabilitation program among COVID-19 patients on symptoms of anxiety, depression and quality of life: Preliminary results from a randomized controlled trial. Int J Environ Res Public Health. 2022; 19(24). Epub 20221217. doi: 10.3390 /ijerph192416980. PubMed PMID: 36554860; PubMed Central PMCID: PMC9779397.
35. Rutkowski S, Bogacz K, Rutkowska A, Szczegielniak J, Casaburi R. Inpatient post-COVID-19 rehabilitation program featuring virtual reality-Preliminary results of randomized controlled trial. Front Public Health. 2023; 11:1121554. Epub 20230206. doi: 10.3389/ fpubh.2023.1121554. PubMed PMID: 36815161; PubMed Central PMCID: PMC9939639.
36. Trzmiel T, Marchewka R, Pieczynska A, Zasadzka E, Zubrycki I, Kozak D, et al. The effect of using a rehabilitation robot for patients with post-Coronavirus disease (COVID-19) fatigue syndrome. Sensors (Basel, Switzerland). 2023; 23(19). Epub 20230927. doi: 10.3390/s23198 120. PubMed PMID: 37836950; PubMed Central PMCID: PMC10575211.
37. Toulgui E, Benzarti W, Rahmani C, Aissa S, Ghannouchi I, Knaz A, et al. Impact of cardiorespiratory rehabilitation program on submaximal exercise capacity of Tunisian male patients with post-COVID19: A pilot study. Front Physiol. 2022; 13:1029766. Epub 20220928. doi: 10.3389/fphys .2022.1029766. PubMed PMID: 36246110; PubMed Central PMCID: PMC9555273.
38. Benzarti W, Toulgui E, Ghram A, Rahmani C, Aissa S, Ghannouchi I, et al. Impact of a pulmonary rehabilitation program on social disadvantage and physical activity data of postCOVID19 patients: A North-African pilot study. F1000Res. 2022; 11:1226. Epub 20221027. doi: 10.12688/f1000 research.126301.1. PubMed PMID: 37547787; PubMed Central PMCID: PMC10403745.
39. Singh SJ, Puhan MA, Andrianopoulos V, Hernandes NA, Mitchell KE, Hill CJ, et al. An official systematic review of the European respiratory society/American thoracic society: measurement properties of field walking tests in chronic respiratory disease. Eur Respir J. 2014; 44(6):1447–78. Epub 20141030. doi: 10.1183/09031936.00150414. PubMed PMID: 25359356.
40. Crisafulli E, Clini EM. Measures of dyspnea in pulmonary rehabilitation. Multidiscip Respir Med. 2010; 5(3):202–10. Epub 20100630. doi: 10.1186/2049-6958-5-3-202. PubMed PMID: 22958431; PubMed Central PMCID: PMC3463047.
41. de Torres JP, Pinto-Plata V, Ingenito E, Bagley P, Gray A, Berger R, et al. Power of outcome measurements to detect clinically significant changes in pulmonary rehabilitation of patients with COPD. Chest. 2002; 121(4): 1092–8. doi: 10.1378/chest.121. 4.1092. PubMed PMID: 11948037.
42. Mahler DA, Wells CK. Evaluation of clinical methods for rating dyspnea. Chest. 1988; 93(3):580–6. Epub 1988/03/01. doi: 10.1378/chest .93.3.580. PubMed PMID: 3342669.
43. American Thoracic Society. ATS statement: guidelines for the six-minute walk test. Am J Respir Crit Care Med. 2002; 166(1):111–7. doi: 10.1164 /ajrccm.166.1.at1102. PubMed PMID: 12091180.
44. Graham BL, Steenbruggen I, Miller MR, Barjaktarevic IZ, Cooper BG, Hall GL, et al. Standardization of spirometry 2019 update. An official American thoracic society and European respiratory society technical statement. Am J Respir Crit Care Med. 2019; 200(8):e70–e88. doi: 10.1164/rccm.201908-1590ST. PubMed PMID: 31613151; PubMed Central PMCID: PMC6794117.

45. Serhier Z, Bendahhou K, Ben Abdelaziz A, Bennani MO. Methodological sheet n degrees 1: How to calculate the size of a sample for an observational study? Tunis Med. 2020; 98(1):1–7. Epub 2020/05/13. PubMed PMID: 32395771.
46. Rodriguez-Blanco C, Gonzalez-Gerez JJ, Bernal-Utrera C, Anarte-Lazo E, Perez-Ale M, Saavedra-Hernandez M. Short-term effects of a conditioning telerehabilitation program in confined patients affected by COVID-19 in the acute phase. A pilot randomized controlled trial. Medicina (Kaunas, Lithuania). 2021; 57(7). Epub 20210703. doi: 10.3390/medicina57070684. PubMed PMID: 34356965; PubMed Central PMCID: PMC8305888.
47. Revel MP, Parkar AP, Prosch H, Silva M, Sverzellati N, Gleeson F, et al. COVID-19 patients and the radiology department – advice from the European society of radiology (ESR) and the European society of thoracic imaging (ESTI). Eur Radiol. 2020; 30(9):4903–9. Epub 20200420. doi: 10.1007/s00330-020-06865-y. PubMed PMID: 32314058; PubMed Central PMCID: PMC7170031.
48. Simpson R, Robinson L. Rehabilitation after critical illness in people with COVID-19 infection. Am J Phys Med Rehabil. 2020; 99(6):470–4. Epub 2020/04/14. doi: 10.1097/PHM.0000000000001443. PubMed PMID: 32282359; PubMed Central PMCID: PMC7253039.
49. Ghram A, Ayadi H, Knechtle B, Ben Saad H. What should a family physician know about nutrition and physical exercise rehabilitation' advices to communicate to 'long-term COVID-19' patients? Postgrad Med. 2022; 134(2):143–7. Epub 20220209. doi: 10.1080/00325481.2022.2035589. PubMed PMID: 35083948.
50. Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc. 1982; 14(5):377–81. PubMed PMID: 7154893.
51. Tsai AG, Wadden TA. In the clinic: obesity. Ann Intern Med. 2013; 159(5):ITC3–1–ITC3–15; quiz ITC3–6. Epub 2013/09/13. doi: 10.7326/0003-4819-159-5-201309030-01003. PubMed PMID: 24026335.
52. Ben Saad H. Review of the current use of global lung function initiative norms for spirometry (GLI-2012) and static lung volumes (GLI-2021) in Great Arab Maghreb (GAM) countries and steps required to improve their utilization. Libyan J Med. 2022; 17(1):2031596. doi: 10.1080/19932820.2022.2031596. PubMed PMID: 35080480; PubMed Central PMCID: PMC8794060.
53. Tanaka H, Monahan KD, Seals DR. Age-predicted maximal heart rate revisited. J Am Coll Cardiol. 2001; 37(1):153–6. Epub 2001/01/12. doi: 10.1016/s0735-1097(00)01054-8. PubMed PMID: 11153730.
54. Fabre C, Chehere B, Bart F, Mucci P, Wallaert B, Grosbois JM. Relationships between heart rate target determined in different exercise testing in COPD patients to prescribed with individualized exercise training. Int J Chron Obstruct Pulmon Dis. 2017; 12:1483–9. Epub 20170516. doi: 10.2147/COPD.S129889. PubMed PMID: 28553100; PubMed Central PMCID: PMC5439969.
55. Bourahli MK, Bougrida M, Martani M, Mehdioui H, Ben Saad H. 6-Min walk-test data in healthy North-African subjects aged 16–40 years. Egypt J Chest Dis Tuberc. 2016; 65(1):349–60.
56. Ben Saad H, Prefaut C, Tabka Z, Mtir AH, Chemit M, Hassaoune R, et al. 6-minute walk distance in healthy North Africans older than 40 years: influence of parity. Respir Med. 2009; 103(1):74–84. Epub 20081128. doi: 10.1016/j.rmed.2008.07.023. PubMed PMID: 19041233.
57. Carter R, Holiday DB, Nwasuruba C, Stocks J, Grothues C, Tiep B. 6-minute walk work for assessment of functional capacity in patients with COPD. Chest. 2003; 123(5):1408–15. doi: 10.1378/chest.123.5.1408. PubMed PMID: 12740255.
58. Ben Saad H, Babba M, Boukamcha R, Ghannouchi I, Latiri I, Mezghenni S, et al. Investigation of exclusive narghile smokers: deficiency and incapacity measured by spirometry and 6-minute walk test. Respir Care. 2014; 59(11):1696–709. Epub 20140708. doi: 10.4187/respcare.03058. PubMed PMID: 25006270.
59. Ben Abdelkarim S, Ben Saad H. Cardiorespiratory rehabilitation. A practical session of daily exercise training. Zenodo; 2023. Link: https://zenodo.org/records/10444215 (Last visit: February 24, 2024) 2005.
60. Andrejak C, Blanc F-X, Costes F, Crestani B, Debieuvre D, Perez T, et al. Guide for follow-up of patients with SARS-CoV-2 pneumonia. Management proposals developed by the French-language Respiratory Medicine Society. Version of 10 May 2020. Rev Mal Respir. 2020; 37(6):505–10. doi: 10.1016/j.rmr.2020.05.001. Epub 2020 May 14. PMID: 32410773; PMCID: PMC7221358.
61. Stein J, Visco CJ, Barbuto S. Rehabilitation medicine response to the COVID-19 pandemic. Am J Phys Med Rehabil. 2020; 99(7):573–9. Epub 2020/05/21. doi: 10.1097/PHM.0000000000001470. PubMed PMID: 32433243; PubMed Central PMCID: PMC7268871.
62. Agostini F, Mangone M, Ruiu P, Paolucci T, Santilli V, Bernetti A. Rehabilitation setting during and after Covid-19: An overview on recommendations. J Rehabil Med. 2021; 53(1):jrm00141. Epub 20210105. doi: 10.2340/16501977-2776. PubMed PMID: 33284353; PubMed Central PMCID: PMC8772378.
63. World health organization. Support for rehabilitation self-management after COVID-19-related illness. Link: https://cdn.who.int/media/docs/default-source/ageing/support-for-rehabilitation-self-management-after-covid-19-related-illness-engf5cec00b-350b-4eb0-bc24-0704df509ae1.pdf?sfvrsn=203566f0_1& download=true (Last visit: February 24, 2024).
64. Benzarti W, Toulgui E, Prefaut C, Chamari K, Ben Saad H. General practitioners should provide the cardiorespiratory rehabilitation' 'minimum advice' for long COVID-19 patients. Libyan J Med. 2022; 17(1):2009101. doi: 10.1080/19 932820.2021.2009101. PubMed PMID: 34839808; PubMed Central PMCID: PMC8635671.
65. Barker-Davies RM, O'Sullivan O, Senaratne KPP, Baker P, Cranley M, Dharm-Datta S, et al. The Stanford Hall consensus statement for post-COVID-19 rehabilitation. Br J Sports Med. 2020; 54(16):949–59. Epub 20200531. doi: 10.1136/bjsports-2020-102596. PubMed PMID: 32475821; PubMed Central PMCID: PMC7418628.
66. European society of cardiology. Guidance for the diagnosis and management of CV disease during the COVID-19 pandemic. Link: https://www.escardio.org/Education/COVID-19-and-Cardiology/ESC-COVID-19-Guidance (Last visit: February 24, 2024).
67. Olejnik S, Algina J. Measures of effect size for comparative studies: Applications, interpretations, and limitations. Contemp Educ Psychol. 2000; 25(3):241–86. doi: 10.1006/ceps.2000.1040. PubMed PMID: 10873373.
68. ATS/ACCP. ATS/ACCP Statement on cardiopulmonary exercise testing. Am J Respir Crit Care Med. 2003; 167(2):211–77. doi: 10.1164/rccm.167.2.211. PubMed PMID: 12524257.
69. Ahmed I, Mustafaoglu R, Yeldan I, Yasaci Z, Erhan B. Effect of pulmonary rehabilitation approaches on dyspnea, exercise capacity, fatigue, lung functions, and quality of life in patients with COVID-19: A systematic review and meta-analysis. Arch Phys Med Rehabil.

2022; 103(10):2051–62. Epub 20220729. doi: 10.1016 /j.apmr.2022.06.007. PubMed PMID: 35908659; PubMed Central PMCID: PMC9334878.
70. Al-Mhanna SB, Mohamed M, Noor NM, Afolabi HA, Irekeola AA, Bello KE, et al. Effectiveness of pulmonary rehabilitation among COVID-19 patients: A systematic review and meta-analysis. Healthcare (Basel). 2022; 10(11). Epub 20221026. doi: 10.3390 /healthcare10112130. PubMed PMID: 36360471; PubMed Central PMCID: PMC9691193.
71. Chen H, Shi H, Liu X, Sun T, Wu J, Liu Z. Effect of pulmonary rehabilitation for patients with post-COVID-19: A systematic review and meta-analysis. Front Med (Lausanne). 2022; 9:837420. Epub 20220221. doi: 10.3389/fmed.2022.837420. PubMed PMID: 35265644; PubMed Central PMCID: PMC8899076.
72. Reinert G, Muller D, Wagner P, Martinez-Pozas O, Cuenca-Zaldivar JN, Fernandez-Carnero J, et al. Pulmonary rehabilitation in SARS-CoV-2: A systematic review and meta-analysis of post-acute patients. Diagnostics (Basel). 2022; 12(12). Epub 20221202. doi: 10.3390/diagnostics12123032. PubMed PMID: 36553039; PubMed Central PMCID: PMC9776761.
73. Rosero ID, Barreto J, Cardona C, Ordonez-Mora LT. Physical, functional, psychological, and social effects of a physical activity program in adults and older adults during and/or after hospitalization for COVID-19: A systematic review. Risk Manag Healthc Policy. 2022; 15:2399–412. Epub 20221222. doi: 10.2147/RMHP. S386708. PubMed PMID: 36578453; PubMed Central PMCID: PMC9791952.
74. Seid AA, Aychiluhm SB, Mohammed AA. Effectiveness and feasibility of telerehabilitation in patients with COVID-19: a systematic review and meta-analysis. BMJ open. 2022; 12(10):e063961. Epub 20221005. doi: 10.1136/bmjopen-2022-063961. PubMed PMID: 36198459; PubMed Central PMCID: PMC9534777.
75. Ahmed I, Inam AB, Belli S, Ahmad J, Khalil W, Jafar MM. Effectiveness of aerobic exercise training program on cardio-respiratory fitness and quality of life in patients recovered from COVID-19. Eur J Physiother. 2021:1–6. DOI: 10.1080/21679169.2021.1909649.
76. Spruit MA, Singh SJ, Garvey C, ZuWallack R, Nici L, Rochester C, et al. An official American thoracic society/ European respiratory society statement: key concepts and advances in pulmonary rehabilitation. Am J Respir Crit Care Med. 2013; 188(8):e13–64. doi: 10.1164 /rccm.201309-1634ST. PubMed PMID: 24127811.
77. Shi L, Wang Y, Wang Y, Duan G, Yang H. Dyspnea rather than fever is a risk factor for predicting mortality in patients with COVID-19. J Infect. 2020; 81(4):647–79. Epub 20200515. doi: 10.1016/j.jinf.2020.05.013. PubMed PMID: 32417316; PubMed Central PMCID: PMC7228739.
78. Wong AW, Lopez-Romero S, Figueroa-Hurtado E, Vazquez-Lopez S, Milne KM, Ryerson CJ, et al. Predictors of reduced 6-minute walk distance after COVID-19: a cohort study in Mexico. Pulmonology. 2021; 27(6):563–5. Epub 20210326. doi: 10.1016/j. pulmoe.2021.03.004. PubMed PMID: 33832849; PubMed Central PMCID: PMC7997705.
79. Aladin AI, Whelton SP, Al-Mallah MH, Blaha MJ, Keteyian SJ, Juraschek SP, et al. Relation of resting heart rate to risk for all-cause mortality by gender after considering exercise capacity (the Henry Ford exercise testing project). Am J Cardiol. 2014; 114(11):1701–6. Epub 20140916. doi: 10.1016/j. amjcard .2014.08.042. PubMed PMID: 25439450.
80. Aune D, Sen A, o'Hartaigh B, Janszky I, Romundstad PR, Tonstad S, et al. Resting heart rate and the risk of cardiovascular disease, total cancer, and all-cause mortality – A systematic review and dose-response meta-analysis of prospective studies. Nutr Metab Cardiovasc Dis. 2017; 27(6):504–17. Epub 20170421. doi: 10.1016 /j.numecd.2017.04.004. PubMed PMID: 28552551.
81. Schmidt JF, Hansen PR, Andersen TR, Andersen LJ, Hornstrup T, Krustrup P, et al. Cardiovascular adaptations to 4 and 12 months of football or strength training in 65- to 75-year-old untrained men. Scand J Med Sci Sports. 2014; 24 Suppl 1:86–97. Epub 20140605. doi: 10 .1111/sms.12217. PubMed PMID: 24902992.
82. Greenland P, Daviglus ML, Dyer AR, Liu K, Huang CF, Goldberger JJ, et al. Resting heart rate is a risk factor for cardiovascular and noncardiovascular mortality: the Chicago heart association detection project in industry. Am J Epidemiol. 1999; 149(9):853–62. Epub 1999/04/30. doi: 10.1093 /oxfordjournals.aje.a009901. PubMed PMID: 10221322.
83. Soler X, Diaz-Piedra C, Ries AL. Pulmonary rehabilitation improves sleep quality in chronic lung disease. COPD. 2013; 10(2):156–63. Epub 20130320. doi: 10.3109 /15412555 .2012.729622. PubMed PMID: 23514215.
84. Calvache-Mateo A, Heredia-Ciuro A, Martin-Nunez J, Hernandez- -Hernandez S, Reychler G, Lopez- -Lopez L, et al. Efficacy and safety of respiratory telerehabilitation in patients with long COVID-19: A systematic review and meta-analysis. Healthcare (Basel). 2023; 11(18). Epub 20230912. doi: 10.3390/healthcare11182519. PubMed PMID: 37761716; PubMed Central PMCID: PMC10530340.
85. Lee HM, Le H, Lee BT, Lopez VA, Wong ND. Forced vital capacity paired with Framingham Risk Score for prediction of all-cause mortality. Eur Respir J. 2010; 36(5):1002–6. Epub 20100618. doi: 10.1183/0903 1936.00042410. PubMed PMID: 20562119.
86. Guler SA, Ebner L, Aubry-Beigelman C, Bridevaux PO, Brutsche M, Clarenbach C, et al. Pulmonary function and radiological features 4 months after COVID-19: first results from the national prospective observational Swiss COVID-19 lung study. Eur Respir J. 2021; 57(4). Epub 20210429. doi: 10.1183 /13993003.03690-2020. PubMed PMID: 33419891; PubMed Central PMCID: PMC8082329.
87. Mascha EJ, Vetter TR. Significance, errors, power, and sample size: The blocking and tackling of statistics. Anesth Analg. 2018; 126(2):691–8. Epub 2018/01/19. doi: 10.1213 /ANE.0000000000002741. PubMed PMID: 29346210.
88. Sciurba F, Criner GJ, Lee SM, Mohsenifar Z, Shade D, Slivka W, et al. Six-minute walk distance in chronic obstructive pulmonary disease: reproducibility and effect of walking course layout and length. Am J Respir Crit Care Med. 2003; 167(11):1522–7. Epub 20030220. doi: 10.1164/rccm .200203-166OC. PubMed PMID: 12615634.
89. Brooks D, Solway S, Weinacht K, Wang D, Thomas S. Comparison between an indoor and an outdoor 6-minute walk test among individuals with chronic obstructive pulmonary disease. Arch Phys Med Rehabil. 2003; 84(6):873–6. doi: 10.1016/s0003 -9993(03)00011-x. PubMed PMID: 12808541.
90. Ben Saad H, Ben Hassen I, Ghannouchi I, Latiri I, Rouatbi S, Escourrou P, et al. 6-Min walk-test data in severe obstructive-sleep-apnea-hypopnea-syndrome (OSAHS) under continuous-positive-airway-pressure (CPAP) treatment. Respir Med. 2015; 109(5):642–55. Epub 20150316. doi: 10.1016/j.rmed.2015.03.001. PubMed PMID: 25820157.
91. Troosters T, Hornikx M, Demeyer H, Camillo CA, Janssens W. Pulmonary

rehabilitation: timing, location, and duration. Clin Chest Med. 2014; 35(2):303–11. Epub 20140412. doi: 10.1016/j.ccm.2014.02.002. PubMed PMID: 24874126.
92. American College of Sports M, Chodzko-Zajko WJ, Proctor DN, Fiatarone Singh MA, Minson CT, Nigg CR, et al. American College of Sports Medicine position stand. Exercise and physical activity for older adults. Med Sci Sports Exerc. 2009; 41(7):1510–30. Epub 2009/06/12. doi: 10.1249/MSS .0b013e3181a0c95c. PubMed PMID: 19516148.
93. Yaddanapudi LN. The American Statistical Association statement on P-values explained. J Anaesthesiol Clin Pharmacol. 2016; 32(4):421–3. Epub 2017/01/18. doi: 10.4103/0970 -9185.194772. PubMed PMID: 28096569; PubMed Central PMCID: PMC5187603.
94. Hojat M, Xu G. A visitor's guide to effect sizes: statistical significance versus practical (clinical) importance of research findings. Adv Health Sci Educ Theory Pract. 2004; 9(3):241–9. doi: 10.1023/B:AHSE .0000038173 .00909.f6. PubMed PMID: 15316274.
95. Schober P, Bossers SM, Schwarte LA. Statistical significance versus clinical importance of observed effect sizes: What do p values and confidence intervals really represent? Anesth Analg. 2018; 126(3):1068–72. doi: 10.1213/ANE .0000000000002798. PubMed PMID: 29337724; PubMed Central PMCID: PMC5811238.
96. Williams B, Mancia G, Spiering W, Agabiti Rosei E, Azizi M, Burnier M, et al. 2018 ESC/ESH guidelines for the management of arterial hypertension: The task force for the management of arterial hypertension of the European society of cardiology and the European society of hypertension. J Hypertens. 2018; 36(10):1953–2041. doi: 10.1097/HJH.000000000000 1940. PubMed PMID: 30234752.
97. Imamura S, Inagaki T, Abe M, Terada J, Kawasaki T, Nagashima K, et al. Impaired dynamic response of oxygen saturation during the 6-min walk test is associated with mortality in chronic fibrosing interstitial pneumonia. Respir Care. 2023; 68(3):356–65. doi: 10.4187/respcare.10231. PubMed PMID: 36828581; PubMed Central PMCID: PMC10027139.
98. Maniscalco M, Fuschillo S, Ambrosino P, D'Anna SE, Accardo MS, Matera MG, et al. Bronchodilator response as a possible predictor of lung function improvement after pulmonary rehabilitation in post-COVID-19 patients. Arch Bronconeumol. 2022; 58(6):517–9. Epub 20210618. doi: 10.1016/j.arbres.2021.06.004. PubMed PMID: 34219862; PubMed Central PMCID: PMC8233876.
99. Torres-Castro R, Vasconcello-Castillo L, Alsina-Restoy X, Solis-Navarro L, Burgos F, Puppo H, et al. Respiratory function in patients post-infection by COVID-19: a systematic review and meta-analysis. Pulmonology. 2021; 27(4):328–37. Epub 20201125. doi: 10.1016/j.pulmoe.2020.10.013. PubMed PMID: 33262076; PubMed Central PMCID: PMC7687368.
100. Dergaa I, Chamari K, Zmijewski P, Ben Saad H. From human writing to artificial intelligence generated text: examining the prospects and potential threats of ChatGPT in academic writing. Biol Sport. 2023; 40(2):615–22. Epub 20230315. doi: 10.5114/biolsport.2023.125623. PubMed PMID: 37077800; PubMed Central PMCID: PMC10108763.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.139074
© Institute of Sport – National Research Institute

Current practices in physical fitness assessment and monitoring among coaches of individual and team sports: a survey in Portugal, Spain, and Romania

AUTHORS: XiaoYuan Wen[1], Rui Miguel Silva[2,3], Qi Xu[4], Francisco Tomás González-Fernández[5], Ana Filipa Silva[2,3], Georgian Badicu[6], Xiaodan Guo[4], Filipe Manuel Clemente[2,3,4]

[1] ChengDu Sports Univ, Chengdu 610041, Peoples R China
[2] Research Center in Sports Performance, Recreation, Innovation and Technology (SPRINT), 4960-320 Melgaço, Portugal
[3] Escola Superior Desporto e Lazer, Instituto Politécnico de Viana do Castelo, Rua Escola Industrial e Comercial de Nun'Álvares, 4900-347 Viana do Castelo, Portugal
[4] Gdansk University of Physical Education and Sport, 80-336 Gdańsk, Poland
[5] Department of Physical and Sports Education, Faculty of Education and Sports Sciences, Melilla Campus, University of Granada, 52006 Melilla, Spain
[6] Department of Physical Education and Special Motricity, Transilvania University of Brasov, 500068 Brasov, Romania

ABSTRACT: The objective of this study was to characterize surveyed coaches and elucidate the practices of physical fitness assessment and monitoring for both male and female athletes across three countries. A total of 165 coaches participated by completing a comprehensive 32-question survey. Pre-season assessments are a priority for coaches, with a significant range from 60.5% to 87.7% in Romania, while Portuguese and Spanish coaches tend to prefer testing during the competition (26.3% and 16.9%, respectively). Portuguese and Spanish coaches predominantly favor aerobic tests (50% and 46.8% respectively), whereas Romanian coaches exhibit a preference for sprint (56.9%) and skill tests (52.3%). Notably, change of direction tests are less commonly employed, ranging from 10.5% to 21% across the countries. In terms of exercise intensity determination, Portuguese coaches predominantly employ maximal heart rate (31.6%), while Spanish coaches often rely on the 220-age formula or perceived exertion (27.4%). For strength assessment, Portuguese coaches lean towards direct (34.2%) or estimated (31.6%) maximal repetition methods. When it comes to maximal speed sprint, Portuguese and Romanian coaches show preference (50% and 43.1% respectively), while Spanish coaches exhibit a relative lack of emphasis on individualized speed measures (37.1%). Perceptual scales are the preferred method for recovery monitoring, with adoption rates of 57.9% in Portugal, 53.2% in Spain, and 44.6% in Romania. In summary, this study underscores the distinct assessment and monitoring practices employed by coaches in Portugal, Spain, and Romania. These findings are in alignment with established literature standards, highlighting the diversity of approaches used in different countries.

CITATION: Wen XY, Silva RM, Xu Q et al. Current practices in physical fitness assessment and monitoring among coaches of individual and team sports: a survey in Portugal, Spain, and Romania. Biol Sport. 2024;41(4):219–230.

Received: 2023-08-17; Reviewed: 2023-12-07; Re-submitted: 2023-12-07; Accepted: 2024-03-24; Published: 2024-04-25.

Corresponding author:
Filipe Manuel Clemente
Research Center in Sports Performance, Recreation, Innovation and Technology (SPRINT), 4960-320 Melgaço Portugal
E-mail: filipeclemente@esdl.ipvc.pt

ORCID:
XiaoYuan Wen
0009-0005-4016-140

Rui Miguel Silva
0000-0003-3380-864X

Qi Xu
0009-0002-8801-3203

Francisco Tomás González-Fernández
0000-0002-1480-7521

Ana Filipa Silva
0000-0002-1772-1272

Georgian Badicu
0000-0003-4100-8765

Filipe Manuel Clemente
0000-0001-9813-2842

Key words:
Training monitoring
Recovery
Well-being
Athletic performance
Sports training

INTRODUCTION

The implementation of periodic assessments and monitoring practices allows coaches and practitioners to evaluate athletes' overall physical fitness status, and how they are coping with the training process [1]. The periodic assessments focus on quantifying and qualifying the athletes' anthropometric characteristics, body composition, physical qualities, technical capacities, and tactical behaviors. On the other hand, monitoring allows for a comprehensive picture regarding the responses to the imposed external training loads, such as objective and subjective measures of training intensity, well-being, and readiness [2]. By conducting periodic assessments and monitoring, coaches can identify immediate and long-term responses to training, adjusting training according to the athlete's individual needs.

Different laboratory- and field-based tests are available to assess the physical fitness status of athletes [3, 4]. However, in the overall sports setting, implementing laboratory tests can be challenging due to logistical and time constraints. Therefore, previous studies have recommended the use of a field-based testing battery specifically designed for youth and adult sports contexts [5, 6]. Before selecting which tests to include in the battery, a needs analysis should be conducted to determine the specific physical and physiological demands of the sport. Moreover, conducting physical fitness tests at a single

time point is insufficient for providing a comprehensive evaluation of an athlete's overall fitness levels [6]. To comprehensively understand an athlete's physical capabilities, it's crucial to regularly conduct periodic fitness assessments [3].

Training monitoring practices play a crucial role in optimizing athlete performance and minimizing the risk of injuries. Understanding sports training load involves breaking it down into two main components: internal and external sports training load [7]. External sports load encompasses measurable training demands like distance covered, sprint distance, and accelerations [8]. Conversely, internal sports training load refers to physiological and psychological responses, including heart rate, perceived exertion, well-being, and readiness [9]. Coaches must also consider individual differences, such as fitness level, age, sex, and injury history, to tailor training programs effectively [10].

In soccer, monitoring practices are particularly prevalent, aiming to track player training load, recovery, and injury risk [11]. Various technologies, including GPS, heart rate monitors, and accelerometers, are utilized to measure different aspects of player performance and health [12]. A recent study delved into the training load monitoring practices and perceptions of coaches and practitioners in elite soccer [13]. Surveying 118 participants, the above-mentioned study found a general consensus on the importance of training load monitoring, despite some discrepancies in practices and perceptions. Coaches often relied on subjective measures like RPE, while practitioners preferred objective measures such as GPS and heart rate monitoring [13]. Additionally, a comprehensive review investigated training monitoring methods across sports, revealing a lack of consensus among coaches and practitioners who employed a wide range of approaches [14].

While some studies have explored strength and conditioning coaches' methodologies in various sports [15–17], these primarily characterize common practices without delving into specific monitoring approaches. Notably, existing research on training monitoring practices is limited, with a predominant focus on soccer [18]. Other studies aimed at developing monitoring guidelines lack a comprehensive survey of practices and needs across diverse sports [19]. Only one systematic review has investigated monitoring practices, but it included studies of different designs without coach surveys [14]. Similarly, only one study, confined to football, surveyed coaches on periodic assessment practices [13]. The present study addresses these critical gaps by providing a comprehensive survey-based exploration of periodic assessment and monitoring practices across diverse sports.

Given that, the present study aimed to survey several coaches from a broad range of both individual and collective sports with certified credentials from their respective sports federations, to: (i) characterize the population of surveyed coaches; (ii) describe the implemented periodic assessments; and (iii) describe the implemented monitoring by sports coaches of male and female athletes from different sports.

MATERIALS AND METHODS

Study design

This study employed a descriptive cross-sectional research design to investigate and provide comprehensive insights into the prevailing practices of sports coaches concerning the implementation of periodic assessments and training monitoring procedures. Participants, spanning various coaching roles (head coaches, assistant coaches, sports scientists, strength and conditioning coaches, and physical trainers), were recruited from three distinct countries, representing diverse sports disciplines. The study aimed to gather detailed insights into how coaches currently employ periodic assessments and training monitoring in different sports contexts, with a focus on understanding predominant trends and methodologies.

Setting

A survey was conducted online using Google Forms and distributed via email to all the coaches participating in this study. Coaches of any gender, age group, or academic level were considered eligible for inclusion. There were no limitations to the fact that they currently exercise functions. Any sports coach of any nationality was considered eligible for the study, as long as they held a professional license validated by their respective sport's official federation. The present study followed the ethical recommendations for the study in humans as suggested by the Declaration of Helsinki (updated version from 2013).

Participants

A total of 165 coaches participated in the present study. 38 coaches from Portugal, 62 from Spain, and 65 from Romania responded to the survey. All coaches provided informed consent to initiate the anonymous online survey, and only fully completed surveys were used for analyses. Also, the anonymity and confidentiality of your data will be ensured and maintained, and it is an obligation to guarantee confidentiality and the researchers' duty of secrecy towards the subject evaluated. An anonymous report was produced to provide global information on the evaluation processes and training control carried out by all participating sports coaches, and the participants could request the reports. The participation was completely voluntary, and if at any time during the course of the study any participant considered that any intervention/question put them in an uncomfortable situation, they could leave the questionnaire without having to justify themselves. The study received approval from the Ethics Committee for Social Sciences, Life, and Health at Instituto Politécnico de Viana do Castelo, under reference number 4/A/2023.

Table 1 provides an overview of the participants' characteristics and backgrounds, including their academic qualifications, certificate levels in sports coaching, experience, and the competitive levels in which they are currently involved.

Table 2 provides an overview of the different sports the surveyed coaches participate in.

Table 1. Demographic characterization of survey respondents.

	Portuguese	Portuguese	Spanish	Spanish	Romanian	Romanian
	Men (N = 31)	Women (N = 7)	Men (N = 55)	Women (N = 7)	Men (N = 41)	Women (N = 9)
Age						
18–25 years old	1 (3.2%)	0 (0%)	16 (29.1%)	1 (14.3%)	0 (0%)	4 (16.7%)
26–30 years old	1 (3.2%)	1 (14.3%)	10 (18.2%)	1 (14.3%)	3 (7.3%)	1 (4.2%)
31–35 years old	2 (6.5%)	0 (0%)	6 (10.9%)	4 (57.1%)	5 (12.2%)	0 (0%)
36–40 years old	4 (12.9%)	0 (0%)	6 (10.9%)	0 (0%)	9 (22.0%)	2 (8.3%)
41–45 years old	5 (16.1%)	2 (28%)	5 (9.1%)	0 (0%)	8 (19.5%)	8 (33.3%)
46–50 years old	4 (12.9%)	0 (0%)	5 (9.1%)	0 (0%)	3 (7.3%)	3 (12.5%)
51–55 years old	4 (12.9%)	3 (42.9%)	6 (10.9%)	0 (0%)	5 (12.2%)	5 (20.8%)
> 55 years old	10 (32.3%)	1 (14.3%)	1 (1.8%)	1 (14.3%)	8 (19.5%)	1 (4.2%)
Education						
Basic education	0 (0%)	0 (0%)	2 (3.6%)	0 (0%)	0 (0%)	0 (0%)
Secondary school	10 (32.3%)	0 (0%)	8 (14.5%)	0 (0%)	2 (4.9%)	0 (0%)
Graduation	14 (45.2%)	3 (42.9%)	34 (61.8%)	3 (42.9%)	13 (31.7%)	8 (33.3%)
Master degree	6 (19.4%)	2 (28.6%)	7 (12.7%)	2 (28.6%)	23 (56.1%)	14 (58.3)
Ph.D. degree	1 (3.2%)	2 (28.6%)	4 (7.3%)	2 (28.6%)	3 (7.3%)	2 (8.3%)
Role in sports						
Head coach	28 (90.3%)	3 (42.9%)	38 (69.1%)	5 (71.4%)	33 (80.5%)	15 (62.5%)
Assistant coach	1 (3.2%)	1 (14.3%)	5 (9.1%)	0 (0%)	0 (0%)	3 (12.5%)
Physical trainer	1 (3.2%)	0 (0%)	5 (9.1%)	1 (14.3%)	1 (2.4%)	0 (0%)
Physiologist	1 (3.2%)	1 (14.3%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Match analyst	0 (0%)	0 (0%)	1 (1.8%)	0 (0%)	0 (0%)	0 (0%)
Other	0 (0%)	2 (28.6%)	6 (10.9%)	1 (14.3%)	7 (17.1%)	6 (25.0%)
License level						
Without level	0 (0%)	9 (0%)	9 (16.4%)	1 (14.3%)	0 (0%)	0 (0%)
Level I	4 (12.9%)	3 (42.9%)	20 (36.4%)	0 (0%)	19 (46.3%)	7 (29.2%)
Level II	11 (35.5%)	3 (42.9%)	11 (20.0%)	4 (57.1%)	11 (26.8%)	2 (8.3%)
Level III	14 (45.2%)	1 (14.3%)	15 (27.3%)	2 (28.6%)	6 (14.6%)	10 (41.7%)
Level IV	2 (6.5%)	0 (0%)	0 (0%)	0 (0%)	5 (12.2%)	5 (20.8%)
Experience in coaching						
0–5 years of experience	8 (25.8%)	4 (57.1%)	28 (50.9%)	2 (28.6%)	9 (22.0%)	10 (41.7%)
6–10 years of experience	2 (6.5%)	2 (28.6%)	14 (25.5%)	4 (57.1%)	8 (19.5%)	4(16.7%)
11–15 years of experience	5 (16.1%)	0 (0%)	4 (7.3%)	1 (14.3%)	4 (9.8%)	4 (16.7%)
16–20 years of experience	4 (12.9%)	1 (14.3%)	8 (14.5%)	0 (0%)	4 (9.8%)	3 (12.5%)
21–25 years of experience	5 (16.1%)	0 (0%)	0 (0%)	0 (0%)	5 (12.2%)	2 (8.3%)
> 25 years of experience	7 (22.6%)	0 (0%)	1 (1.8%)	0 (0%)	11 (26.8%)	1 (4.2%)

Periodic assessments and monitoring survey

A survey was developed exclusively for this research project. Initially, the key domains and questions about periodic assessments and monitoring were formulated. This process involved collaborative efforts from three researchers, who based the questions on existing literature related to the subject [6, 14, 20–23]. To ensure the survey's quality and validity, it underwent evaluation by three independent academic experts in periodic assessments and monitoring, all of whom were highly esteemed researchers according to ExpertScape. These experts had published a minimum of three recent papers on the subject. Their valuable feedback and comments on the wording and structure of the questions were thoughtfully considered, leading to revisions and reorganization of the survey. The main recommendations from experts emphasized the inclusion of specific practical

Table 2. Sports of the surveyed coaches.

Sports	Portuguese (n = 38)	Spanish (n = 62)	Romanian (n = 65)
Handball	8 (21.1%)	0 (0%)	11 (16.9%)
Canoeing	6 (15.8%)	0 (0%)	0 (0%)
Gymnastics	0 (0%)	1 (1.6%)	5 (7.7%)
Golf	1 (2.6%)	0 (0%)	0 (0%)
Judo	2 (5.3%)	0 (0%)	4 (6.2%)
Swimming	2 (5.3%)	0 (0%)	5 (7.7%)
Skating	0 (0%)	0 (0%)	3 (4.6%)
Tennis	0 (0%)	0 (0%)	2 (3.1%)
Basketball	2 (5.3%)	1 (1.6%)	6 (9.2%)
Motorsports	0 (0%)	0 (0%)	1 (1.5%)
Climbing	0 (0%)	0 (0%)	4 (6.2%)
Futsal	1 (2.6%)	1 (1.6%)	0 (0%)
Orientation	0 (0%)	0 (0%)	1 (1.5%)
Rowing	2 (5.3%)	0 (0%)	0 (0%)
Table tennis	1 (2.6%)	0 (0%)	0 (0%)
Chess	0 (0%)	0 (0%)	1 (1.5%)
Athletics	2 (5.3%)	1 (1.6%)	2 (3.1%)
Adapted sports	1 (2.6%)	0 (0%)	0 (0%)
Fencing	0 (0%)	0 (0%)	2 (3.1%)
Rink hockey	1 (2.6%)	0 (0%)	0 (0%)
Paddle tennis	0 (0%)	1 (1.6%)	0 (0%)
Martial arts	0 (0%)	0 (0%)	3 (4.6%)
Archery	2 (5.3%)	0 (0%)	0 (0%)
Soccer	4 (10.5%)	57 (91.9%)	14 (21.5%)
Volleyball	3 (7.9%)	0 (0%)	1 (1.5%)

scenarios clarifying the context in which monitoring processes took place.

Following these modifications, the refined survey was then distributed to three additional experts, all of whom were experienced coaches holding a minimum level II coaching license and possessing an academic background in the field. Their input and feedback played a vital role in further refining the survey. After incorporating the valuable suggestions from both the academic experts and coaches, the final version of the survey was once again sent to the initial three independent academic experts for their evaluation. Upon receiving their approval, the definitive survey, presented as a supplementary file, was launched online through Google Forms.

Before proceeding with the survey, participants were provided with a clear explanation of its aim, research design, and assurances concerning anonymity, confidentiality, and data protection. Participants voluntarily confirmed their willingness to participate and provided their consent to proceed with the questionnaire. The survey consisted of 32 closed-ended questions (no scales used). Five sections were included as follows (see supplementary material): (i) study information; (ii) personal and academic information; (iii) coaching experience; (iv) implementation of periodic assessments; (v) implementation of monitoring practices. An investment of 15 minutes was estimated to complete the questionnaire.

Data acquisition and statistical procedures

The data acquired from the Google Forms survey was exported and consolidated into an Excel file for subsequent analysis. As all the questions required mandatory responses, there were no missing cases, and consequently, all the items were deemed valid upon inspection. Closed-ended questions were subjected to a frequency analysis, chosen for their ability to provide a systematic and comprehensive examination of the distribution and occurrence of various response options. This quantitative assessment, through frequency analysis, offers a clear understanding of the participants' choices and preferences within the predefined response categories, allowing for a straightforward interpretation of the data. Frequency analysis was deemed particularly suitable for capturing the prevalence of specific responses, a key aspect in exploring the prevailing trends and patterns in coaches' practices.

RESULTS

Table 3 describes the characterization of the application of physical fitness, and technical and tactical periodic assessments. Based on survey results, player assessments are most frequently conducted during pre-season, ranging from 60.5% in Portugal to 87.7% in Romania. In Portugal, only 26.3% of coaches assess players during the season, while in Romania and Spain, the percentages are 16.9% and 45.2%, respectively. A noteworthy observation is that a small percentage of coaches in Portugal and Spain (13.2% and 14.5%, respectively) reported never assessing players, and in Romania, the percentage was even lower at 4.6%.

The majority of responders in Portugal and Spain reported assessing players three times a year, accounting for 28.9% and 35.5%, respectively. Conversely, in Romania, the majority reported assessing players twice a year, constituting 29.2%.

The frequency of player assessments varied among responders across countries. In Romania, most responders reported monthly testing, while in Portugal and Spain, the majority indicated assessments every three months, with percentages of 34.2% in Portugal and 29% in Spain.

Differences in the types of tests used by coaches for measuring athlete performance emerged across countries. In Portugal and Spain, the majority preferred tests for measuring aerobic performance, with percentages of 50% and 46.8%, respectively. In Romania, responders were more focused on Sprint tests (56.9%) and skill tests (52.3%). Notably, change-of-direction tests were the least employed across all three countries, with percentages varying from 10.5% in Portugal to 21% in Spain and 18.5% in Romania.

Table 3. Characterization of the application of physical fitness, technical and tactical periodic assessments

	Portuguese (n = 38)	Spanish (n = 62)	Romanian (n = 65)
When do you apply physical, technical, and/or tactical assessment tests?			
During the pre-season	23 (60.5%)	46 (74.2%)	57 (87.7%)
During the competitive season	10 (26.3%)	28 (45.2%)	11 (16.9%)
After the season	0 (0%)	12 (19.4%)	7 (10.8%)
Never	5 (13.2%)	9 (14.5%)	3 (4.6%)
How many times do you apply physical, technical, and/or tactical tests during the sports season?			
0	6 (15.8%)	8 (12.9%)	12 (18.5%)
1	3 (7.9%)	7 (11.3%)	9 (13.8%)
2	8 (21.1%)	10 (16.1%)	19 (29.2%)
3	11 (28.9%)	22 (35.5%)	7 (10.8%)
4	2 (5.3%)	3 (4.8%)	11 (16.9%)
5	3 (7.9%)	6 (9.7%)	0 (0%)
6	2 (5.3%)	0 (0%)	1 (1.5%)
7	3 (7.9%)	0 (0%)	1 (1.5%)
8	0 (0%)	1 (1.6%)	1 (1.5%)
> 9	3 (7.9%)	5 (9.1%)	4 (6.2%)
All the sessions			
What is the frequency with which you apply physical, technical, and/or tactical tests during the sports season?			
Never	7 (18.4%)	10 (16.1%)	6 (9.2%)
Monthly	5 (13.2%)	10 (16.1%)	26 (40.0%)
Every two months	6 (15.8%)	10 (16.1%)	8 (12.3%)
Every three months	13 (34.2%)	18 (29.0%)	8 (12.3%)
Every four months	1 (2.6%)	8 (12.9%)	1 (1.5%)
Every five months	1 (2.6%)	2 (3.2%)	2 (3.1%)
Every six months	5 (13.2%)	4 (6.5%)	14 (21.5%)
Which of the following tests do you use in the implementation of periodic assessment for your athletes?			
None	6 (15.8%)	11 (17.7%)	1 (1.5%)
Anthropometry and body composition	17 (44.7%)	12 (19.4%)	21 (32.3%)
Maximum strength and power	19 (50.0%)	20 (32.3%)	20 (30.8%)
Muscular endurance	12 (31.6%)	18 (29.0%)	11 (16.9%)
Aerobic	19 (50.0%)	29 (46.8%)	26 (40%)
Anaerobic	13 (34.2%)	22 (35.5%)	19 (29.2%)
Speed and/or acceleration	15 (39.5%)	25 (40.3%)	37 (56.9%)
Change of direction	4 (10.5%)	13 (21.0%)	12 (18.5%)
Agility	7 (18.4%)	12 (19.4%)	17 (26.2%)
Mobility, stability, and/or flexibility	9 (23.7%)	14 (22.6%)	14 (21.5%)
Motor coordination	8 (21.1%)	13 (21.0%)	20 (30.8%)
Specific technical skills	16 (42.1%)	19 (30.6%)	34 (52.3%)
Specific tactical behaviors	5 (13.2%)	14 (22.6%)	17 (26.2%)

Table 4 characterizes the implementation by coaches of the most common measures used in practice. In Portugal, 31.6% of responders favored using maximal heart rate in field-based tests, while in Spain, the majority preferred the formula 220-age or the rate of perceived exertion (27.4%). In Romania, 26.9% reported utilizing training heart rate (maximal heart rate minus recovery heart rate) to estimate exercise intensity.

Table 4. Characterization of the periodic assessment measures used for practice.

	Portuguese (n = 38)	Spanish (n = 62)	Romanian (n = 65)
How do you determine the intensity in the context of aerobic/anaerobic training?			
I don't determine	8 (21.1%)	18 (29%)	13 (20%)
Based on maximum heart rate	12 (31.6%)	8 (12.9%)	16 (24.6%)
Based on estimated maximum heart rate (e.g., 220-age)	10 (26.3%)	17 (27.4%)	16 (24.6%)
Based on training heart rate (considering both maximum and resting heart rates)	8 (21.1%)	11 (17.7%)	24 (36.9%)
Based on maximum oxygen volume measured through spirometry	2 (5.3%)	1 (1.6%)	2 (3.1%)
Based on estimated maximum oxygen volume in field tests	3 (7.9%)	0 (0%)	2 (3.1%)
Based on blood lactate levels	5 (13.2%)	4 (6.5%)	5 (7.7%)
Based on subjective perception of effort	7 (18.4%)	17 (27.4%)	5 (7.7%)
Based on maximum aerobic speed (measured with spirometry)	2 (5.3%)	0 (0%)	2 (3.1%)
Based on estimated maximum aerobic speed in field tests	3 (7.9%)	4 (6.5%)	7 (10.8%)
Based on anaerobic speed reserve	3 (7.9%)	1 (1.6%)	1 (1.5%)
How do you determine intensity in strength training?			
I don't determine	9 (23.7%)	24 (38.7%)	23 (35.4%)
Estimation of one-repetition maximum (indirect method)	12 (31.6%)	9 (14.5%)	13 (20%)
One-repetition maximum	13 (34.2%)	9 (14.5%)	14 (21.5%)
Determination of the force-velocity curve	8 (21.1%)	8 (12.9%)	10 (15.4%)
Utilization of perceived methods (e.g., perceived exertion, repetitions in reserve)	5 (13.2%)	13 (21%)	7 (10.8%)
Training to failure	4 (10.5%)	5 (8.1%)	3 (4.6%)
Trial and error	3 (7.9%)	3 (4.8%)	0 (0%)
How do you determine intensity in the context of speed training?			
I don't determine	17 (44.7%)	23 (37.1%)	11 (16.9%)
Based on maximum running speed	19 (50%)	19 (30.6%)	28 (43.1%)
Based on strength-speed profile	6 (15.8%)	22 (35.5%)	28 (43.1%)
Do you use the assessment results in your training programming practice to direct the focus of training?			
No	4 (10.5%)	15 (24.2%)	8 (12.3%)
Yes, in the case of physical qualities	24 (63.2%)	35 (56.5%)	44 (67.7%)
Yes, in the case of technical skills	19 (50%)	22 (35.5%)	31 (47.7%)
Yes, in the case of tactical behaviors	6 (15.8%)	22 (35.5%)	20 (30.8%)
If you do not use assessments as markers for training programming, this is due to:			
Not all tests are capable of providing information to adjust training	13 (34.2%)	29 (46.8%)	15 (23.1%)
Technically, I am unable to interpret the obtained values and convert them for programming	6 (15.8%)	15 (24.2%)	14 (21.5%)
I only use the data to assess the athletes' condition	19 (50%)	18 (29%)	36 (55.4%)

Differences in methods for standardizing the intensity of strength training were evident. In Portugal, responders predominantly used direct maximal repetition (34.2%) or estimated maximal repetition (31.6%). In Spain and Romania, the majority reported not using any measure for standardization, with percentages of 38.7% in Spain and 35.4% in Romania.

Regarding speed training, in Portugal, 50% of responders reported using maximal speed sprint for standardization, while in Romania, it was either maximal speed sprint (43.1%) or force-velocity profile (43.1%). In Spain, 37.1% reported not using any measure for individualizing speed training.

Across all countries, a majority of responders (63.2% in Portugal, 56.5% in Spain, and 67.7% in Romania) used physical fitness test results to plan training. However, disparities emerged in the use of tactical behaviors. In Portugal, only 15.8% used tactical behaviors for planning, while in Spain and Romania, higher percentages

of responders reported using tactical behaviors, with percentages of 35.5% in Spain and 30.8% in Romania.

Reasons for not using player assessments to individualize training varied. In Portugal and Romania, the major reason (50% and 55.4%, respectively) was using assessments solely for player status. In Spain, 46.8% reported not using assessments because not all could be applied to individualize training. Additionally, 15.8% in Portugal and 24.2% in Spain cited a lack of technical knowledge to interpret assessment values, emphasizing the need for coach education and development in interpreting and applying assessment results to individualize training programs.

Table 5 describes the implementation monitoring practices of coaches. In Spain, a majority (59.7%) reported no use of these monitoring tools in either training or matches. Conversely, in Portugal and Romania, the majority reported using these tools exclusively in training sessions, with percentages of 39.5% in Portugal and 52.3% in Romania.

Differences in monitoring tools for controlling training intensity were evident. In Spain, 50% of responders reported no use of any monitoring tools for controlling training intensity. In Portugal and Romania, the majority used heart rate, with percentages of 28.9% and 32.3%, respectively. Both Portugal and Spain reported using rate of perceived exertion, with percentages of 26.3% in Portugal and 21% in Spain, while in Romania, only 12.3% of responders used these scales. These findings indicate a lack of consistency in the use of monitoring tools for controlling training intensity among coaches across countries and contexts.

Variations were observed in the instruments used for measuring technical/tactical behavior in training. In Spain, 56.5% reported using observational tools, while in Portugal, the majority also reported using observational tools (31.6%). In Romania, the majority used kinematic analysis (38.5%), with a significant implementation in Portugal (28.9%). However, only 11.3% of responders in Spain reported using kinematic analysis.

Differences in the use of instruments for measuring intensity in competition were noted. The majority of coaches in Portugal, Spain, and Romania reported not using instruments for measuring intensity in competition (39.5%, 45.2%, and 44.6%, respectively). Among those using such instruments, perceptive scales were predominant in Portugal and Spain (31.6% and 25.8%, respectively), while in Romania, 20% used heart rate monitors.

Similarities and differences emerged in the use of monitoring tools for technical/tactical performance. Observational analysis was the primary tool in all three countries, with percentages of 39.5% in Portugal, 53.2% in Spain, and 44.6% in Romania. In Romania, a significant percentage (47.7%) reported using kinematic analysis in competition, while in Portugal, 28.9% used it, and in Spain, only 19.4% reported its use.

Similarities and differences were also observed in the use of instruments/measures for monitoring recovery status. The majority in Portugal (57.9%), Spain (53.2%), and Romania (44.6%) used well-being perceptive scales. Additionally, in Portugal and Romania, the second most used instrument/measure was heart rate variability, with percentages of 31.6% and 33.8%, respectively. In Spain, a higher percentage (41.9%) of responders used heart rate variability.

DISCUSSION

The aim of this study was to outline the methods of periodic assessments and monitoring that sports coaches employ across various sports in European countries. Among the participating coaches from the three nations, a predominant male representation was observed, with Spain exhibiting the highest male demographic. A majority of coaches held a bachelor's degree, with a subset possessing master's degrees, particularly evident in Romania. Principal roles within coaching were led by head coaches across all nations, while ancillary positions such as physiologists and match analysts exhibited modest engagement. Coaching tenure was primarily within the 0–5 year range, except in Portugal where some coaches demonstrated greater experience.

Notably, the evaluation of players predominantly occurred during the pre-season phase, although variations existed among the surveyed countries. Spain and Portugal favored maximal heart rate assessments, while Romania demonstrated a preference for sprint and skill evaluations. Importantly, outcomes of physical fitness tests played a pivotal role in the formulation of training programs. The incorporation of monitoring tools, encompassing training load and well-being indicators, was most prominent during training sessions in Portugal and Romania. In contrast, a notable proportion of Spanish coaches abstained from employing such tools. The preferred methodology for monitoring remained rooted in perceptual scales, while Romanian coaches indicated the use of heart rate monitors as an adjunct approach.

The following discussion delves into two key aspects of our study results: (i) a comparison of the periodic assessments and monitoring practices used in sports with the existing literature, and (ii) whether coaches are utilizing periodic assessment tests and monitoring tools that are established as both valid and reliable.

Periodic Assessments

Are coaches aligning with literature suggestions in their implementation of periodic assessment practices?

Considering the current practices of physical fitness testing in sports, a recent study surveyed fifty-two sports scientists from professional soccer leagues across 18 countries [23]. The authors revealed that 58% of sports scientists and coaches incorporated physical fitness assessments during the pre-season, 42% during the in-season, and 4% during the off-season [23]. Another study that surveyed 156 strength and conditioning coaches (SCCs) from different sports, countries, and expertise levels, showed that 94% of the coaches conducted periodic assessments [24]. Predominant testing times were year-round (54%), pre-season (46%), off-season (30%), in-season (18%), and training camp (10%) [24].

Table 5. Characterization of the monitoring practices.

	Portuguese (n = 38)	Spanish (n = 62)	Romanian (n = 65)
When do you apply effort monitoring systems (e.g., RPE, HR, GPS) and/or well-being (e.g., sleep quality, DOMS, stress, fatigue)?			
Never	14 (36.8%)	37 (59.7%)	17 (26.2%)
On training days	15 (39.5%)	16 (25.8%)	34 (52.3%)
On match/game days	1 (2.6%)	6 (9.7%)	9 (13.8%)
Every day of the week	8 (21.1%)	5 (8.1%)	10 (15.4%)
What instruments do you use to analyze effort during exercise/training?			
I do not use	11 (29.8%)	31 (50.0%)	20 (30.8%)
Subjective perception of effort scales	10 (26.3%)	13 (21.0%)	8 (12.3%)
GPS and/or IMU	4 (10.5%)	8 (12.9%)	7 (10.8%)
Heart rate monitors	11 (28.9%)	10 (16.1%)	21 (32.2%)
Gas analyzer (spirometry)	0 (0%)	0 (0%)	0 (0%)
Lactate analyzer	1 (2.6%)	0 (0%)	3 (4.6%)
Kinematic systems (multiple cameras; smartphone)	1 (2.6%)	0 (0%)	6 (9.2%)
What instruments do you use to analyze the technical/tactical performance in exercise/training?			
I do not use	11 (28.9%)	18 (29.0%)	13 (20.0%)
Kinematic analysis systems (e.g., cameras)	11 (28.9%)	7 (11.3%)	25 (38.5%)
Observational and notational systems	12 (31.6%)	35 (56.5%)	24 (36.9%)
GPS (Global Positioning System) systems	4 (10.5%)	2 (3.2%)	3 (4.6%)
What instruments do you use to analyze effort during competition?			
I do not use	15 (39.5%)	28 (45.2%)	29 (44.6%)
Subjective perception of effort scales	12 (31.6%)	16 (25.8%)	7 (10.8%)
GPS and/or IMU	6 (15.8%)	9 (14.5%)	5 (7.7%)
Heart rate monitors	4 (10.5%)	7 (11.3%)	13 (20.0%)
Gas analyzer (spirometry)	0 (0%)	0 (0%)	0 (0%)
Lactate analyzer	0 (0%)	0 (0%)	4 (6.2%)
Kinematic systems (multiple cameras)	1 (2.6%)	2 (3.2%)	7 (10.8%)
What instruments do you use to analyze technical/tactical performance during competitions?			
I do not use	9 (23.7%)	20 (32.3%)	13 (20%)
Kinematic systems (multiple cameras)	11 (28.9%)	12 (19.4%)	31 (47.7%)
Observational and notational systems	15 (39.5%)	33 (53.2%)	29 (44.6%)
GPS systems	3 (7.9%)	4 (6.5%)	2 (3.1%)
What instruments/measures do you use to analyze recovery?			
Heart rate variability with heart rate monitors	12 (31.6%)	26 (41.9%)	22 (33.8%)
Blood markers	1 (2.6%)	0 (0%)	1 (1.5%)
Submaximal tests	1 (2.6%)	0 (0%)	3 (4.6%)
Saliva analysis	0 (0%)	0 (0%)	1 (1.5%)
Neuromuscular tests	2 (5.3%)	3 (4.8%)	9 (13.8%)
Well-being questionnaires	22 (57.9%)	33 (53.2%)	29 (44.6%)

RPE: rate of perceived exertion; HR: heart rate; GPS: global positioning systems; IMU: inertial measurement unit; DOMS: delayed onset muscle soreness

These findings align with our survey, where the majority of coaches emphasize pre-season player assessments, ranging from 60.5% in Portugal to 87.7% in Romania. Conversely, in Portugal, only 26.3% assess players during the competitive season, while Romania and Spain are at 16.9% and 45.2%. A smaller portion of coaches in Portugal and Spain (13.2% and 14.5% respectively) abstain from player assessments. Romania's non-assessment rate is even lower, at 4.6%. These findings highlight varied player assessment methods across countries. Some coaches focus on pre-season assessments, while others assess throughout the season [6, 25]. Consistent player assessment is essential for effective coaching, enabling the identification of strengths, tracking development, and adjusting strategies.

Among those who implemented physical fitness tests throughout the sports season, it was previously shown that the majority of coaches working in professional sports contexts from different modalities, included cardiorespiratory tests (92%), strength tests (81%), power tests (62%), linear speed tests (81%), acceleration tests (56%), change of direction (COD) tests (40%), and anaerobic capacity tests (31%) [23]. Our survey results revealed a similar trend at a lower extent in performance test preferences among coaches from the included countries. For instance, Portugal and Spain favored aerobic tests (50% and 46.8% respectively), while Romania leaned towards Sprint (56.9%) and skill tests (52.3%). COD tests were least used in all countries, ranging from 10.5% (Portugal) to 21% (Spain) and 18.5% (Romania). These findings suggest varied strategies for assessing athlete performance based on coaches' preferences. Using diverse tests provides a holistic insight into athlete aptitudes. Coaches could benefit from exploring various testing methods for a comprehensive assessment.

What post-assessment measures do coaches utilize for training programming?

In the present study, Portuguese coaches used maximal heart rate (31.6%) through field-based tests, Spanish employed the 220-age formula to estimate the maximal HR, or perceived exertion methods (27.4%), and Romanian coaches favored training HR (26.9%) by subtracting the HR from the recovery HR, to estimate exercise intensity. A recent systematic review that analyzed studies conducted on both professional and amateur sports levels, stated that the HR measure was a common metric in the majority of the reviewed studies [14], as it serves various purposes such as indicating early signs of illness or assessing aerobic fitness. However, only two studies provided information regarding resting HR and heart rate variability (HRV) [14]. Moreover, coaches often gathered HR data more frequently than the recommended guidelines, often collecting it every session or daily [26]. However, there is a lack of information regarding the timing and frequency of data analysis, as well as whether it influenced subsequent training plans or recovery strategies [14].

Another survey conducted among SSCs who worked in Division 1 (53.1%), division 2 (28.6%), division 3 (6.1%), and division 4 (12.2%) of the Brazilian National Championship, revealed that movement velocity-based (24%) and subjective estimations (24%) are the most common, with the rating of perceived exertion (18%) and athlete-dependent approaches (16%) following [16]. Notably, in that study, only 10% of SCCs used repetition maximum (1RM) tests. Other approaches included trial and error (8%), training to failure (6%), and alternative methods (16%) [16]. These results underscore diverse SCC practices and contextual influences. In our study, Portuguese coaches favored direct (34.2%) or estimated (31.6%) maximal repetition for strength training intensity. Spanish (38.7%) and Romanian coaches (35.4%) had majorities not using intensity measures for strength training. There is an increasing interest in using velocity-based instruments, such as linear transducers, to estimate the 1RM and for training programming [27, 28]. The velocity-based training (VBT) has been preferred by coaches over traditional methods, as it allows coaches to adjust the intensity of training in real-time to align with the intended session goals [29]. This is helpful as personal 1RM can change due to factors like fatigue, nutrition, and sleep [29]. These results underscore that there is significant heterogeneity between SCCs practices, which may be due to the different sporting contexts.

For speed training programming, in the present study, the Portuguese and Romanian coaches preferred maximal speed sprint (50% and 43.1% respectively), whereas Spanish coaches lacked individualized measures (37.1%). Another previously mentioned study observed a similar trend for speed programming [16]. That study showed that maximum speed sprinting (76%), and strength outcomes (67%), are the primary measure used by coaches for enhancing speed performance [16]. The findings highlight distinct preferences among coaches from different countries for speed training programming and emphasize the importance of tailoring speed training strategies to specific national contexts and underscore the significance of incorporating maximal speed sprinting and strength training for effective speed enhancement.

Monitoring Practices

Are coaches aligning with literature suggestions in their implementation of monitoring practices?

Regarding the monitoring practices, based on the survey results, there were differences in the use of training load or well-being monitoring among coaches across the different countries included in the study. Specifically, the majority of coaches in Spain (59.7%) reported not using training load or well-being monitoring in either training or competition. In Portugal and Romania, however, the majority of coaches reported using training load or well-being monitoring, but only in training sessions. The percentages were 39.5% in Portugal and 52.3% in Romania. It has been demonstrated that studies conducted at both professional and amateur sports levels commonly employ a variety of tools and measures to assess various aspects of training and performance [14]. GPS measures are employed to quantify external training load, while HR measures are utilized to gauge physiological. On the other hand, different RPE scales are

commonly used to evaluate the physiological response to training sessions, and self-report questionnaires were employed to assess the psychological responses to training [14].

In our study, of the coaches utilizing training monitoring tools to regulate training intensity, a significant proportion indicated reliance on heart rate, with prevalence rates of 28.9% in Portugal and 32.3% in Romania. Furthermore, both Portuguese and Spanish coaches incorporated the rate of perceived exertion as a monitoring metric, accounting for 26.3% in Portugal and 21% in Spain. Conversely, in Romania, a relatively smaller proportion, specifically 12.3% of coaches, reported utilizing such perceptual scales for monitoring. Although in the last decade, there has been a growing interest in the investigation of GPS systems for quantifying training intensity [12, 30], our study showed that the majority of the coaches from the three countries opted to use RPE scales and HR monitors. This can be explained by the fact that GPS systems, despite being more accessible in terms of cost, the majority of the clubs cannot afford such instruments for training intensity monitoring.

Considering the well-being/recovery monitoring practices, the majority of coaches in Portugal (57.9%), Spain (53.2%), and Romania (44.6%) reported using well-being perceptive scales to monitor recovery status. In addition to well-being perceptive scales, the second most used instrument for monitoring recovery status among coaches in Portugal and Romania was heart rate variability, with percentages of 31.6% and 33.8%, respectively. In Spain, the percentage of coaches using heart rate variability was higher, with a percentage of 41.9%. Contrary to our results, a systematic review showed that the utilization of well-being/recovery surveys was limited [14]. Specifically, within the mentioned investigation [14], only 13% of participants employed the recovery stress questionnaire for athletes. In comparison, both the profile of mood states (POMS) and the daily analysis of life demand a mere 2% of employed athletes (DALDA).

Overall, these findings suggest that there may be a lack of consistency in the use of monitoring tools for controlling training intensity among coaches across different countries and contexts. Still, this holistic approach indicates that a combination of objective and subjective measures was employed to comprehensively understand athletes' responses to training and their overall performance. Also, there may be differences in the use of instruments/measures for monitoring recovery status among coaches across different countries and contexts.

Are coaches harnessing periodic assessment tests and monitoring tools that demonstrate validity and reliability?

The surveyed coaches in the present study used field-based tests and the 220-age formula to estimate maximal heart rate. Considering strength tests, coaches favored direct and estimated 1RM methods. Whereas for speed measures, coaches preferred using maximal speed sprint measure.

Coaches play a pivotal role in optimizing athletes' training programs through informed decision-making. The insights garnered from this study's findings underscore the significance of utilizing periodic assessment tests and monitoring tools that possess proven validity and reliability. Particularly, the reliance on field-based tests and the 220-age formula for estimating maximal heart rate, as observed among the surveyed coaches, aligns with the established validity and reliability of these methods [31, 32]. The fact that the age-predicted HR_{max} equations did not exhibit comparable levels of validity and reliability in predicting HR_{max} implies the need for caution when employing such equations for training prescription. Similarly, coaches' inclination towards both direct and estimated 1RM methods for strength assessments is warranted by the robust test-retest reliability demonstrated across various factors, thereby ensuring accurate strength profiling [33]. In terms of speed measures, the preference for maximal speed sprint tests finds support in their recognized validity and reliability for programming effective speed training sessions [34].

Furthermore, the use of the rate of perceived exertion scales to monitor training intensity is one of the most common methods used by coaches [14]. In fact, the RPE method was proved to be both valid and reliable in its origins, with the RPE demonstrating a strong relationship with HR and work intensity [35]. With the evolution of the RPE measure in recent decades, other metrics, such as session-RPE (which relates to the overall session intensity rather than focusing on individual exercises), have also proven to be valid and reliable measures of intensity. [36].

Considering the perceptual scales of well-being and recovery status, its use is a crucial aspect that should be incorporated alongside performance enhancement, especially in elite-level sports that help limit the presence of bad overreaching and/or overtraining syndrome [37, 38]. Moreover, diverse methodologies are employed for the application and analysis of single-item self-report measures in the monitoring of team-sport athletes [39]. Both composite and single-item wellness measures have demonstrated diverse associations with training load measures, spanning from negligible correlations to substantial relationships [39]. Subjective well-being consistently reflects the impact of training stress, declining with heightened and prolonged training, and rebounding with reduced training [21]. Given their responsiveness in reflecting changes in athlete well-being, coaches can confidently utilize self-report measures for athlete well-being and recovery monitoring.

Coaches should prioritize evidence-based assessment tools and techniques that have been proven to be both valid and reliable [40]. This approach ensures that the information gathered from assessments accurately reflects athletes' physiological capacities and helps guide personalized training interventions. By making informed decisions based on reliable data, coaches can optimize training programming, monitor progress, and ultimately enhance athletes' overall performance outcomes [18]. The fact that coaches from different countries are utilizing these techniques is indicative of a growing awareness within the coaching community about the importance of valid and reliable assessment methods. This convergence in

practices suggests a positive trend toward evidence-based coaching approaches.

Limitations

While this study provides valuable insights into the practices of sports coaches in Portugal, Spain, and Romania regarding periodic assessments and monitoring tools, it is important to acknowledge certain limitations that may influence the interpretation of the findings. Firstly, the study's sample size and geographical scope may limit the generalizability of the results to a broader international context. The surveyed coaches were exclusively from these three European countries, and their practices might not fully represent those of coaches from other regions with distinct sporting cultures and infrastructures. Therefore, caution should be exercised when extrapolating these findings to a global coaching population.

Secondly, the utilization of self-report data through the survey method introduces the potential for response bias. Coaches' perceptions and self-reported practices may be influenced by memory recall, social desirability, and other cognitive factors that could impact the accuracy and completeness of the information provided. Despite efforts to ensure anonymity and confidentiality, it is impossible to entirely eliminate the influence of these biases. Moreover, the survey questionnaire was crafted based on existing literature and the research objectives. The study primarily relied on quantitative data to analyze coaches' practices, offering a limited exploration of the underlying reasons and contexts for their choices. Lastly, the study centered on the practices of coaches themselves, without directly evaluating the effectiveness or impact of these practices on athlete performance or well-being. While the study provides insights into coaches' behaviors, future research could delve into the outcomes of these practices on athletes' performance, injury prevention, and overall well-being.

CONCLUSIONS

The findings of the present study underscore notable distinctions in assessment protocols and the adoption of training load/well-being monitoring tools across coaches in Portugal, Spain, and Romania. The prospects of embracing diverse methodologies for gauging intensity and overseeing recovery merits careful consideration, potentially yielding synergistic insights that culminate in a more comprehensive grasp of athlete performance dynamics. These insights furnish a robust framework for curating bespoke educational resources that cater to the unique exigencies of coaches, thereby engendering a substantive advancement in the realm of sports coaching.

Funding

This study is conducted within the framework of the project "Enhancing Coaching through Digital Empowerment: Electronic Monitoring and Assessment Resources for Sport Coaches," which is funded by the European Commission under the ERASMUS-SPORT-2021-SSCP program, with the reference number 101049096.

Ethical approval

The study received approval from the Ethics Committee for Social Sciences, Life, and Health at Instituto Politécnico de Viana do Castelo, under reference number 4/A/2023.

Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. Dugdale JH, Arthur CA, Sanders D, Hunter AM. Reliability and validity of field-based fitness tests in youth soccer players. Eur J Sport Sci. 2019; 19(6):745–56.
2. Gabbett T, Nassis GP, Oetter E, Pretorius J, Johnston N, Medina D, Rodas G, Myslinski T, Howells D, Beard A, Ryan A. The athlete monitoring cycle: a practical guide to interpreting and applying training monitoring data. Br J Sports Med. 2017; 51:1451–2.
3. Clemente FM, Silva R. Avaliar para Treinar: Um guia prático de avaliação e controlo do treino para o treinador. 1a edição. Lisboa: Prime Books; 2021. 296 p.
4. Impellizzeri FM, Rampinini E, Marcora SM. Physiological assessment of aerobic training in soccer. J Sports Sci. 2005; 23(6):583–92.
5. Hulse MA, Morris JG, Hawkins RD, Hodson A, Nevill AM, Nevill ME. A field-test battery for elite, young soccer players. Int J Sports Med. 2013; 34(4):302–11.
6. Turner A, Walker S, Stembridge M, Coneyworth P, Reed G, Birdsey L, Barter P, Moody J. A Testing Battery for the Assessment of Fitness in Soccer Players. Strength Cond J. 2011 Oct; 33(5):29–39.
7. Foster C, Rodriguez-Marroyo JA, De Koning JJ. Monitoring training loads: The past, the present, and the future. Int J Sports Physiol Perform. 2017; 12:2–8.
8. Akubat I, Barrett S, Abt G. Integrating the Internal and External Training Loads in Soccer. Int J Sports Physiol Perform. 2013; 9(3):457–62.
9. Borresen J, Ian Lambert M. The Quantification of Training Load, the Training Response and the Effect on Performance. Sport Med. 2009 Sep; 39(9):779–95.
10. Halson SL. Monitoring Training Load to Understand Fatigue in Athletes. Sport Med. 2014 Sep; 44(2):139–47.
11. Carling C, Lacome M, McCall A, Dupont G, Le Gall F, Simpson B, Buchheit M. Monitoring of Post-match Fatigue in Professional Soccer: Welcome to the Real World. Sport Med. 2018; 48(12):2695–702.
12. Buchheit M, Allen A, Poon TK, Modonutti M, Gregson W, Di Salvo V. Integrating different tracking systems in football: multiple camera semi-automatic system, local position measurement and GPS technologies. J Sports Sci . 2014; 32(20):1844–57. Available from: http://dx.doi.org/10.1080/02640414.2014.942687.
13. Weston M. Training load monitoring in elite English soccer: a comparison of practices and perceptions between coaches and practitioners. Sci Med Footb. 2018 Jul; 2(3):216–24.
14. McGuigan H, Hassmén P, Rosic N, Stevens CJ. Training monitoring methods

used in the field by coaches and practitioners: A systematic review. Int J Sport Sci Coach. 2020; 15(3):439–51.
15. Weldon A, Duncan MJ, Turner A, Lockie RG, Loturco I. Practices of strength and conditioning coaches in professional sports: A systematic review. Biol Sport. 2022; 39(3):715–26.
16. Loturco I, Freitas TT, Alcaraz PE, Kobal R, Hartmann Nunes RF, Weldon A, Pereira LA. Practices of strength and conditioning coaches in Brazilian elite soccer. Biol Sport. 2022; 39(3):779–91.
17. Weldon A, Duncan MJ, Turner A, Christie CJ, Pang CMC. Contemporary practices of strength and conditioning coaches in professional cricket. Int J Sport Sci Coach. 2021; 16(3):585–600.
18. Ryan S, Kempton T, Impellizzeri FM, Coutts AJ. Training monitoring in professional Australian football: theoretical basis and recommendations for coaches and scientists. Sci Med Footb . 2020; 4(1):52–8. Available from: https://doi.org/10.1080/24733938.2019.1641212.
19. West SW, Clubb J, Torres-Ronda L, Howells D, Leng E, Vescovi JD, Carmody S, Posthumus M, Dalen-Lorentsen T, Windt J. More than a Metric: How Training Load is Used in Elite Sport for Athlete Management. Int J Sports Med. 2021; 42(4):300–6.
20. Rago V, Brito J, Figueiredo P, Costa J, Barreira D, Krustrup P, Rebelo A. Methods to collect and interpret external training load using microtechnology incorporating GPS in professional football: a systematic review. Res Sport Med . 2020; 28(3):437–58. Available from: https://doi.org/10.1080/15438627.2019.1686703.
21. Saw AE, Main LC, Gastin PB. Monitoring the athlete training response: Subjective self-reported measures trump commonly used objective measures: A systematic review. Br J Sports Med. 2016; 50(5):281–91.
22. Salter J, De Ste Croix MBA, Hughes JD, Weston M, Towlson C. Monitoring practices of training load and biological maturity in uk soccer academies. Int J Sports Physiol Perform. 2021; 16:395–406.
23. Weldon A, Duncan MJ, Turner A, Sampaio J, Noon M, Wong DP, Lai VW. Contemporary practices of strength and conditioning coaches in professional soccer. Biol Sport. 2021; 38(3):377–90.
24. Weldon A, Duncan MJ, Turner A, Laplaca D, Sampaio J, Christie CJ. Practices of Strength and Conditioning Coaches: A Snapshot From Different Sports, Countries, and Expertise Levels. J Strength Cond Res. 2022; 36(5):1335–44.
25. Fernandez-Fernandez J, Ulbricht A, Ferrauti A. Fitness testing of tennis players: how valuable is it? Br J Sports Med. 2014 Apr; 48 Suppl 1(Suppl 1):i22–31.
26. Starling LT, Lambert MI. Monitoring rugby players for fitness and fatigue: What do coaches want? Int J Sports Physiol Perform. 2018; 13(6):777–82.
27. Galiano C, Pareja-Blanco F, Hidalgo de Mora J, Sáez de Villarreal E. Low-Velocity Loss Induces Similar Strength Gains to Moderate-Velocity Loss During Resistance Training. J Strength Cond Res. 2020; (12):1.
28. Morán-Navarro R, Martínez-Cava A, Escribano-Peñas P, Courel-Ibáñez J. Load-velocity relationship of the deadlift exercise. Eur J Sport Sci . 2020; 0(0):1–19. Available from: https://doi.org/10.1080/17461391.2020.1785017.
29. Weakley J, Mann B, Banyard H, McLaren S, Scott T, Garcia-Ramos A. Velocity-Based Training: From Theory to Application. Strength Cond J. 2021 Apr; 43(2):31–49.
30. Malone J, Lovell R, Varley MC, Coutts AJ. Unpacking the black box: Applications and considerations for using gps devices in sport. Int J Sports Physiol Perform. 2017; 12(2):18–26.
31. Paravlic AH, Simunic B, Pisot R, Rauter S, Stuhec S, Vodicar J. The reliability, validity and usefulness of the 30–15 intermittent fitness test for cardiorespiratory fitness assessment in military personnel. Sci Rep. 2022; 12(1):1–8. Available from: https://doi.org/10.1038/s41598-022-20315-3.
32. Lima dos Santos A, Cavalcante Silva S, de Tarso Veras Farinatti P, Monteiro WD. Peak heart rate responses in maximum laboratory and field tests. Rev Bras Med do Esporte. 2005; 11(3):177–80.
33. Grgic J, Lazinica B, Schoenfeld BJ, Pedisic Z. Test–Retest Reliability of the One-Repetition Maximum (1RM) Strength Assessment: a Systematic Review. Sport Med – Open. 2020; 6(1).
34. Altmann S, Ringhof S, Neumann R, Woll A, Rumpf MC. Validity and reliability of speed tests used in soccer: A systematic review. PLoS One. 2019; 14(8):1–38.
35. Stamford BA. Validity and reliability of subjective ratings of perceived exertion during work. Ergonomics. 1976; 19(1):53–60.
36. Haddad M, Stylianides G, Djaoui L, Dellal A, Chamari K. Session-RPE method for training load monitoring: Validity, ecological usefulness, and influencing factors. Front Neurosci. 2017; 11.
37. Giles S, Fletcher D, Arnold R, Ashfield A, Harrison J. Measuring Well-Being in Sport Performers: Where are We Now and How do we Progress? Sport Med . 2020; 50(7):1255–70. Available from: https://doi.org/10.1007/s40279-020-01274-z.
38. Kenttä G, Hassmén P. Overtraining and recovery. A conceptual model. Sport Med. 1998; 26(1):1–16.
39. Duignan C, Doherty C, Caulfield B, Blake C. Single-item self-report measures of team-sport athlete wellbeing and their relationship with training load: A systematic review. J Athl Train. 2020; 55(9):944–53.
40. Johnson SR, Pas ET, Bradshaw CP. Understanding and measuring coach-teacher alliance: A glimpse inside the 'black box.' Prev Sci. 2016; 17(4):439–49.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.139075
© Institute of Sport – National Research Institute

Heavier loads in flywheel exercise induce greater post-activation performance enhancement in countermovement jumps compared to heavy Smith machine squats in males

AUTHORS: Jianhua Shi[1,2†], Bing Yan[1,3†], Mengjie Yu[1,4], Zhe Wang[1], Yang Wang[1,3], Haoyang Liu[5], Wei Zhang[5], Olivier Girard[6]

[1] China Institute of Sport and Health Science, Beijing Sport University, Beijing, China
[2] School of Physical Education, Yanching Institute of Technology, Langfang, China
[3] Key Laboratory for Performance Training & Recovery of General Administration of Sport, Beijing, China
[4] Sanya Branch School of High School Affiliated Renmin University, Sanya, China
[5] School of Sports Engineering, Beijing Sport University, Beijing, China
[6] School of Human Sciences (Exercise and Sport Science), University of Western Australia, Perth, Western Australia
[†] These authors contributed equally to this work

Corresponding author:
Bing Yan
China Institute of Sport and Health Science, Beijing Sport University, Beijing, China
E-mail: yanbing@bsu.edu.cn

ORCID:
Jianhua Shi
0000-0002-5290-9502

Bing Yan
0000-0003-0951-9186

Mengjie Yu
0009-0002-3072-2402

Zhe Wang
0000-0003-0951-9186

Yang Wang
0000-0002-0338-1641

Haoyang Liu
0000-0003-2027-7501

Wei Zhang
0000-0001-6092-5863

Olivier Girard
0000-0002-4797-182X

ABSTRACT: We evaluated the effects of post-activation performance enhancement through flywheel exercise with varying inertial loads compared to traditional resistance exercise on countermovement jump performance and muscle recruitment. In a randomized crossover design, 13 trained men completed four main experimental trials after three familiarization sessions. These conditions included a traditional trial consisting of 5 sets of 1 repetition using the Smith machine (SM) squat at 90% 1RM, and three flywheel ergometer trials. Each flywheel protocol consisted of 3 sets of 8 repetitions with 3-minute rest intervals between sets, utilizing one of three inertial loads (0.0465, 0.0784, and 0.1568 $kg \cdot m^2$ for light, moderate, and heavy, respectively). Participants performed countermovement jumps before (baseline), immediately after (0 minute), and at the fourth (+4 minutes), eighth (+8 minutes), and twelfth (+12 minutes) minute following exercise. Compared to baseline, jump height was higher at +4 minutes for SM squats ($p = 0.009$). All flywheel conditions exhibited higher jump heights at +4 minutes ($p < 0.05$), +8 minutes ($p < 0.001$), and +12 minutes ($p < 0.001$) compared to baseline. Additionally, moderate and heavy loads resulted in higher jump heights at 0 minute (both $p < 0.001$). Integrated electromyographic activity values, a proxy for muscle recruitment, were significantly higher for the *gluteus maximus* muscle at both +8 minutes and +12 minutes for moderate (both $p = 0.004$) and heavy loads ($p \leq 0.002$) compared to SM squats. Overall, flywheel protocols produce greater post-activation performance enhancement, extend the time window for improvement, and recruit more active musculature compared to heavy-load SM squats, particularly with heavier loads acting as a stronger preload stimulus.

CITATION: Shi J, Yan B, Yu M et al. Heavier loads in flywheel exercise induce greater post-activation performance enhancement in countermovement jumps compared to heavy Smith machine squats in males. Biol Sport. 2024;41(4):231–240.

Received: 2023-10-27; Reviewed: 2023-12-02; Re-submitted: 2023-12-14; Accepted: 2024-04-04; Published: 2024-04-25.

Key words:
Flywheel
Post-activation performance enhancement
Resistance exercise
Conditioning activities
Vertical jump ability
Back squats

INTRODUCTION

Post-activation performance enhancement (PAPE) refers to a significant increase in an athlete's power output shortly after a preconditioning activity, typically occurring within 4–12 minutes; however, earlier or later potentiation responses have also been observed [1]. Importantly, PAPE should not be confused with post-activation potentiation, which pertains to increases in twitch forces evoked by prior muscle activity and phosphorylation of myosin regulatory light chains [1, 2]. PAPE is commonly incorporated into pre-competition or pre-training warm-up routines to optimize athlete performance. This phenomenon is often attributed to the enhancement of the neuromuscular state of athletes, resulting in increased power output and subsequently improved sprint and/or vertical jump performance [2]. Nevertheless, it is widely acknowledged that an athlete's performance in a countermovement jump (CMJ) depends on the contraction speed of the working muscle groups and the maximum force generated during the eccentric phase [3]. There is substantial evidence to suggest that single sets of heavy back squats (i.e., 80–90% 1RM [4]), also referred to as traditional protocols, can effectively induce PAPE during explosive movements [5]. However, alternative conditioning activities in the form of eccentric-overload resistance exercise have emerged as an alternative method to traditional protocols [6, 7].

Flywheel training has gained popularity as an approach to intensifying the eccentric phase of exercises compared to traditional weight-stack exercise, promoting significant skeletal muscle adaptations [8]. Isoinertial devices, also known as flywheel ergometers, provide an

accentuated eccentric muscle action and have proven effective in enhancing stretch-shortening cycle performance, thereby positively impacting explosive whole-body movements including jumping and sprinting [9]. Previous research has demonstrated that several weeks of inertial resistance training significantly increase the maximum strength of major muscle groups during the eccentric phase, leading to improvements in athletes' vertical jump performance [8]. inertial flywheel resistance training stands out for its short familiarization period, even for inexperienced athletes [10]. Additionally, the portability of flywheel devices (typically weighting < 15 kg) has contributed to their growing popularity.

In recent years, there has been a substantial increase in studies exploring the effects of PAPE on vertical jumps (CMJ [11] and squat jumps [12]) using flywheel eccentric overload exercises (e.g., squat). As reviewed by Beato et al. [11], the volume (number of sets) and intensity (inertia) can be manipulated to influence the balance between neuromuscular potentiation and fatigue, which in turn determine the onset and magnitude of the PAPE response. For instance, a minimum of two sets of flywheel eccentric overload half-squats is required to enhance peak power responses during CMJ, even if no differences were observed in jump height, in male university soccer players [13]. Additionally, practitioners can use different inertia intensities (e.g., 0.03–0.11 $kg \cdot m^2$; [14]). However, most studies have primarily examined a single load when assessing PAPE time windows and magnitudes, and some have omitted reporting the intensity [7, 12], resulting in uncertainty regarding the effects of load intensity.

The effects of different flywheel inertial load intensities on PAPE in vertical jump performance have recently come under scrutiny [14, 15]. In a recent study by Fu et al. [15], the magnitude of PAPE in CMJ was influenced by the degree of inertial loads applied with increasing inertial loads (0.041, 0.057, and 0.122 $kg \cdot m^2$, respectively). On the contrary, there were no PAPE differences between small and large loads (0.029 *vs*. 0.061 $kg \cdot m^2$ [16]) or between medium and large flywheel loads (0.029 *vs*. 0.061 $kg \cdot m^2$ [14]) on subsequent athletic performance. More research on the dose-dependent effects of flywheel conditioning intensity on PAPE is necessary and can provide valuable insights into prescribing the appropriate intensity to acutely enhance explosive performance [11].

Surface electromyography (EMG) can be employed to assess the underlying neural mechanisms contributing to improvements in mechanical variables during CMJ [17]. Despite growing research determining the PAPE effects of flywheel exercise [18], there is a scarcity of studies that have examined specific muscle activity levels (i.e., measured by surface EMG) during movements. The execution of flywheel exercise across a range of inertial loads has produced conflicting results regarding motor unit recruitment. Some studies report modifications in motor unit recruitment with graded inertial loads [19], while others indicate no noticeable effect [20]. One important shortcoming in the current PAPE literature is the absence of studies comparing surface EMG data after completing flywheel and gravity-based load protocols. To date, there is a lack of time-course and magnitude data available regarding the muscle recruitment strategies that occur during jump execution following flywheel exercise, notably when comparing different inertial loads.

The aim of this study was to compare the impact of flywheel resistance exercise with varying inertial loads to traditional resistance training on PAPE and the accompanying muscle recruitment during the CMJ. We hypothesized that flywheel exercise, especially with heavier loads, would enhance CMJ performance by increasing motor unit recruitment compared to traditional resistance exercise. The significance of this study is underscored by the observation that the majority of the fifty-one practitioners (~84%) surveyed by de Keijzer et al. [21] 'agreed' or 'strongly agreed' that *"isoinertial protocols can acutely enhance (PAPE) sport-specific performance"*.

MATERIALS AND METHODS

Participants

An *a priori* power analysis ($\alpha = 0.05$, $1\text{-}\beta = 0.95$) was performed using G*Power (Version 3.1.9.7) for the change in vertical jump height. The power calculation considered an ANOVA with repeated measures, involving four groups and five time points, considering a within-between interaction (correlation among repeated measures: 0.5). The averaged effect size for an acute change in vertical jump height, derived from expected performance improvement occurring from baseline to +4 minutes post-conditioning routine using moderate-to-large inertia levels (0.057–0.122 $kg \cdot m^2$), is 0.94 [15]. To express our results with 95% confidence, a minimum sample size of 8 participants was obtained, with ten allowing for a 20% attrition rate. Therefore, we recruited thirteen males, each with at least two years of resistance training history (mean ± SD, training history: 4.7 ± 0.9 years; height: 177.4 ± 2.5 cm; body mass: 73.6 ± 8.2 kg). Participants were classified as 'Highly trained/National level' (Tier 3) using established criteria [22] and were active in different sports (i.e., basketball, volleyball, track and field). They reported a two-year history of resistance training, including at least two sessions per week, and demonstrated experience in the back squat, with a minimum 1RM of 1.5 times their body mass (back squat 1RM: 141.5 ± 27.8 kg). The study was approved by the local ethics committee, and complied with the principles of the Declaration of Helsinki, with written informed consent obtained from participants.

Study design

This study employed a randomized, cross-over design. Participants attended the laboratory on eight separate occasions over a 9-week period. The sessions included one preliminary testing session (visit 1), three familiarization sessions (visits 2–4) in line with the recommendation of Sabido et al. [10], and four main experimental trials (visits 5–8). All sessions were conducted at the same time of day (± 1 h) and separated by at least 48 hours [23].

The preliminary testing session (~60 minutes) aimed to collect biometric data, explain testing procedures, and complete 1RM back

squat and CMJ assessments. During familiarization visits (~30 minutes each), participants familiarized themselves with study procedures including CMJ test, flywheel operation and PAPE protocol. During each visit, they practice flywheel resistance exercise procedures, which included three sets of eight repetitions with Light (FL), Moderate (FM), or Heavy (FH) inertial loads (visits 2, 3, and 4, respectively). During the four main sessions (visits 5–8), participants either performed a traditional trial consisting of five sets of one repetition using the barbell back squat (BS) with 90% 1RM or one of three inertial flywheel trials. Each flywheel trial consisted of three sets of eight repetitions, utilizing one of the three inertial loads. During experimental trials, three CMJ attempts were performed before (Baseline), immediately after (0 minute), and at the fourth (+4 minutes), eighth (+8 minutes), and twelfth (+12 minutes) minute following each conditioning routine. Participants were provided 30 seconds of rest between each CMJ attempt, and the best of three trials (jump height) was recorded for subsequent analysis.

Participants were instructed to avoid alcohol and caffeine consumption and to refrain from strenuous training in the 24 h prior to each session. They were also asked to maintain a 24-hour food diary before testing and replicate their diet before the four trials. During the testing period, they were instructed to maintain their normal diet, avoiding the use of nutritional supplements. Each trial had a duration of ~35 min, and the air temperature was maintained at a constant level around ~22°C.

Experimental trials

The structure of the experimental visits is depicted in Figure 1. Upon arrival at the laboratory, participants completed a 15-minute standardized warm-up, which included jogging followed by plyometric exercises. After five minutes of passive seated rest, they underwent baseline testing for CMJ and then proceeded with a conditioning routine in one of the four experimental conditions.

In the traditional barbell protocol, subjects using the Smith machine perform a barbell BS with 90% 1RM, which consists of five sets of one repetition, with a 1-minute rest interval between sets.

In the inertial flywheel protocol, participants utilized a flywheel device (D11 Full, Desmotec, Biella, Italy) equipped with various inertial loads (0.0465, 0.0784, and 0.1568 kg·m^2 for FL, FM, and FH, respectively) for three sets of eight repetitions of the half-squat exercise, with 3-minute rest intervals between sets. Each participants assumed a half-squat position, with their thighs parallel to the floor, crossing their hands on their shoulders and positioning their feet shoulder-width apart. The first two repetitions served to initiate the movement [15]. Subsequently, the next six repetitions were executed with maximal effort, aiming for maximal possible concentric

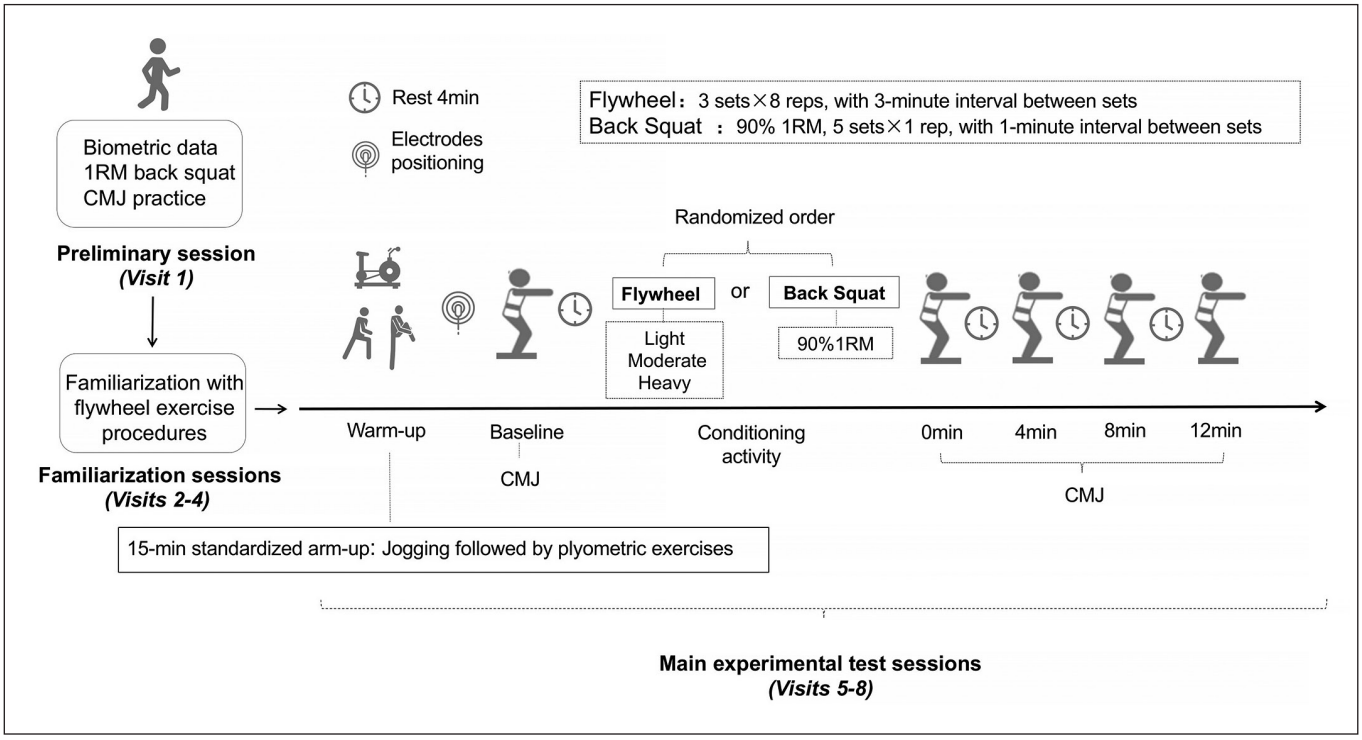


FIG. 1. Experimental overview

The four conditions include conditioning with a traditional trial, which consists of five sets of one repetition using the barbell squat BS) with 90% 1RM, or one of three inertial flywheel trials. Each flywheel trial consists of three sets of eight repetitions, utilizing one of the three inertial loads (Light, Moderate, Heavy).

speed during the entire concentric phase, which ranged from a 90° knee flexion to near full extension [13]. Since inertial forces initiate the reversed eccentric action at the end of the concentric phase, participants had to exercise control during the initial one-third of the movement and then apply maximal force to stop the motion at ~90° knee flexion [8].

Procedures

One-repetition maximum testing

Before the test performed on a Smith machine, participants completed a brief warm-up protocol consisting of submaximal squats at 50, 70, 80, and 90% of their self-estimated 1RM. This entailed 10, 6, 3 and 1 repetition(s) for each percentage, respectively, with a 2-minute rest between sets. Then, the load was gradually increased in 4–5 trials with at least 3 minutes of rest between each trial until the participant reached their 1RM [24]. The squat depth was individually standardized to parallel, meaning that they descended to reach a 90° knee angle. All participants reached their 1RM within a maximum of five trials.

Countermovement jumps

To perform the CMJ test, participants were instructed to jump as high as possible. They started from a standing position and performed a downward countermovement to a self-selected depth, followed immediately by a rapid jump in one continuous movement. Participants were instructed to keep their hands on their hips to eliminate any influence of arm swing. The jumping was performed while participants stood on a force platform, which allowed for direct measurement of the vertical ground reaction forces. Data were sampled at a frequency of 1,000 Hz (model 9286BA, Kistler Corporation, Switzerland). Vertical jump height, peak power output, and take-off velocity were all calculated using the MARS software (version 4.0; Kistler Corporation, Switzerland). Participants completed three trials of the CMJ, with a 30-second rest between each trial. For the final analysis, we utilized the best result from three trials, determined by vertical jump height.

Surface electromyography

A wireless receiver (Noraxon Inc, USA) was used to record raw surface EMG signals during the CMJ test from the *gluteus maximus*, *rectus femoris*, and *biceps femoris* muscles at a sampling rate of 1,000 Hz using MyoResearch Version 3.12 software (Noraxon Inc, USA). Before electrode placement, the skin was prepared by shaving hair off the desired area, lightly abrading, and cleaning with an alcohol swab. Bipolar surface electrodes with an interelectrode distance of 30 mm were then attached to the skin, aligned parallel to the underlying muscle fibers. Raw EMG signals were processed offline using MyoResearch software V.3.12 with a bandwidth of 10–500 Hz. EMG signal segments selected and integrated (i.e., iEMG value) for analysis correspond to the muscles of the dominant leg during the concentric stage. Each value represents the maximal EMG response for CMJ at various time points under each condition, expressed in absolute terms (uV·s).

Statistical Analyses

Values are expressed as means ± SD along with the mean difference and its 95% confidence interval. Two-way repeated-measures ANOVA (Condition [BS, FL, FM and FH] × Time [baseline, 0 min, +4 min, +8 min, and +12 min]) were used to compare dependent variables. Normal distribution of the residuals was tested using the Kolmogorov–Smirnov test. Data variance was first assessed using Mauchly test of sphericity, and a Greenhouse–Geisser correction was applied when required. Post hoc pairwise comparisons were performed using Bonferroni-adjusted P values. For each ANOVA, partial eta-squared (η_p^2, with $\eta_p^2 \geq 0.06$ representing a *moderate* effect and $\eta_p^2 \geq 0.14$ a *large* effect) were calculated as measures of effect size. Cohen's *d* effect sizes were calculated to determine meaningful differences, with $d < 0.2$, $d = 0.2$–0.5, $d = 0.5$–0.8 and $d > 0.8$ representing *trivial*, *small*, *moderate* and *large* effect sizes,

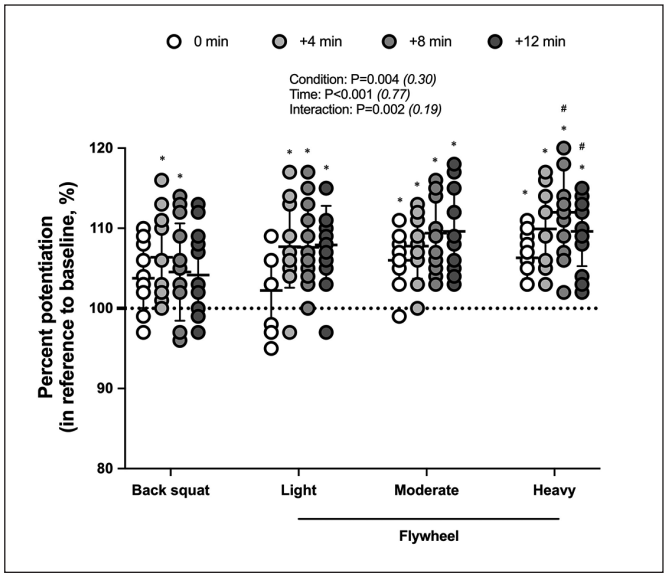


FIG. 2. Individual data for percent potentiation (jump height) at various time points following four conditioning routines in reference to baseline.

The four conditions include conditioning with a traditional trial, which consists of five sets of one repetition using the barbell squat with 90% 1RM, or one of three inertial flywheel trials. Each flywheel trial consists of three sets of eight repetitions, utilizing one of the three inertial loads (Light, Moderate, Heavy).

Values are mean ± SD (n = 13). Note that values less than 100 indicate performance decrement, while values greater than 100 indicate performance benefits.

* *P < 0.05, significantly different from baseline (assigned the value 100) in a given condition;* # *P < 0.05, significant different from back squat at the same time.*

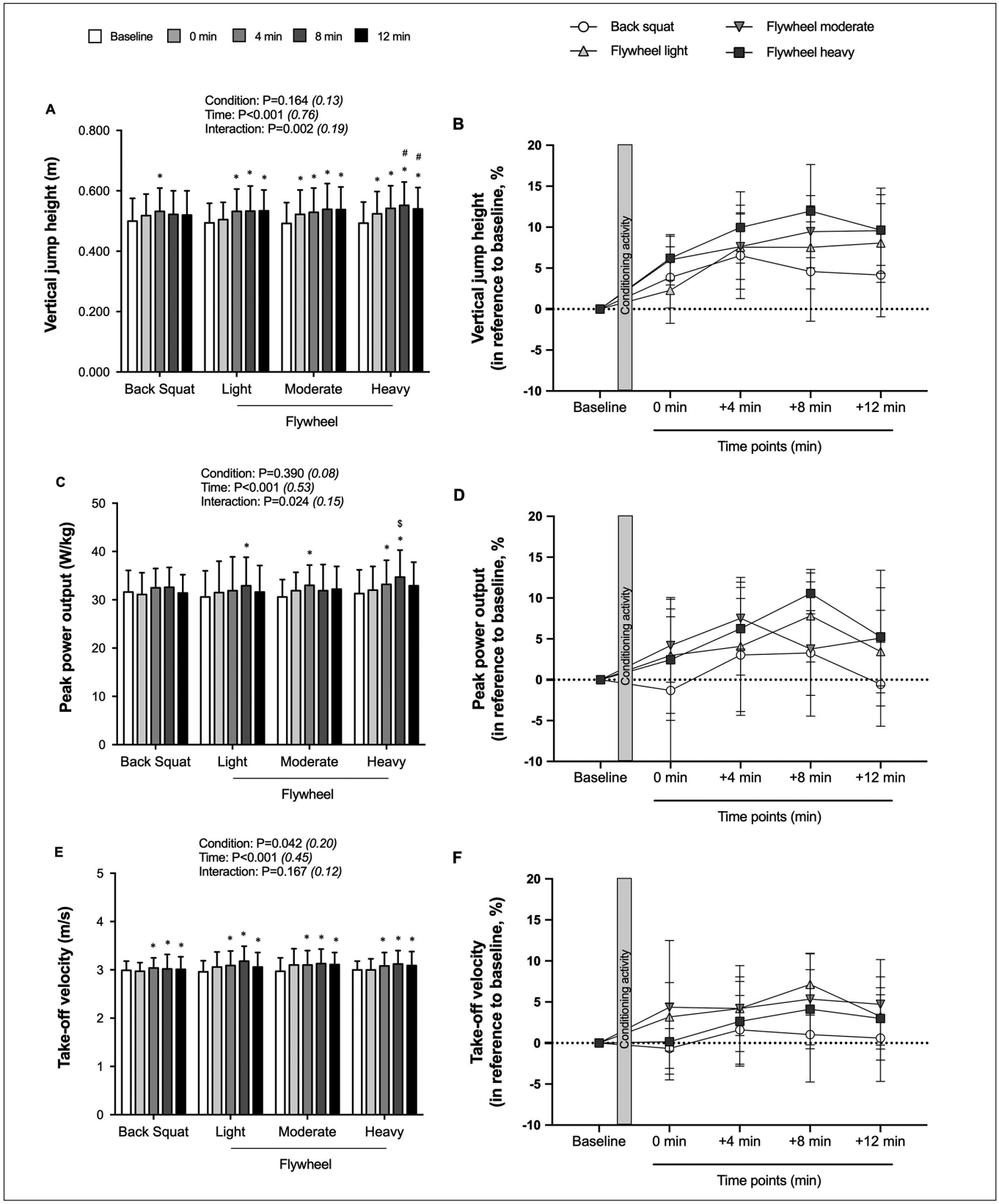


FIG. 3. Mechanical variables (absolute values [left panels] and relative changes [right panels]) at various time points following four conditioning routines in reference to baseline. Changes in vertical jump height (A and B), relative peak power output (C and D), and vertical velocity at take-off (E and F).

Values are mean ± SD (n = 13). The four conditions include conditioning with a traditional trial, which consists of five sets of one repetition using the barbell squat with 90% 1RM, or one of three inertial flywheel trials. Each flywheel trial consists of three sets of eight repetitions, utilizing one of the three inertial loads (Light, Moderate, Heavy).

** P < 0.05, significantly different from baseline in a given condition; # P < 0.05, significant different from back squat at the same time. $ P < 0.05, significant different from flywheel moderate at the same time.*

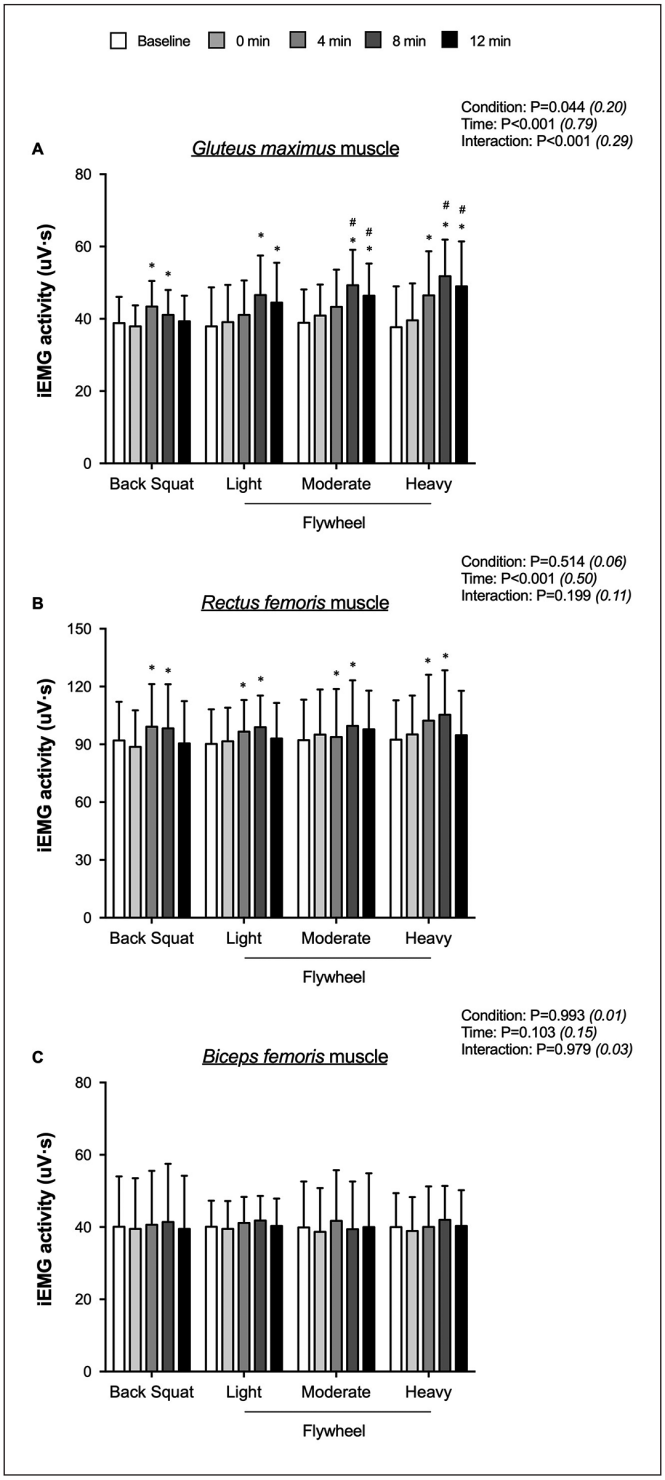


FIG. 4. Integrated electromyographic (iEMG) activity for *gluteus maximus* (A), *rectus femoris* (B), and *biceps femoris* (C) muscles at various time points following four conditioning routines in reference to baseline.

Values are mean ± SD (n = 13). The four conditions include conditioning with a traditional trial, which consists of five sets of one repetition using the barbell squat with 90% 1RM, or one of three inertial flywheel trials. Each flywheel trial consists of three sets of eight repetitions, utilizing one of the three inertial loads (Light, Moderate, Heavy).

* *P < 0.05, significantly different from baseline in a given condition;* $^{\#}$ *P < 0.05, significant different from back squat at the same time.*

respectively. Dependent variables were expressed as the percent change (%) from the baseline measurements. Statistical significance was set at $p \leq 0.05$.

RESULTS

Mechanical performance

Figure 2 displays percent potentiation (derived from jump height) individual data.

Compared to baseline, vertical jump height was higher at +4 minutes for BS (p = 0.009; *d* = -0.42; -0.032 [-0.057; -0.007]) (Figure 3A-B). Regarding FL, vertical jump height values were higher at +4 minutes (p = 0.003; *d* = -0.54; -0.037 [-0.063; -0.012]), +8 minutes (p < 0.001; *d* = -0.51; -0.038 [-0.064; -0.012]) and +12 minutes (p < 0.001; *d* = -0.59; -0.040 [-0.061; -0.018]) *versus* baseline. For both FM and FH, vertical jump height values were higher at 0 minute (p < 0.001; *d* = -0.40; -0.030 [-0.047; -0.014] and p < 0.001; *d* = -0.43; -0.031 [-0.044; -0.017]), +4 minutes (p < 0.001; *d* = -0.51; -0.038 [-0.057; -0.019] and p < 0.001; *d* = -0.68; -0.049 [-0.069; -0.029]), +8 minutes (p < 0.001; *d* = -0.61 -0.047 [-0.070; -0.024] and p < 0.001; *d* = -0.80; -0.059 [-0.085; -0.033]) and +12 minutes (p < 0.001; *d* = -0.64; -0.046 [-0.070; -0.023] and p < 0.001; *d* = -0.67; -0.047 [-0.066; -0.027]) *versus* baseline. Higher vertical jump values were noted for FH at +8 minutes (p = 0.013; *d* = -0.38; -0.030 [-0.054; -0.006]) and +12 minutes (p = 0.031; *d* = -0.26; -0.020 [-0.038; -0.001]) in reference to BS.

Compared to baseline, peak power output was higher at +8 minutes for FL (p = 0.003; *d* = -0.42; -2.369 [-3.960; -0.778]), +4 minutes for FM (p < 0.001; *d* = -0.60; -2.331 [-3.471; -1.190]), and both +4 minutes (p = 0.017; *d* = -0.38; -1.892 [-3.504; -0.281]) and +8 minutes (p < 0.001; *d* = -0.63; -3.323 [-4.282; -2.364]) for FL (Figure 3C-D). Higher peak power output values were noted for FH at +8 minutes (p = 0.002; *d* = -0.38; -2.746 [-4.456; -1.037]) in reference to FM. Irrespective of condition, take-off velocity was higher at +4 minutes (p = 0.018; *d* = -0.41; -0.095 [-0.176; -0.014]), +8 minutes (p = 0.010; *d* = -0.53; -0.132 [-0.236; -0.028]), and +12 minutes (p = 0.044; *d* = -0.37; -0.086 [-0.169; -0.002]) in reference to baseline (Figure 3E-F).

Surface EMG activity

For BS, *gluteus maximum* iEMG values were higher at +4 minutes (p < 0.001; *d* = -0.63; -4.562 [-6.462; -2.662]) and +8 minutes (p = 0.011; *d* = -0.33; -2.331 [-4.193; -0.468]) in reference to baseline. Compared to baseline, *gluteus maximum* iEMG values were higher at both +8 minutes and +12 minutes for FL (p = 0.001; *d* = -0.81 -8.731 [-13.937; -3.524] and p = 0.027; *d* = -0.61; -6.638 [-12.671; -0.606]) and FM (p < 0.001; *d* = -1.10; -10.392 [-15.128; -5.656] and p = 0.002; *d* = -0.83; -7.492 [-12.404; -2.580]). Regarding FH, *gluteus maximum* iEMG values were higher at +4 minutes (p = 0.011; *d* = -0.75;

-8.800 [-15.858; -1.742]), +8 minutes ($p < 0.001$; d = -1.31; -14.100 [-20.659; -7.541]) and +12 minutes ($p = 0.002$; d = -0.95; -11.308 [-18.634; -3.981]) *versus* baseline. Higher *gluteus maximum* iEMG values were noted at both +8 minutes and +12 minutes for FM ($p = 0.004$; d = -0.96; -8.131 [-13.769; -2.493] and $p = 0.004$; d = -0.66; -7.115 [-12.042; -2.189]) and FH ($p < 0.001$; d = -1.23; -10.677 [-16.028; -5.326] and $p = 0.002$; d = -0.78; -9.769 [-16.062; -3.476]) in reference to BS. Irrespective of condition, *rectus femoris* iEMG values was higher at +4 minutes ($p = 0.050$; d = -0.33; -6.283 [-12.568; 0.003]), and +8 minutes ($p = 0.006$; d = -0.46; -8.846 [-15.468; -2.224]) in reference to baseline (Figure 4 A-C).

DISCUSSION

Flywheel protocols with varying loads

As hypothesized, the magnitude and time course of CMJ performance improvements varied depending on flywheel resistance, notably with earlier and more pronounced effects observed with higher inertial loads. Our findings partially align with literature on changes in CMJ performance following PAPE protocols that involve flywheel exercises [14]. In a recent study, Fu et al. [15] found that both moderate resistance (0.057 kg·m^2) and heavy resistance (0.122 kg·m^2) resulted in enhanced CMJ performance between 4 and 8 minutes, whereas no change was observed with light loads (0.041 kg·m^2). However, in our study, PAPE was only evident with moderate and heavy inertial loads immediately after the conditioning activity. Contrastingly, when comparing moderate (0.03 kg·m^2) and high (0.06 kg·m^2) inertial flywheel half-squat intensities, Beato et al. [14] found no significant difference between the protocols regarding the onset and magnitude of the resulting PAPE effects (~10%) in relation to CMJ performance. Despite previous investigations and the current study using the same flywheel device for preconditioning purposes, discrepant findings could be primarily attributed to other methodological differences: 1) the exercise routine included either three sets of six repetitions with two minutes of rest [14] or four sets of seven repetitions with three minutes of rest [15] *versus* three sets of six repetitions with three minutes of rest (current study); 2) inertial loads ranging from 0.03–0.06 kg·m^2 [14] or 0.041–0.122 kg·m^2 [15] *versus* 0.046–0.157 kg·m^2 (current study); 3) differences in training levels of tested individuals (participants in our study exhibited smaller values of concentric peak power compared to those in other studies [14]). Altogether, our findings suggest that when implementing flywheel exercise for PAPE, different inertial loads should not be used interchangeably.

Wider time windows with flywheel protocols

Another novel finding was that flywheel protocols elicit PAPE in a shorter recovery interval compared to BS, with PAPE onset observed at 0 minute for FM and FH and +4 minutes for FL. Previous flywheel studies have shown either decreased [14] or increased [15] CMJ performance immediately after the conditioning activity. Our findings do not support the suggestion of a longer necessary time window between the conditioning activity (i.e., preload) and the subsequent performance test for fatigue to dissipate more quickly, and to achieve PAPE using flywheel compared to traditional protocols [25]. However, the optimal recovery time should be determined individually, as some individuals with light and moderate flywheel loads required more time to dissipate the effects of fatigue (Figure 2).

In our study, the greatest effects with a BS protocol were observed between 4 and 8 minutes, with no differences from baseline outside this interval. Indeed, the effects of BS were short-lived, disappearing after 8 minutes. This finding aligns with conclusions from Dobbs et al. [26], suggesting that the greatest effects on jumping ability are achieved with traditional PAPE protocols after a rest period of 3 to 7 minutes. In contrast, flywheel protocols resulted in a sustained elevation of jump height for 8–12 minutes, regardless of the inertia used, although the effects gradually diminished. Nonetheless, only heavy-load flywheel exercise demonstrated superior effects compared to BS at both +8 and +12 minutes. Previous research has noted that PAPE induced by a single bout of flywheel resistance exercise (0.083 ± 0.03 kg·m^2) on CMJ can persist up to 20 minutes [27]. Remarkably, the positive effects of the heaviest load (FH) were consistent, as all thirteen participants exhibited percent potentiation values exceeding 100% at all time points. Overall, our analysis of the CMJ performance results reveals a broader time window for PAPE in the three flywheel conditions compared to BS, with even earlier effects with moderate and heavy loads.

Surface EMG activity

One remarkable observation was the significantly earlier and larger muscle recruitment of the *gluteus maximus* muscle with increasing inertia levels after the preload. Previous studies have not documented muscle recruitment patterns during CMJs in response to flywheel protocols with varying inertial loads, making comprehensive comparisons with the existing literature difficult. However, since surface EMG activity changes in the *gluteus maximus* muscle tended to follow a similar trend as jump height, it is plausible that increased muscle recruitment may contribute to PAPE [19]. This could result in increased force production through larger muscle recruitment during the concentric phase. The transition from eccentric to concentric phases in flywheel exercises may trigger a more pronounced stretch reflex [28]. Pending confirmatory research, the energy stored in the eccentric phase during this transition may enhance the subsequent concentric action performance to a greater extent compared to traditional resistance exercises or flywheel protocols using lighter loads [11]. In our study, however, significant increases in take-off velocity at 4–12 minutes time intervals were comparable between all conditions.

Surface EMG findings indicate a selective increase in muscle recruitment with varying conditioning protocols. Although *rectus femoris* muscle activity was enhanced at both +4 minutes and +8 minutes, these changes occurred regardless of the condition. Additionally, changes in recruitment for the *biceps femoris* muscle remained

non-significant in our protocol. This suggests that our hypothesis, which proposed that different inertial loads likely differentially activate lower limb musculature, is only partially confirmed. However, it is important to exercise caution when interpreting surface EMG findings since this technique can not differentiate between the number of motor units and their firing frequencies, and there is also an inherent risk of crosstalk from adjacent muscles [29]. Previous studies have reported differences in recruitment sequences during actual flywheel exercises performed with varying inertia levels, indicating that inertia plays a significant role in modulating muscle recruitment. For instance, while the lowest load (0.025 $kg \cdot m^2$) follows the proximal-to-distal principle of muscle activation, higher loads (0.05–0.01 $kg \cdot m^2$) result in a reorganization of the underlying muscle coordination mechanisms [19]. Future studies should expand the number of studied muscle and determine whether jumping movements may be reorganized in response to PAPE.

Individual responses

Compared to BS, the range of individual percent potentiation values was relatively consistent across all time points for the other three conditions, regardless of the inertial load (Figure 2). For instance, percent potentiation values for at least two conditions (BS and FL) ranged from -5% (0 minute) to +15% (+12 minutes) at 0–12 minutes time intervals. Substantial inter-individual variability was noticeable, despite all participants having engaged in resistance exercise at least twice weekly over the previous two years. Given the variations in participants' characteristics, there is no consensus on the optimal PAPE window between a conditioning activity and subsequent explosive activities. A study by Gourgoulis et al. [30] found that stronger athletes (squat weights > 160 kg) experienced a more substantial increase in CMJ height (4% *vs*. 0.4%) compared to weaker athletes (squat weights < 160 kg) after five sets of back squats. Further investigation is needed to determine if stronger participants consistently exhibit a significantly greater PAPE response than their weaker counterparts, possibly due to enhanced activation of fast motor units, at all post-conditioning time points. Therefore, it is reasonable to assume that the PAPE phenomenon may be subject-dependent and lacks optimal standards for both timing and intensity of the stimulus [11].

The wide inter-individual variation underscores the necessity to differentiate between average group responses and the individual diversity in responses to a given conditioning activity [31]. Rather than solely comparing group means at all time points, as done here and in most available studies [11], it is pertinent to also evaluate distinct individual responses to each conditioning protocol. In support of this approach, Scott et al. [32] demonstrated that individualized recovery intervals yielded unique responses for several outcome measures concerning baseline and between conditioning activities (hex bar deadlift and back squat). However, no PAPE response was observed when comparing CMJ variables at different recovery intervals (30 s, 90 s, and 180 s) to baseline measurements [32].

Limitations and additional considerations

Our study is not without limitations. Firstly, adjusting the flywheel's inertial setting during resistance exercise may have differential effects on force, power, and eccentric overload for men and women [33], implying that our conclusions should be limited to the male cohort under study. Secondly, greater concentric outputs during assisted squats lead to increased eccentric outputs and result in a higher mechanical load [34]. This raises the possibility that flywheel-assisted squats may generate a larger and longer-lasting PAPE effect in relation to CMJ. It also suggests that the necessary adjustments in terms of inertia and volume (number of repetitions per set and total number sets [11]), tailored to specific demographics, could be explored for optimal benefits, eventually considering speed-derived peak variables to demonstrate an eccentric overload [35]. In our study, it can not be excluded that a smaller number of repetitions in the conditioning with a traditional trial could, at least in part, explain the relatively lower benefits compared to inertial flywheel trials. Thirdly, most studies, including this one, typically involve exercises performed in a 'traditional set' structure where repetitions are executed consecutively without rest. To manage fatigue when lifting heavier loads or with larger volume (number of repetition) in conditioning exercises, an approach that deserves further attention is to use a 'cluster set' structure to maintain training quality [36], which could potentially enhance PAPE. Finally, this study did not evaluate peripheral adaptations (i.e., twitch responses from percutaneous nerve stimulation) that enable increased muscle responses after both flywheel and barbell squats protocols [37]. These adaptations could potentially account for changes in the balance between transient fatigue and potentiation, thereby explaining the substantial variability in the percent potentiation responses both within and between individuals [1]. Future studies should contemplate the integration of motor nerve or transcranial magnetic stimulation techniques in the realm of flywheel exercise to evaluate post-activation potentiation. This phenomenon, well-described with a short half-life (~28 s), amplifies muscle force production at submaximal levels of calcium saturation, corresponding to submaximal levels of muscle activation [1]. These electrophysiological techniques could provide valuable insights into the specific neuromuscular factors (i.e., post-activation potentiation) contributing to performance enhancement (i.e., PAPE) when modifying inertial load, even though twitch contractile enhancements have been noted without any observable PAPE (e.g., vertical jump height) [38].

Practical implications

The data presented here support and emphasize that flywheel devices with a wide range of inertia levels can be used to induce PAPE. For practitioners seeking to acutely enhance their strength and power during training sessions or before competitions using this preload strategy, our findings suggest that higher inertias should be preferred. The limited time window for achieving an optimal PAPE response can be a challenge for strength and conditioning practitioners in real-world training scenarios, where time and access to heavy weights near the

competition site are often limited. Our observations of a broader time window for PAPE in the three flywheel conditions compared to BS, with effects occurring even earlier with moderate and heavy loads, are highly relevant. In the context of boosting PAPE for CMJ using flywheel exercise, it appears that higher loads offer a better option.

CONCLUSIONS

This study investigated the immediate effects of time intervals on CMJ performance and the corresponding muscle recruitment by comparing heavy-weight back squats with protocols involving flywheel exercise featuring varying levels of inertia. Flywheel exercise, irrespective of inertial loads, was more effective than back squats, as PAPE became apparent after 4–12 minutes, whereas with the traditional protocol, it was observed only after 4 minutes. Furthermore, there were immediate improvements in jump height following flywheel exercise, especially with moderate and heavy loads. Finally, EMG activity in the *gluteus maximus* and *rectus femoris* muscles (but not in the *biceps femoris*) increased in conjunction with PAPE, with the *gluteus maximus* mirroring the effects of inertial loads on jump height. Practically, the utilization of accentuated eccentric loading through flywheel exercise can serve as a strategy to enhance the recruitment of active musculature, potentially resulting in a more pronounced PAPE response [39]. Overall, the time window effect of PAPE after flywheel exercise differs from the traditional protocol in terms of CMJ performance and accompanying muscle recruitment. It demonstrates that flywheel protocols using heavier loads positively impact the magnitude of the PAPE response and the optimal time window.

Conflict of interest

The authors declare no conflict of interest.

REFERENCES

1. Blazevich AJ, Babault N. Post-activation potentiation versus post-activation performance enhancement in humans: historical perspective, underlying mechanisms, and current issues. Front Physiol. 2019; 10:1359.
2. Boullosa D, Beato M, Dello Iacono A, Cuenca-Fernández F, Doma K, Schumann M, et al. A new taxonomy for postactivation potentiation in sport. Int J Sports Physiol Perform. 2020; 15(8):1197–1200.
3. Bishop C, Turner A, Jordan M, Harry J, Loturco I, Lake J, Comfort P. A Framework to guide practitioners for selecting metrics during the countermovement and drop jump tests. Strength Cond J. 2022; 44(4):95–103.
4. Seitz LB, Haff GG. Factors modulating post-activation potentiation of jump, sprint, throw, and upper-body ballistic performances: a systematic review with meta-analysis. Sports Med. 2016; 46(2):231–40.
5. Guo W, Liang M, Lin J, Zhou R, Zhao N, Aidar FJ. Time duration of post-activation performance enhancement (PAPE) in elite male sprinters with different strength levels. Children. 2023; 10(3):53.
6. Cuenca-Fernández F, López-Contreras G, Mourão L, De Jesus K, Zacca R, Vilas-Boas JP, Fernandes RJ, Arellano R. Eccentric flywheel post-activation potentiation influences swimming start performance kinetics. J Sports Sci. 2019; 37(4):443–51.
7. Cuenca-Fernández F, Ruiz-Teba A, López-Contreras G, Arellano R. Effects of 2 types of activation protocols based on postactivation potentiation on 50-m freestyle performance. J Strength Cond Res. 2020; 34(11):3284–92.
8. Maroto-Izquierdo S, García-López D, Fernandez-Gonzalo R, Moreira OC, González-Gallego J, de Paz JA. Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-Analysis. J Sci Med Sport. 2017; 20(10):943–51.
9. Buonsenso A, Centorbi M, Iuliano E, Di Martino G, Della Valle C, Fiorilli G, Calcagno G, Di Cagno A. A systematic review of flywheel training effectiveness and application on sport specific performances. Sports. 2023; 11:76.
10. Sabido R, Hernández-Davo JL, Pereyra-Gerber GT. Influence of different inertial loads on basic training variables during the flywheel squat exercise. Int J Sports Physiol Perform. 2018; 13(4):482–9.
11. Beato M, McErlain-Naylor SA, Halperin I, Dello Iacono A. Current evidence and practical applications of flywheel eccentric overload exercises as postactivation potentiation protocols: A brief review. Int J Sports Physiol Perform. 2020; 15(2):154–61.
12. Timon R, Allemano S, Camacho--Cardeñosa M, Camacho-Cardeñosa A, Martinez-Guardado I, Olcina G. Post-activation potentiation on squat jump following two different protocols: traditional vs. inertial flywheel. J Hum Kinet. 2019; 69:271–81.
13. De Keijzer KL, McErlain-Naylor SA, Dello Iacono A, Beato M. Effect of volume on eccentric overload-induced postactivation potentiation of jumps. Int J Sports Physiol Perform. 2020; 15(7):976–81.
14. Beato M, De Keijzer KL, Leskauskas Z, Allen WJ, Dello Iacono A, McErlain-Naylor SA. Effect of postactivation potentiation after medium vs. high inertia eccentric overload exercise on standing long jump, countermovement jump, and change of direction performance. J Strength Cond Res. 2021; 35(9):2616–21.
15. Fu K, Chen L, Poon ET-C, Wang R, Li Q, Liu H, Ho IMK. Post-activation performance enhancement of flywheel training on lower limb explosive power performance. Front Physiol. 2023; 14:1217045.
16. McErlain-Naylor SA, Beato M. Post flywheel squat potentiation of vertical and horizontal ground reaction force parameters during jumps and changes of direction. Sports. 2021; 9(1):5.
17. Sotiropoulos K, Smilios I, Christou M, Barzouka K, Spaias A, Douda H, Tokmakidis P. Effects of warm-Up on vertical jump performance and muscle electrical activity using half-squats at low and moderate intensity. J Sports Sci Med. 2010; 9(2):326–31.
18. Beato M, Dello Iacono A. Implementing flywheel (isoinertial) exercise in strength training: Current evidence, practical recommendations, and future directions. Front Physiol. 2020; 11:569.
19. Spudić D, Smajla D, David Burnard M, Šarabon N. Muscle activation sequence in flywheel squats. Int J Environ Res Public Health. 2021; 18:3168.
20. Spudić D, Smajla D, Šarabon N. Intra-session reliability of electromyographic measurements in flywheel squats. PLoS ONE. 2020; 15:e0243090.
21. De Keijzer KL, McErlain-Naylor SA, Brownlee TE, Raya-González J, Beato M. Perception and application of flywheel training by professional soccer practitioners. Biol Sport. 2022; 39(4):809–17.
22. McKay AK, Stellingwerff T, Smith ES, Martin DT, Mujika I, Goosey-Tolfrey VL, Sheppard J, Burke L. Defining training and performance caliber: A participant classification framework. Int J Sports Physiol Perform. 2022; 17(3):317–31.

23. Beato M, Bigby AEJ, De Keijzer KL, Nakamura FY, Coratella G, McErlain--Naylor SA. Post-activation potentiation effect of eccentric overload and traditional weightlifting exercise on jumping and sprinting performance in male athletes. PLoS ONE. 2019; 14(9):e0222466.
24. Haff GG, Triplett T. Program design for resistance training. In: Essentials of Strength Training and Conditioning. Champaign, IL: Human Kinetics; 2016. p. 45–453.
25. Sale DG. Postactivation potentiation: Role in performance. Br J Sports Med. 2004; 38(4):386–7.
26. Dobbs WC, Tolusso DV, Fedewa MV, Esco MR. Effect of post-activation potentiation on explosive vertical jump: a systematic review and meta-analysis. J Strength Cond Res. 2019; 33(7):2009–18.
27. Maroto-Izquierdo S, Bautista IJ, Martín Rivera F. Post-activation performance enhancement (PAPE) after a single bout of high-intensity flywheel resistance training. Biol Sport. 2020; 37(4):343–50.
28. Martinez-Hernandez, D. Flywheel eccentric training: how to effectively generate eccentric overload. Strength Cond J. 2023; DOI: 10.1519/SSC.0000 000000000795.
29. Vigotsky AD, Halperin I, Lehman GJ, Trajano GS, Vieira TM. Interpreting signal amplitudes in surface electromyography studies in sport and rehabilitation sciences. Front Physiol. 2018; 8:985.
30. Gourgoulis V, Aggeloussis N, Kasimatis P, Mavromatis G, Garas A. Effect of a submaximal half-squats warm-up program on vertical jumping ability. J Strength Cond Res. 2003; 17(2):342–4.
31. Nibali ML, Chapman DW, Robergs RA, Drinkwater EJ. Considerations for determining the time-course of post-activation potentiation. Appl Physiol Nutr Metab. 2015; 40(11):1163–70.
32. Scott DJ, Ditroilo M, Marshall P. Effect of accommodating resistance on the post-activation potentiation response in rugby league players. J Strength Cond Res. 2018; 32(9):2510–20.
33. Martinez-Aranda LM, Fernandez-Gonzalo R. Effects of inertial setting on power, force, work and eccentric overload during flywheel resistance exercise in women and men. J Strength Cond Res. 2017; 31(6):1653–61.
34. Wren C, Beato M, McErlain-Naylor SA, Dello Iacono A, De Keijzer KL. Concentric phase assistance enhances eccentric peak power during flywheel squats: Intersession reliability and the linear relationship between concentric and eccentric phases. Int J Sports Physiol Perform. 2023; 18(10):428–34.
35. Muñoz-López A, Nakamura F, Beato M. Eccentric overload differences between loads and training variables on flywheel training. Biol Sport. 2023; 40(4):1151–8.
36. Tufano JJ, Conlon JA, Nimphius S, Brown LE, Seitz LB, Williamson BD, Haff GG. Maintenance of velocity and power with cluster sets during high-volume back squats. Int J Sports Physiol Perform. 2016; 11(7):885–92.
37. Spudić D, Dakskobler J, Štirn I. Differences in post-activation potentiation and post-activation performance enhancement between flywheel and barbell squat protocols. Kinesiol Slov. 2023; 29(1):5–29.
38. Prieske O, Maffiuletti NA, Granacher U. Postactivation potentiation of the plantar flexors does not directly translate to jump performance in female elite young soccer players. Front Physiol. 2018; 9:276.
39. Norrbrand L, Pozzo M, Tesch PA. Flywheel resistance training calls for greater eccentric muscle activation than weight training. Eur J Appl Physiol. 2010; 110(5):997–1005.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.136085
© Institute of Sport – National Research Institute

Relative age effect across the talent identification process of youth female soccer players in the United States: Influence of birth year, position, biological maturation, and skill level

AUTHORS: Laura Finnegan[1], Mirelle van Rijbroek[2], José M. Oliva-Lozano[2], Rick Cost[2], Matthew Andrew[3]

[1] Football Research Group, Department of Sport and Exercise Science, South East Technological University, Ireland
[2] United States Soccer Federation, Chicago, Illinois, USA
[3] Department of Sport and Exercise Science, Manchester Metropolitan University Institute of Sport, Manchester, UK

ABSTRACT: The aims of the study were to examine the relative age effect (RAE) in youth female soccer players in the United States (US) and the influence of birth year, playing position, estimated maturation and skill ratings. The sample consisted of 3,364 youth female soccer players who were active in the 2021–2022 US soccer season across three main stages of the talent identification (TID) process for Youth National Team (YNT) players (i.e., *Club*, *TID Center*, and *YNT*). A prevalent RAE for players born in Q1 was present in the full sample. A significant prevalence for Q1 players were identified for both *Club* and *TID Center*, but not *YNT*. A significant RAE prevalence for Q1 players was identified for most of the age groups from U13–U18 at *Club* (except U18) and *TID Center* (except U17). Significant RAEs prevalence for players born in Q1 were found in Goalkeepers, Center Backs, Midfielders, and Center Forwards at *Club* and *TID Center* (except Wide Forwards). The data identified a consistent RAE prevalence for Q1 players in early and on-time-maturers across all levels. An even birthdate spread was evident in YNT with a prevalence for Q4 players and a higher percentage of late-maturers than elsewhere in the TID process. Results reinforce evidence indicating RAEs still exist in soccer, yet show for the first time within a youth female soccer TID process, the influence of contextual factors on the prevalence of RAE. This information can be used to advance TID and development across the US soccer landscape.

CITATION: Finnegan L, van Rijbroek M, Oliva-Lozano JM et al. Relative age effect across the talent identification process of youth female soccer players in the United States: Influence of birth year, position, biological maturation, and skill level. Biol Sport. 2024;41(4):241–251.

Received: 2023-09-18; Reviewed: 2023-11-03; Re-submitted: 2023-12-19; Accepted: 2024-02-14; Published: 2024-05-17.

Corresponding author:
Matthew Andrew
Department of Sport and Exercise Sciences
Manchester Metropolitan University, Manchester, UK
E-mail:
matthew.andrew@mmu.ac.uk

ORCID:
Laura Finnegan
0000-0002-9715-5097

José M. Oliva-Lozano
0000-0002-7257-3620

Rick Cost
0000-0001-8227-300X

Matthew Andrew
0000-0003-2007-910X

Key words:
Selection
Development
Youth National Team
Club
Soccer
Talent

INTRODUCTION

Soccer is one of the most popular female sports worldwide [1]. In the United States (US) this popularity is rising exponentially due to success at domestic and international levels [1]. To continue this success, soccer-teams and -nations identify talented youth players that show the potential to enter a high-performance programme [2]. While research that aims to provide evidenced-based information to support female soccer is slowly rising [3], there is an underrepresentation of female-only research in talent identification (TID) [4], thus calls for female-specific research have been made [2].

One factor that is known to influence TID is when an athlete is born within a selection year, also known as the Relative Age Effect (RAE) [5]. RAE refers to the (dis)advantage of chronological age differences between individuals within annually age-grouped cohorts, with those born close to the start of a cut-off (first quartile of year) date almost 12 months older compared to those born later in the cut-off (fourth quartile of year) date. Due to the subjective nature of TID, scouts may (un)consciously judge older players as more talented than their younger peers and thus they may be more likely to select them into high-performance-environments [6]. This judgement may be associated with the older athletes possessing performance advantages (e.g., anthropometrical) that obscures a scout's ability to observe other predictors such as technical/perceptual skills [7].

Research on RAE in soccer has primarily focused on male soccer players, with most studies indicating this effect still persists at youth and professional levels [8, 9]. The small sample of studies examining RAE in female soccer players have produced inconsistent findings [10]. For example, no RAEs were observed in youth or senior soccer players that competed in European Championships qualification campaigns [11], or senior players representing their nation at Olympic Games [12]. However, retrospective analyses have indicated RAEs in national female soccer players of youth World Cups, particularly midfielders, but did not translate to senior levels [13]. These comparisons between-soccer-nations indicate the impact of global

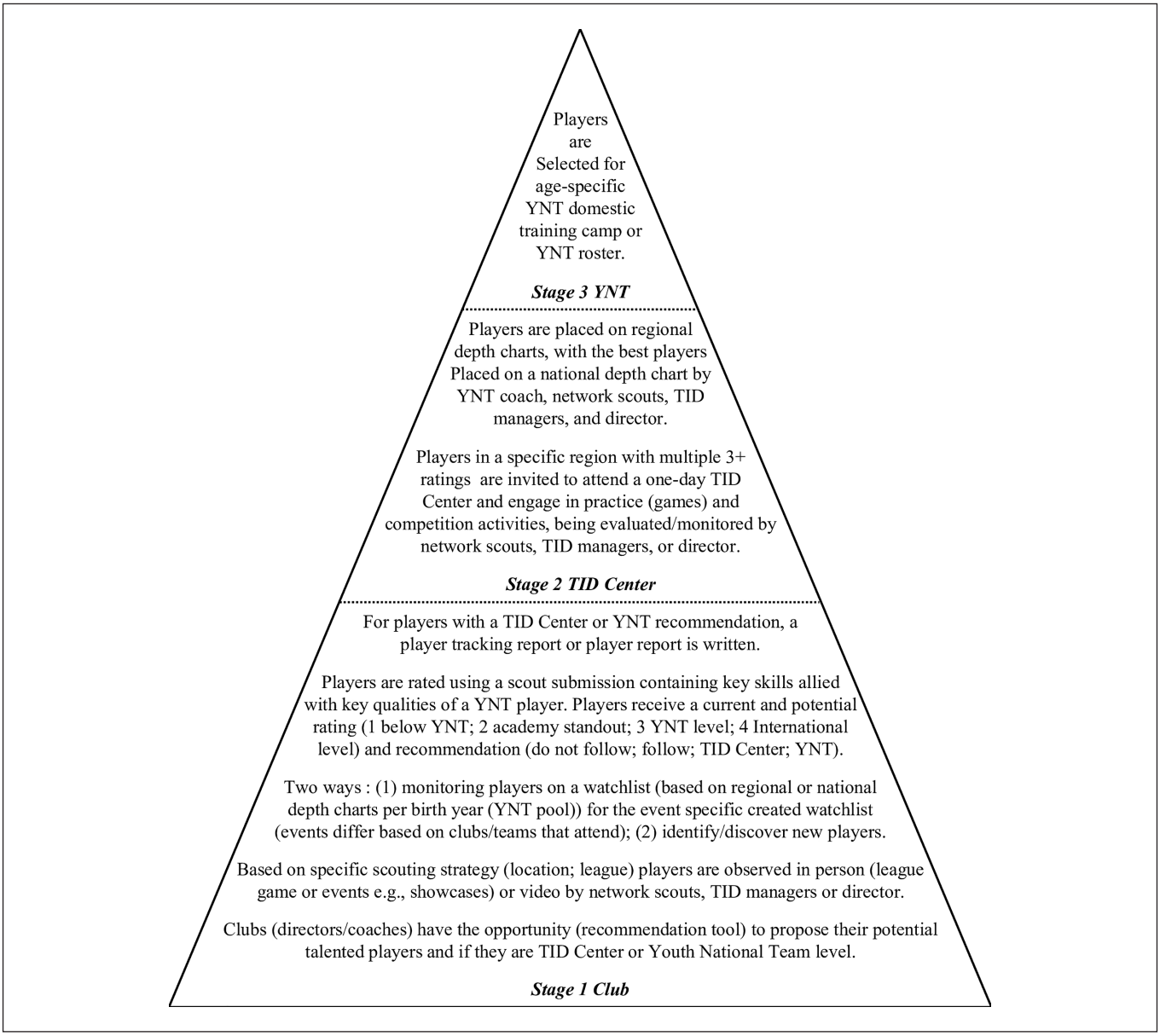


FIG. 1. Three key stages of the talent identification process for Youth National Team players outlined by US Soccer.

contextual factors on the level of RAE in female soccer, such as competition level, birth year, and playing position, and should continue to be studied [13].

Individual-soccer-nation examinations of RAE in female soccer are also historically mixed, with no RAEs observed in league players in France [14] and Brazil [15], or national players in Switzerland [16], but RAEs have been reported in youth players in China [17], and league players in Spain [18], Italy [19], and Japan [20]. Götze and Hoppe [21] reported RAEs for league players in Germany but not youth national players. Whereas Brustio et al. [22] reported RAEs for youth national players, this did not translate to the senior level. It has been suggested that the soccer environments of the individual nations may underpin inconsistencies in RAEs [23, 24]. Soccer nations differ based on demographical (population, size, depth of competition, resources, participation [25]), sociocultural (facilities, schooling, registered coach numbers, hours in practice, socioeconomic status [2, 26, 27]) and TID (scout numbers, players recruited/released, staff roles, objectives [27]) factors. So, the soccer environment should be considered when examining RAE in female soccer players.

The US are one of the most successful female soccer-nations at senior (4 × FIFA Word Cups; 4 × Olympic Gold Medals; 9 × CONCACAF-W-Championships) and youth (3 × FIFA Word Cups; 15 × CONCACAF-W-Championships) levels. To continue their success, the US Soccer Federation (USSF) utilises its TID processes which is multi-layered (an outline of the stages can be seen in Figure 1). There are three main stages: (1) *Club*, based on a specific scouting strategy (location; league), players are observed in their club environment (league/events)

by Youth National Team (YNT) network scouts, TID manager(s)/director, and clubs recommending players (via a recommendation tool). Playing position, estimated biological maturation, birthdate/quartile, rating of current performance and potential ability, and recommendations compared to US YNT key qualities are recorded; (2) *TID Center*, based on these reports, high-rated players in each region attend a single day of training and competition (vs. each other and/or boys' teams), again being evaluated/monitored. Players are placed on regional depth charts, with the players with the highest potential ability on a national depth chart; (3) *YNT*, players are selected for age-specific domestic training camps or rosters. Previous examinations of US youth female soccer have reported RAEs in both youth club-level soccer players between 2012–2013 [28] and U17 national team players [24]. However, it is currently unknown whether RAEs still exist following an exponential rise in participation rates and/or whether it translates to younger and older national players. This historical data may not provide a full picture of the current US female soccer environment and the effects mediated by birth year, maturation, and playing status. Therefore, it is necessary to explore RAEs across the TID process and identify if/where the RAE extent occurs between levels [11].

The present study aimed to examine the influence of RAE in US youth female soccer players across the TID process, and to identify if these are moderated by birth year, playing position, estimated maturation, and skill. Given the limited and mixed literature examining RAEs in female soccer players, we did not make any a priori hypotheses.

MATERIALS AND METHODS

Participants

Birthdates of 3,364 youth female soccer players across the 2021–2022 season were analysed across three stages of the TID process. For *Club* (Stage 1, Figure 1), birthdates were collected from 1,940 players and were categorised by birth year (BY), playing position (as per the player profiles outlined by US Soccer), estimated maturation, and skill rating. For *TID Center* (Stage 2, Figure 1), birthdates were collected from 1,191 players that attended a YNT TID Center event. For *YNT* (Stage 3, Figure 1), birthdates were collected from 233 players who were selected to be part of a domestic training camp and/or roster. Skill ratings were not collected for *YNT* as players are considered the most skilled within their age group. The study was conducted in accordance with the declaration of Helsinki, and ethical approval was gained from an institutional ethics committee (2023-50926-40701).

Procedure

For *Club,* data was taken from 4,818 (2.4 ± 2.0 per player) tracking/player reports completed by 66 US YNT network scouts, TID manager(s) and director following observations of the players within their club setting (e.g., league game; Figure 1). Scout observations were either independent or with another scout, TID manager, or director, where estimated maturation and skill rating were agreed upon. The scouts had between 1–31 years of experience, 1–21 years of which were specifically for US YNT players. Many scouts held USSF coaching licenses (e.g., USSF 'A' and 'B'), and had completed educational courses (including on the topics of TID and the maturation and development of female soccer players) delivered by the research team. Biological maturation was recorded through subjective estimations by the scouts, and consistent with Romann et al. [29] were classified into early-, on-time- and late-maturing players. An interclass correlation coefficient (ICC) was used for players with 2 or more observations that indicated an ICC of 0.61 for inter-interindividual and 0.85 for intra-individual, demonstrating moderate-good reliability. Furthermore, skill was recorded through subjective assessments by the scouts, whereby they compared the players' soccer-specific skills to the US YNT key qualities and provided a skill rating. They were classified into below YNT, follow (TID recommendation), and YNT level. Skill was subdivided into current (present) and potential (possible) performance. Playing position was categorised based on most appearances. For both estimated biological maturation and skill ratings, we created mean values from all observations within the season. For *TID Center,* data was taken from the player reports completed by 61 US YNT network scouts, TID manager(s) and director following the event. Observations were conducted as a small group including scouts, TID manager(s) and director.

The birth month for each player was used to define birth quartile (BQ) and half-year distribution per semester (BS) [5]. In line with the changes in cut-off dates proposed in 2017 by US Soccer [30], we adopted cut-off dates of: Q1 = Jan-Mar; Q2 = Apr-Jun; Q3 = Jul-Sep; Q4 = Oct-Dec, and semesters: S1 = Jan-Jun; S2 = Jul-Dec. For players born 1999–2004, we adopted pre-2017 cut-off dates of: Q1 = Aug-Oct; Q2 = Nov-Jan; Q3 = Feb-Apr; Q4 = May-Jul, and semesters: S1 = Aug-Jan; S2 = Feb-Jul. A failure to be aware of these changes could lead to skewed results within large-scale RAE studies [31].

Data analysis

The Chi-squared (χ^2) test was used to assess differences between observed and expected birthdate distributions across BQs for: each birth year (BY) irrespective of time point; and each BY, playing position, current performance and potential ability ratings per time point. Expected BQs were taken from the National Center for Health Statistics in the Center for Disease Control and Prevention (www.cdc.com) and reflected the average population BQs for the US from 1999–2009 (oldest-youngest within sample). BQs were identified as: Q1 = 24.1%; Q2 = 24.7%; Q3 = 26.3%; Q4 = 24.8%. Odds ratios (ORs) and 95% confidence intervals (95% CI) were calculated to compare the odds of the frequency of a BQ/S to another with a reference group, consisting of the youngest players (Q4 or S2 respectively). An OR of 1.0 indicated that the frequency is equal in both BQs/BSs whilst an OR of 2.0 indicated that the frequency of one BQ/BS is twice as high as the other [10; 21]. ORs were considered significant if the 95%

CI range did not include a value < 1.00. Furthermore, effect sizes (ES) were calculated through Cohen's w [32] and interpreted as small effect (w < 0.30), medium effect (w = 0.30–0.50), and large effect (w > 0.50). Alpha was set at $p < 0.05$. Data were analysed via SPSS Statistics (IBM, Chicago, US).

RESULTS

Overall

The distribution of BQs across *Club*, *TID Center*, and *YNT* are presented in Table 1. Results show RAE prevalence in the full sample (Q1 = 34.8%, Q2 = 28.6%, Q3 = 22.8%, Q4 = 13.8%; χ^2 (3, n = 3,364) = 10.8, p = 0.01, w = 0.33). Overall, for *Club* and *TID Center*, there was a significant RAE, with Q1 players being over-represented. This RAE effect was lesser at *YNT*. To gain further insights at *YNT*, that dataset was compared to both *Club* and *TID Center*, showing significant differences from both, p = 0.02 and p = 0.01, respectively (Table 1).

Birth year

The frequency and percentage distributions of players' BQs for BY are provided in Table 1. In *Club*, the chi-squared indicated significant deviations for U13–U17, with Q1 players being over-represented. Analysis further revealed that although Q1 were over-represented, there was no significant RAE for U18. Within *TID* Centers, the chi-squared indicated significant deviations for U13–U16, with Q1 players being over-represented, and the ORs remaining relatively similar across all BYs. However, for U18, Q3 players were over-represented, with the representation of Q4 players being larger than Q1. Analysis further indicated that for U17, though Q2 were over-represented, a significant RAE did not exist. For *YNT*, the chi-squared indicated significant deviations for U15–U16 only, with Q3 players being over-represented for U16 and Q2 players for U15. For all other BYs, BQs were relatively evenly distributed.

Position

The frequency and percentage distributions of players' BQs for position are presented in Table 2. In *Club*, for full backs, the largest distribution was observed in Q1, yet this did not reach significance. Q1 players represented the largest distribution for all positions, with a progressive decline from Q1–Q4. OR analysis indicated that RAE was highest for the center backs. When analysed by BY, within 2009, from the seven goalkeepers, one was born in S2. In *TID Center*, for full backs and wide forwards, the largest distribution was observed in Q1, yet this did not reach significance. Q1 players also represented the largest distribution for most other positions. For these positions, OR analysis indicated that RAE was highest for center backs and center forwards, remaining relatively similar in goalkeepers and midfielders. For goalkeepers, the largest distribution was Q2. For *YNT*, there was a significant RAE for goalkeepers only, with Q2 and Q3 players being over-represented and Q4 being under-represented. A mixed pattern emerged from the other positional data, with Q4 being most represented in midfielders, Q3 with center backs, and Q2 with wide forwards and center forwards.

Estimated biological maturation

The overall group consisted of 28.9% early-, 60.9% on time-, and 10.2% late-maturers. In *Club*, for late-maturers, the largest distribution was observed in Q3, yet this did not reach significance. Q1 players represented the largest BQ for both the on-time- and early-maturers, which was in line with the general BQ statistics. The fewest players deemed to be early- and on-time-maturers were Q4. OR analysis indicated that RAE was slightly higher for the on-time-, compared to the early-maturers (Table 3). There was a significant difference between BY and estimated maturity ratings (χ^2 (10, n = 1930) = 66.87, $p < .01$, w = 0.42). For BY2009, 19.9% were deemed late-maturing compared to 2.9% of BY2004. In *TID Center*, 34.9% of Q1 players were early-maturers compared to 7.6% of Q4 players. OR analysis indicated that RAE was higher for the early-maturers compared to the on-time. For *YNT*, overall, there was a statistically significant RAE for all players. But, for early-maturers Q2 players were over-represented and Q1 on-time players were over-represented. For late-maturers, this was reversed, with Q4 players being over-represented. *YNT* had the highest proportion of late-maturers (14.6%), compared to *Club* (9.5%) and *TID Center* (10.8%).

Skill ratings

The frequency and percentage distributions of players' BQs for current performance and potential ability are presented in Table 4. For current performance, in both *Club* and *TID Center*, the chi-squared indicated significant deviations for all current performance ratings, with Q1 players being over-represented and the ORs being relatively similar across groups. Q3 were least likely to attain the highest current rating ('YNT level') at *Club* and *TID Center*. A greater % of Q4 players were provided the highest rating, compared to at Club level 21.4% v 15.5%). For potential ability, the chi-squared indicated there were significant deviations for the middle and highest-rated players in *Club*, with Q1 players being over-represented. For the lowest-rated players, the largest distribution was observed in Q1, yet this did not reach significance. At *TID Center,* the chi-squared indicated significant deviations for all potential ability ratings, with Q1 players being over-represented. With the recognition that there were unequal numbers of players represented from the BQs, the descriptive percentage results of current performance and potential ability for each BQ at *Club* and *TID Center* are presented. For current performance (Figure 2), Q3 were least likely to attain a 'YNT level' rating at *Club* (2a) and *TID Center* (2b). At *TID Center*, more Q4 players were rated as 'YNT level'. For potential ability (Figure 3), Q4 players were more likely to be rated as 'below YNT' but also more likely than Q1 to be rated as 'YNT level'. At *TID Center*, Q4 were more likely to be rated as 'YNT level'. Q3 were least likely to be rated as 'YNT level' rating at *Club* (3a) and *TID Center* (3b).

TABLE 1. Birth quartile distribution by birth year.

		Birthdate Distribution (%)				Odds Ratio (95% CI)						
	n	Q1	Q2	Q3	Q4	Q1 vs. Q2	Q1 vs. Q3	Q1 vs. Q4	S1 vs. S2	χ^2	p	w
Club												
2004 (U18)	247	83 (33.6)	59 (23.9)	47 (19.0)	58 (23.5)	1.4 (0.7–3.1)	1.9 (0.9–4.2)	1.5 (0.7–3.2)	1.4 (0.8, 2.5)	5.87	0.12	0.24 (Small)
2005 (U17)	383	134 (35.0)	104 (27.2)	98 (25.6)	47 (12.3)	1.3 (0.6–2.8)	1.5 (0.7–3.2)	2.9 (1.2–6.9)	1.7 (1.0–3.0)	11.50*	0.01	0.34 (Medium)
2006 (U16)	448	163 (36.4)	127 (28.3)	111 (24.8)	47 (10.5)	1.3 (0.6–2.8)	1.6 (0.8–3.4)	3.6 (1.5–8.7)	1.9 (1.1–3.4)	15.13*	0.00	0.39 (Medium)
2007 (U15)	379	127 (33.5)	126 (33.2)	77 (20.3)	49 (12.9)	1.0 (0.5–2.2)	1.8 (0.8–3.9)	2.7 (1.1–6.3)	2.1 (1.2–3.7)	13.67*	0.00	0.37 (Medium)
2008 (U14)	341	128 (37.5)	89 (26.1)	73 (21.4)	51 (15.0)	1.5 (0.7–3.1)	1.6 (0.7–3.3)	2.6 (1.1–5.8)	1.8 (1.0–3.2)	12.32*	0.01	0.35 (Medium)
2009 (U13)	142	56 (39.4)	46 (32.4)	35 (24.6)	5 (3.5)	1.2 (0.6–2.6)	1.7 (0.8–3.7)	11.6 (3.4–39.6)	2.7 (1.5–4.8)	30.52*	0.00	0.55 (Large)
All	1940	691 (35.6)	551 (28.4)	441 (22.7)	257 (13.2)	1.3 (2.7–0.6)	1.7 (0.8–3.7)	2.8 (1.2–6.5)	1.9 (1.1–3.3)	11.96*	0.01	0.35 (Medium)
TID Center												
2004 (U18)	13	2 (15.4)	2 (15.4)	5 (38.5)	4 (30.8)	1.0 (0.4, 2.5)	0.4 (0.2–1.0)	0.5 (0.2–1.2)	0.5 (0.2–0.8)	13.75*	0.00	0.37 (Medium)
2005 (U17)	42	10 (23.8)	14 (33.3)	8 (19.0)	10 (23.8)	0.7 (0.3, 1.6)	1.4 (0.6–3.1)	1 (0.5–2.3)	1.4 (0.7–2.4)	5.06	0.17	0.23 (Small)
2006 (U16)	292	101 (34.6)	83 (28.4)	76 (26.0)	32 (11.0)	1.2 (0.6, 2.6)	1.5 (0.7–3.1)	3.2 (1.3–7.8)	1.8 (1–3.1)	12.81*	0.01	0.36 (Medium)
2007 (U15)	387	130 (33.6)	129 (33.3)	83 (21.4)	45 (11.6)	1.0 (0.5, 2.2)	1.7 (0.8–3.7)	3.0 (1.2–7.1)	2.1 (1.2–3.8)	14.68*	0.00	0.38 (Medium)
2008 (U14)	434	167 (38.5)	116 (26.7)	91 (21.0)	60 (13.8)	1.5 (0.7, 31)	2.0 (0.9–4.3)	2.9 (1.2–6.6)	2 (1.1–3.5)	14.71*	0.00	0.3 (Medium)
2009 (U13)	23	10 (43.5)	6 (26.1)	6 (26.1)	1 (4.3)	1.7 (0.8, 3.6)	1.8 (0.9–3.8)	10.4 (3.3–32.5)	2.4 (1.3–4.3)	32.64*	0.00	0.57 (Large)
All	1191	421 (35.3)	350 (29.4)	269 (22.6)	152 (12.8)	1.2 (0.6, 2.6)	1.7 (0.8–3.7)	2.8 (1.2–6.6)	1.9 (1.1–3.4)	12.43*	0.01	0.35 (Medium)
YNT												
[a]1999–2001 (U23)	44	10 (22.7)	13 (29.5)	12 (27.3)	9 (20.5)	0.7 (0.3–1.6)	1.3 (0.6–3.1)	1.4 (0.6–3.2)	1.1 (0.7–2.0)	1.80	0.62	0.13 (Small)
[a]2002–2004 (U20)	60	17 (28.3)	12 (20.0)	12 (20.0)	19 (31.7)	1.2 (0.5–3.0)	0.5 (0.3–1.2)	1.3 (0.6–3.0)	1.0 (0.6–1.7)	5.06	0.17	0.22 (Small)
2005 (U17)	47	13 (27.7)	13 (27.7)	10 (21.3)	11 (23.4)	1.0 (0.5–2.2)	1.4 (0.6–3.1)	1.2 (0.6–2.7)	1.3 (0.7–2.3)	1.93	0.59	0.14 (Small)
2006 (U16)	23	5 (21.7)	4 (17.4)	10 (43.5)	4 (17.4)	1.5 (0.7–3.2)	1.5 (0.7–3.4)	0.9 (0.4–2.0)	0.7 (0.4–1.2)	15.85*	0.00	0.39 (Medium)
2007 (U15)	59	15 (25.4)	21 (35.6)	12 (20.3)	11 (18.6)	0.8 (0.4–1.7)	0.9 (0.4–2.0)	1.1 (0.5–2.6)	1.6 (0.9–2.9)	7.80*	0.05	0.28 (Small)
All	233	60 (25.8)	63 (27.0)	56 (24.0)	54 (23.2)	0.7 (0.3–1.6)	1.3 (0.6–3.1)	1.4 (0.6–3.2)	1.2 (0.7–2.0)	0.64	0.89	0.08 (Small)

TID = talent identification; YNT = Youth National Team; Q1 = Jan-Mar; Q2 = Apr-Jun; Q3 = Jul-Sep; Q4 = Oct-Dec, S1 = Jan-Jun, S2 = Jul-Dec, aQ1 = Aug-Oct; Q2 = Nov-Jan; Q3 = Feb-Apr; Q4 = May-Jul, and semesters: S1 = Aug-Jan; S2 = Feb-Jul, χ^2 = Chi-squared, *Significant at an alpha level of $p < 0.05$, w = Cohen's w effect size.

TABLE 2. Birth quartile distribution by position.

		Birthdate Distribution (%)				Odds Ratio (95% CI)						
	n	Q1	Q2	Q3	Q4	Q1 vs. Q2	Q1 vs. Q3	Q1 vs. Q4	S1 vs. S2	χ^2	p	w
Club												
Goalkeeper	177	63 (35.6)	62 (35.0)	33 (18.6)	19 (10.7)	1.0 (0.5–2.2)	2.1 (0.9–4.6)	3.4 (1.4–8.3)	2.5 (1.4–4.5)	20.06*	0.00	0.45 (Medium)
Full Backs	221	72 (32.6)	56 (25.3)	55 (24.9)	38 (17.2)	1.3 (0.6–2.8)	1.4 (0.7–3.1)	2.0 (0.9–4.4)	2.1 (1.1–3.7)	5.42	0.14	0.23 (Small)
Center Backs	286	125 (43.7)	86 (30.1)	51 (17.8)	24 (8.4)	1.5 (0.7–3.1)	2.7 (1.2–5.8)	5.4 (2.1–13.5)	3 (1.6–5.3)	30.71*	0.00	0.51 (Large)
Midfields	701	248 (35.4)	187 (26.7)	167 (23.8)	99 (14.1)	1.4 (0.6–2.9)	1.6 (0.8–3.5)	2.6 (1.1–5.9)	1.7 (1.0–3.0)	10.32*	0.02	0.32 (Medium)
Wide Forwards	330	106 (32.1)	97 (29.4)	79 (23.9)	48 (14.5)	1.1 (0.5–2.4)	1.5 (0.7–3.2)	2.3 (1.0–5.3)	1.7 (1.0–2.9)	8.05*	0.05	0.28 (Small)
Center Forward	221	74 (33.5)	62 (28.1)	56 (25.3)	29 (13.1)	1.2 (0.6–2.6)	1.4 (0.7–3.1)	2.6 (1.1–6.2)	1.7 (1.0–2.9)	9.69*	0.02	0.31 (Medium)
TID Center												
Goalkeeper	114	34 (29.8)	41 (36.0)	27 (23.7)	12 (10.5)	0.8 (0.4–1.8)	1.4 (0.6–3.0)	2.9 (1.2–7.2)	2.0 (1.1–3.6)	15.02*	0.00	0.39 (Medium)
Full Backs	162	49 (30.2)	47 (29.0)	35 (21.6)	31 (19.1)	1.1 (0.5–2.3)	1.5 (0.7–3.3)	1.6 (0.7–3.6)	1.5 (0.9–2.7)	4.45	0.22	0.21 (Small)
Center Backs	182	78 (42.9)	51 (28.0)	35 (19.2)	18 (9.9)	1.6 (0.8–3.3)	2.4 (1.1–5.3)	4.5 (1.8–10.9)	2.6 (1.4–4.6)	25.97*	0.00	0.51 (Large)
Midfields	367	128 (34.9)	106 (28.9)	88 (24)	45 (12.3)	1.2 (0.6–2.6)	1.6 (0.7–3.4)	2.9 (1.2–6.9)	1.8 (1.0–3.2)	12.06*	0.01	0.35 (Medium)
Wide Forwards	190	58 (30.5)	50 (26.3)	49 (25.8)	33 (17.4)	1.2 (0.6–2.6)	1.3 (0.6–2.8)	1.8 (0.8–4.1)	1.4 (0.8–2.4)	4.02	0.26	0.20 (Small)
Center Forward	134	53 (39.6)	46 (34.3)	28 (20.9)	7 (5.2)	1.2 (0.6–2.4)	2.1 (1.0–4.4)	7.8 (2.7–22.9)	3.0 (1.6–5.4)	30.29*	0.00	0.55 (Large)
YNT												
Goalkeeper	24	7 (29.2)	8 (33.3)	8 (33.3)	1 (4.2)	0.9 (0.4–1.9)	1.0 (0.5–2.0)	7.2 (2.2–23.0)	1.7 (1.0–3.1)	23.03*	0.00	0.48 (Medium)
Full Backs	30	8 (26.7)	9 (30.0)	5 (16.7)	8 (26.7)	0.9 (0.4–2.0)	1.7 (0.8–4.0)	1.0 (0.5–2.2)	1.4 (0.8–2.4)	5.08	0.67	0.22 (Small)
Center Backs	39	10 (25.6)	10 (25.6)	11 (28.2)	8 (20.5)	1.0 (0.5–2.2)	1.0 (0.5–2.1)	1.3 (0.6–2.9)	1.1 (0.6–1.9)	1.01	0.80	0.10 (Small)
Midfields	79	19 (24.1)	17 (21.5)	19 (24.1)	24 (30.4)	1.1 (0.5–2.6)	1.1 (0.5–2.4)	0.8 (0.4–1.8)	0.9 (0.5–1.5)	1.86	0.60	0.14 (Small)
Wide Forwards	38	10 (26.3)	12 (31.6)	7 (18.4)	9 (23.7)	0.9 (0.4–1.8)	1.6 (0.7–3.5)	1.1 (0.5–2.5)	1.4 (0.8–2.5)	4.56	0.21	0.21 (Small)
Center Forward	23	6 (26.1)	7 (30.4)	6 (26.1)	4 (17.4)	0.9 (0.4–1.9)	1.1 (0.0–2.4)	1.6 (0.7–3.6)	1.4 (0.8–2.4)	3.88	0.28	0.31 (Medium)

TID = talent identification; YNT = Youth National Team; Q1 = Jan-Mar; Q2 = Apr-Jun; Q3 = Jul-Sep; Q4 = Oct-Dec, S1 = Jan-Jun, S2 = Jul-Dec, aQ1 = Aug-Oct; Q2 = Nov-Jan; Q3 = Feb-Apr; Q4 = May-Jul, and semesters: S1 = Aug-Jan; S2 = Feb-Jul, χ^2 = Chi-squared, *Significant at an alpha level of $p < 0.05$, w = Cohen's w effect size.

TABLE 3. Birth quartile distribution by estimated maturation.

		Birthdate Distribution (%)				Odds Ratio (95% CI)						
	n	Q1	Q2	Q3	Q4	Q1 vs. Q2	Q1 vs. Q3	Q1 vs. Q4	S1 vs. S2	χ^2	p	w
Club												
Early-Maturers	556	211 (38.0)	158 (28.4)	117 (21.0)	70 (12.6)	1.4 (0.7–2.9)	2.0 (0.9–4.2)	3.1 (1.3–7.2)	2.1 (1.2–3.7)	15.53*	0.00	0.39 (Medium)
On-Time-Maturers	1191	430 (36.1)	355 (29.8)	268 (22.5)	138 (11.6)	1.2 (0.6–1.8)	1.8 (0.8–3.8)	3.2 (1.3–7.6)	2 (1.1–3.6)	14.61*	0.00	0.38 (Medium)
Late-Maturers	183	45 (24.6)	37 (20.2)	55 (30.1)	46 (25.1)	1.2 (0.6–2.8)	0.9 (0.4–1.9)	1.0 (0.5–2.2)	0.9 (0.5–1.5)	1.37	0.71	0.12 (Small)
TID Center												
Early-Maturers	343	129 (37.6)	106 (30.9)	82 (23.9)	26 (7.6)	1.2 (0.6–2.6)	1.7 (0.8–3.6)	5.1 (1.9–13.3)	2.3 (1.3–4.1)	21.26*	0.00	0.46 (Medium)
On-Time-Maturers	700	244 (34.9)	210 (30.0)	150 (21.4)	96 (13.7)	1.2 (0.6–2.5)	1.8 (0.8–3.8)	2.6 (1.1–6.1)	1.9 (1.1–3.4)	11.86*	0.01	0.34 (Medium)
Late-Maturers	126	43 (34.1)	24 (19.0)	34 (27.0)	25 (19.8)	1.8 (0.8–4.1)	1.4 (0.7–2.9)	1.8 (0.8–3.9)	1.2 (0.7–2.1)	6.49	0.09	0.26 (Small)
YNT												
Early-Maturers	33	7 (21.2)	15 (45.5)	6 (18.2)	5 (15.2)	0.5 (0.2–1.0)	1.3 (0.6–2.9)	1.4 (0.6–3.4)	2.1 (1.2–3.7)	24.08*	0.00	0.49 (Medium)
On-Time-Maturers	72	23 (31.9)	21 (29.2)	20 (27.8)	8 (11.1)	1.1 (0.5–2.4)	1.3 (0.6–2.7)	3.0 (1.2–7.2)	1.6 (0.9–2.9)	10.99*	0.01	0.33 (Medium)
Late-Maturers	18	3 (16.7)	1 (5.6)	4 (22.2)	10 (55.6)	3.1 (1.0–9.3)	0.8 (0.4–1.9)	0.3 (0.1–0.7)	0.3 (0.2–0.6)	55.87*	0.00	0.75 (Large)

TID = talent identification; YNT = Youth National Team; Q1 = Jan-Mar; Q2 = Apr-Jun; Q3 = Jul-Sep; Q4 = Oct-Dec, S1 = Jan-Jun, S2 = Jul-Dec, aQ1 = Aug-Oct; Q2 = Nov-Jan; Q3 = Feb-Apr; Q4 = May-Jul, and semesters: S1 = Aug-Jan; S2 = Feb-Jul, χ^2 = Chi-squared, *Significant at an alpha level of $p < 0.05$, w = Cohen's w effect size.

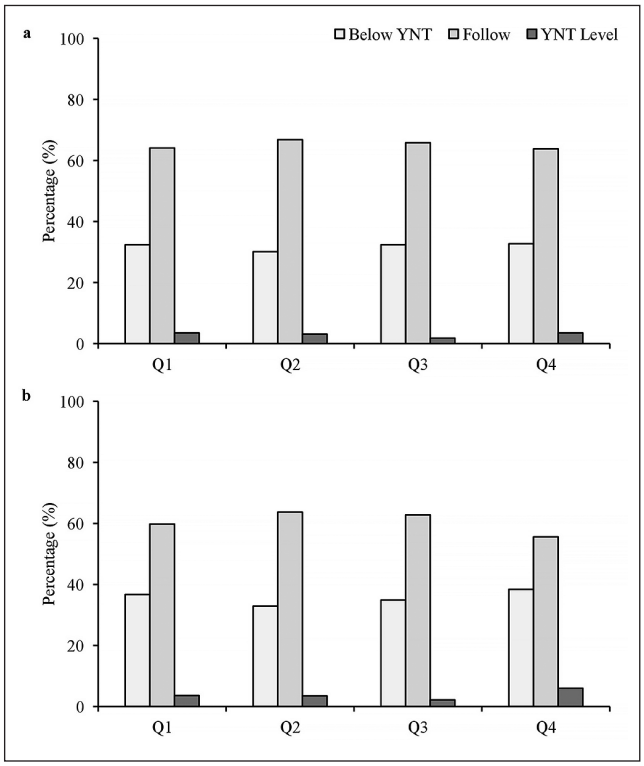


FIG. 2. BQ distribution for Club (a) and TID Center (b) presented as a function of overall performance rating.
YNT = Youth National Team.

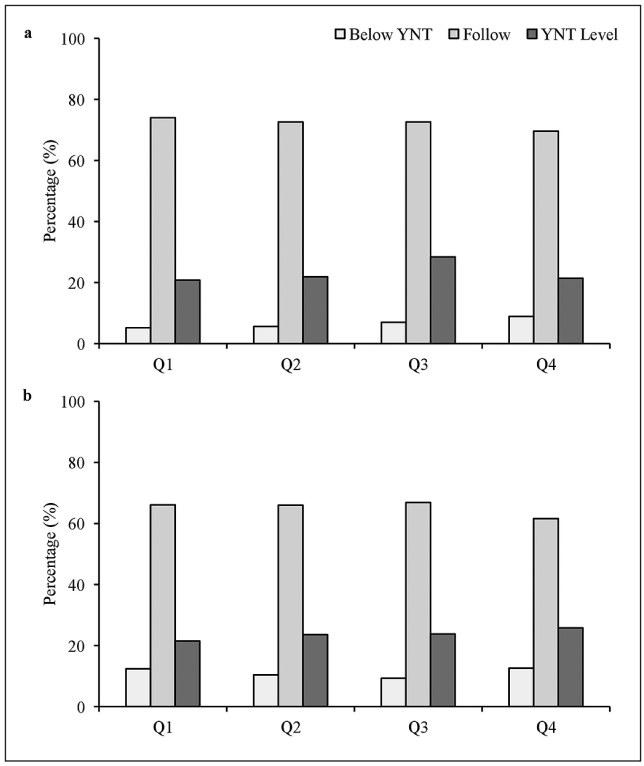


FIG. 3. BQ distribution for Club (a) and TID Center (b) presented as a function of potential rating.
YNT = Youth National Team

TABLE 4. Birth quartile distribution by current and potential skill rating.

		Birthdate Distribution (%)				Odds Ratio (95% CI)						
	n	Q1	Q2	Q3	Q4	Q1 vs. Q2	Q1 vs. Q3	Q1 vs. Q4	S1 vs. S2	χ^2	p	w
Overall Rating												
Club												
Below YNT	617	224 (36.3)	166 (26.9)	143 (23.2)	84 (13.6)	1.4 (0.7–2.9)	1.7 (0.8–3.7)	2.7 (1.2–6.4)	1.8 (1.0–3.2)	11.80*	0.01	0.34 (Medium)
Follow	1265	443 (35.0)	368 (29.1)	290 (22.9)	164 (13.0)	1.2 (0.6–2.6)	1.7 (0.8–3.6)	2.8 (1.2–6.5)	1.9 (1.1–3.3)	11.77*	0.01	0.34 (Medium)
YNT level	58	24 (41.4)	17 (29.3)	8 (13.8)	9 (15.5)	1.4 (0.7–3.0)	3.3 (1.4–7.5)	2.7 (1.2–6.2)	2.5 (1.4–4.5)	22.71*	0.00	0.48 (Medium)
TID Center												
Below YNT	420	154 (36.7)	114 (27.1)	94 (22.4)	58 (13.8)	1.4 (0.7–2.9)	1.8 (0.8–3.0)	2.7 (1.2–6.3)	1.8 (1.0–3.3)	12.28*	0.01	0.35 (Medium)
Follow	725	251 (34.6)	221 (30.5)	169 (23.3)	84 (11.6)	1.2 (0.6–2.4)	1.6 (0.8–3.5)	3.1 (1.3–7.3)	2.0 (1.1–3.5)	11.77*	0.00	0.37 (Medium)
YNT level	42	15 (35.7)	12 (28.6)	6 (14.3)	9 (21.4)	1.3 (0.6, 2.7)	2.7 (1.2–6.2)	1.7 (0.8–3.7)	1.9 (1.1–3.3)	12.15*	0.01	0.35 (Medium)
Potential Rating												
Club												
Below YNT	121	36 (29.8)	31 (25.6)	31 (25.6)	23 (19)	1.2 (0.6, 2.6)	1.3 (0.6–2.7)	1.6 (0.7–3.6)	1.3 (0.7–2.3)	2.76	0.43	0.17 (Small)
Follow	1410	511 (36.2)	400 (28.4)	320 (22.7)	179 (12.7)	1.3 (0.6, 2.8)	1.7 (0.8–3.7)	2.9 (1.3–6.9)	1.9 (1.1–3.4)	13.13*	0.00	0.36 (Medium)
YNT level	409	144 (35.2)	120 (29.3)	90 (22.0)	55 (13.4)	1.2 (0.6, 2.6)	1.7 (0.8–3.8)	2.7 (1.2–6.3)	1.9 (1.1–3.4)	11.92*	0.01	0.35 (Medium)
TID Center												
Below YNT	132	52 (39.4)	36 (27.3)	25 (18.9)	19 (14.4)	1.5 (0.7, 3.1)	2.3 (1.0–5.0)	2.8 (1.2–6.4)	2.1 (1.2–3.7)	16.43*	0.00	0.41 (Medium)
Follow	779	277 (35.6)	229 (29.4)	180 (23.1)	93 (11.9)	1.2 (0.6, 2.6)	1.7 (0.8–3.6)	3.1 (1.3–7.3)	1.9 (1.1–3.4)	13.48*	0.00	0.36 (Medium)
YNT level	275	90 (32.7)	82 (29.8)	64 (23.3)	39 (14.2)	1.1 (0.5, 2.4)	1.5 (0.7–3.3)	2.4 (1.0–5.5)	1.7 (1.0–3.1)	9.00*	0.03	0.30 (Medium)

TID = talent identification; YNT = Youth National Team; Q1 = Jan-Mar; Q2 = Apr-Jun; Q3 = Jul-Sep; Q4 = Oct-Dec, S1 = Jan-Jun, S2 = Jul-Dec, aQ1 = Aug-Oct; Q2 = Nov-Jan; Q3 = Feb-Apr; Q4 = May-Jul, and semesters: S1 = Aug-Jan; S2 = Feb-Jul, χ^2 = Chi-squared, *Significant at an alpha level of $p < 0.05$, w = Cohen's w effect size.

DISCUSSION

This study investigated RAE prevalence of youth female soccer players in the US across three stages of the TID process. The main findings were: (1) RAE was present in *Club* and *TID Center*, but not in *YNT*; (2) RAE existed for most positions in *Club* and *TID Centers* (with the consistent exception of full backs across both stages, and wide forwards in the latter). At *YNT*, RAE was only evident in goalkeepers: (3) and RAE was evident in players estimated as early- or on-time-maturers, but not in late-maturing players in *Club* and *TID Centers*, *YNT* had a greater percentage of late-maturing players, with a reverse RAE. Differences emerged along the TID process, which underlines the value of taking a broader lens when trying to understand RAE in a particular context.

Our data indicated RAEs for *Club* players, with Q1 players over-represented between U13–U17. Similar patterns were observed at *TID Center*, with Q1 over-represented from U13–U16, Q2 being the dominant quarter at U17, and Q3 and Q4 being over-represented at U18. At *YNT*, RAEs were observed at U15–U16 yet this didn't follow the typical patterns, with Q2 and Q3 being over-represented. RAE increased from youth-to-senior transitions in female soccer players in Germany [21], yet this was not observed in the US, with U16 *YNT* showing bias to S2 players. Between-country examinations showed no RAEs in U17 players in Europe (11), yet youth players in North and Central America displayed RAEs [13, 24], highlighting the contextual nature of RAE. One of the strongest RAEs was observed in BY2009 at both *Club* and *TID Center* and is in-line with Korgaokar

et al. [28] who observed RAEs in US youth female soccer players between 2012–13, yet they only examined one league platform.

More competitive game/platform structures with increased competition for places can lead to more pronounced RAEs at all levels, resulting in the potential for talented players to be overlooked [10]. Therefore, it is possible that an emphasis on earlier-born players is facilitated by the competitive, multi-platform landscape of youth female soccer in the US, as well as opportunities for players to be exposed to college scouts (the next step of the talent pathway) and highly lucrative athletic scholarships may pressure club-level coaches to achieve instant success (playoffs). Although relationships between RAE and success (e.g., final league position) in youth male soccer players in Germany have been reported [33], this was not the same for female national players [13], whilst Andrew et al. [11] reported significant RAEs for U19 players who did not qualify for European Championships. The effect size of RAE decreased from U13–U17, yet it is unclear whether this was due to the levelling of certain advantages, or an overall strengthening of RAEs in female soccer in the last decade [34]. As in our *Club* and previous data [30], scouts may be selecting from an already unequal sample, thus increasing the possibility of RAEs at international levels [24], yet the bias for selecting Q1 players continued to *YNT* for U15 players only.

When analysing RAE and playing position, our data indicated RAEs for midfielders and center forwards with medium effect size, and center backs with a large effect size at *Club* and *TID Center*, with an overrepresentation of Q1 players, yet no RAE at *YNT*. Previous examinations of the role of playing position have reported RAE is most prevalent in female goalkeepers and defenders in Spain [18], defenders and midfielders in Italy [19], only forwards in Olympic teams [12]. Like U17 female players in Italy [22], Q1 midfielders were three times more likely to be selected vs. Q4, yet as previously suggested [13] and consistent with YNT position profiles, we made distinctions between wide and central positions that may have influenced the results. For goalkeepers, RAE was observed, with an overrepresentation Q2 players. Whilst this was only evident in this position, it is consistent with female goalkeepers in Spain [18] and youth players in Europe, North/Central America [24]. It has been suggested that RAE in goalkeepers may be underpinned by a preference for 'taller' players [16], but we did not measure stature. A possible explanation could be that it is associated with early physical development being a socially constructed disadvantage for female athletes during puberty and may result in higher disengagement from Q1 players [23: 35] yet the current data showed higher levels of *YNT* labelled as early-maturers from Q2.

Maturity status and RAE play an independent and important role in the TID process of youth female soccer players [36]. Overall, our data showed fewer on-time and late-maturing players, and more early-maturing players, indicating preferences at *Club* and *Talent ID Center* for players with advanced physical maturity. The less late-maturing players (10.2%) observed was similar when compared to previous observations of youth soccer players (17.5% [36]), yet we observed a greater overrepresentation of early-maturing players (28.9% vs. 18.3% [36]). These findings may be related to the accuracy of the non-invasive methods utilised within the present study, yet moderate agreement between invasive and non-invasive methods for assessing maturation have been reported from youth male soccer players [37]. Whilst coaches have been shown to be good at judging biological maturation relative to chronological age [29], the high level of early-maturing players at *Club* in the present study may be due to their respective coach's selection being focused on current over future performance [13]. Regarding biological maturation, early-maturing male soccer players have previously been reported to be 'taller' and 'heavier' than late-maturing players [38]. Because of the constraints of youth male soccer competition, early-maturing players are able to exploit their physical advantage and progress through the talent pathway [38–40]. In comparison, in youth female soccer players, whilst this seems to be the case at *Club* and *TID Centers*, there were more late-maturing players at *YNT*. This is noteworthy as our sample includes U15–U23 players and does not include the typical ages where maturity differences are greatest in youth female soccer [41] and may be related to recent investments in TID education at *YNT* within US Soccer. Furthermore, the data identified a consistent RAE in early- and on-time-maturing players across the TID process, including an OR of 5.1 between Q1 and Q4 being an early-maturing player at *TID Center*. No RAE was evident for late-maturers within *Club* and *TID Center*, with an RAE reversal [42)] evident in *YNT* players, with late-maturers more likely to be from BQ4 and this group consisted of a higher percentage of late-maturers than from elsewhere in the TID process.

The analysis of current performance and potential ability provides more information on the mechanisms of RAE in youth female soccer. Studies in European female soccer are mixed, with Ginés et al. [36] identifying Q3 and Q4 U12–U14 players as less likely to be perceived as having the potential for future success. Yet Brustio et al. [22] reported that Q4 players were most likely to transition from youth-to-senior international level. Our data indicated that Q3 players had the lowest numbers of current performance rating of 'YNT level' (the highest rating possible to achieve), at both *Club* and *TID Center*, yet Q3 players were significantly over-represented at U16 YNT. Ratings for Q4 players were split, with both being most likely to be recommended as the lowest (below YNT) or highest (YNT) levels at *TID Center*. Regarding potential ability, players with the lowest ratings at *Club* were the only non-significant result, they contained less Q1 but more Q4 players than the highest-rated players (i.e., continue to follow/invite to *TID Center*). Relatively younger players may have physical, psychosocial, and motor disadvantages [43] and therefore, to enter and survive in high-performance environments, they may have to acquire higher levels of other skills (e.g., technical/tactical) necessary to overcome RAEs [42]. While relatively older players may not have to possess the same skills to enter the same environment [44], it has been suggested that soccer-nations must give thought to interventions at grassroots (*Club*) level to potentially limit RAEs [45],

providing the opportunity for long-term development. It should be noted that US Soccer has recently reformed the TID department (education, courses), thus it would be advantageous to revisit our data to examine the impact of these potential interventions.

CONCLUSIONS

To conclude, our data showed an RAE of youth female soccer players within the US. At *Club* and *TID Center*, this RAE was most prominent in goalkeepers, center backs, midfielders, and center forwards, and for U13–U18 ages, but these did not typically transfer to *YNT*. Consistent RAEs were observed in early- and on-time-maturers across all levels. A reversal of 'typical' RAE was evident at *YNT*, with late-maturers more likely to be from Q4 and a higher percentage than elsewhere in the TID process. When interpreting all the data, some limitations should be acknowledged. Due to the large volume of players and the club soccer environment, we used estimated measurements of maturation. Future research may examine comparisons between scouts' perceptions and actual biological maturation status. Moreover, we only provided a 'snapshot' of RAE in youth female soccer in the US. Therefore longitudinal, cross-sectional analysis examining youth-to-senior transitions would be beneficial to identify if there were different patterns of RAE amongst players retained across the stages in comparison to those newly selected [22].

Conflict of Interest

The authors declared no conclict of interest.

REFERENCES

1. FIFA. Setting the Pace. FIFA benchmarking report women's football [online]. 2022. Available from: https://digitalhub.fifa.com [Accessed June 2nd, 2023].
2. Williams AM, Ford PR, Drust B. Talent identification and development in soccer since the millennium. J Sports Sci. 2020; 38(11–12):1199–1210.
3. Okholm Kryger K, Wang A, Mehta R, Impellizzeri FM, Massey A, McCall A. Research on women's football: A scoping review. Sci Med Footb. 2021:1–10.
4. Curran O, MacNamara A, Passmore D. What about the girls? Exploring the gender data gap in talent development. Front Spo Act Living. 2019; 1:3.
5. Cobley S, Baker J, Wattie N, McKenna J. Annual age-grouping and athlete development: A meta-analytical review of relative age effects in sport. Sports Med. 2009; 39:235–256.
6. Røsten S, Sæther SA, Aspvik NP, Bjørndal CT. Embedded, embodied, enculturated, and enabling processes: The identification and evaluation of sporting talent by ice hockey coaches in Norwegian youth national teams. Int J Sports Sci Coach. 2023; 1(1):1–11.
7. Leyhr D, Bergmann F, Schreiner R, Mann D, Dugandzic D, Höner O. Relative age-related biases in objective and subjective assessments of performance in talented youth soccer players. Front Sport Act Living. 2021; 3:664231.
8. Finnegan L, Richardson D, Littlewood M, McArdle J. The influence of date and place of birth on youth player selection to a National Football Association elite development programme. Sci Med Footb. 2017; 1(1):30–39.
9. Dugdale JH, McRobert AP, Unnithan VB. "He's just a wee laddie": The relative age effect in male Scottish soccer. Front Psychol. 2021; 12:103.
10. Smith KL, Weir PL, Till K, Romann M, Cobley S. Relative age effects across and within female sport contexts: A systematic review and meta-analysis. Sports Med. 2018; 48:1451–1478.
11. Andrew M, Finnegan L, Datson N, Dugdale JH. Men are from quartile one, women are from? relative age effect in European soccer and the influence of age, success, and playing status. Children. 2022; 9(11):1747.
12. Barreira J, Bueno B, Chiminazzo JGC. Relative age effect and age of peak performance: An analysis of women's football players in the Olympic games (1996–2016). Motriz: Rev de Edu Física. 2021; 27.
13. Ribeiro E, Barreira J, Carraco D, Galatti L, Götze M, Cal Abad CC. The relative age effect in under-17, under-20, and adult elite female soccer players. Sci Med Footb. 2023:1–8.
14. Delorme N, Boiché J, Raspaud M. The relative age effect in elite sport: The French case. Res Q Exerc Sport. 2009; 80(2):336–344.
15. Teoldo I, Machado V, Casanova F, Cardoso F. Talent map of female soccer: How does the birthplace and birthdate impact the participation of soccer players in Brazilian Serie A1 Championship?. J Hum Sport Exerc. 2023: Press-Press.
16. Romann M, Fuchslocher J. Influence of the selection level, age and playing position on relative age effects in Swiss women's soccer. Tal Dev Excel. 2011; 3(2):239–247.
17. Li Z, Mao L, Steingröver C, Wattie N, Baker J, Schorer J, Helsen WF. Relative age effects in Elite Chinese soccer players: Implications of the 'one-child' policy. PLoS One. 2021; 15(2):e0228611.
18. Sedano S, Vaeyens R, Redondo JC. The relative age effect in Spanish female soccer players. Influence of the competitive level and a playing position. J Hum Kinet. 2015; 46:129–137.
19. Brustio PR, Boccia G, De Pasquale P, Lupo C, Ungureanu AN. Small relative age effect appears in professional female Italian team sports. Int J Environ Res Public Health. 2021; 19(1):385.
20. Matsuda S, Ishigaki H. Trends in Relative Age effects of top-level female soccer players: A Japanese study. Percept Mot Skills. 2023; 130(3):984–998.
21. Götze M, Hoppe MW. Relative age effect in elite German soccer: Influence of gender and competition level. Front Psychol. 2021; 11:587023.
22. Brustio PR, Modena R, Boccia G, Vogliazzo M, Kelly AL. Youth-to-senior transition in women's and girls' football: Towards a better understanding of relative age effects and gender-specific considerations. PLoS One. 2023; 18(5):e0283781.
23. Baker J, Schorer J, Cobley S, Bräutigam H, Büsch D. Gender, depth of competition and relative age effects in team sports. Asian J Exe Sports Sci. 2009; 6(1):1–7.
24. Romann M, Fuchslocher J. Influences of player nationality, playing position, and height on relative age effects at women's under-17 FIFA World Cup. J Sports Sci. 2013; 31(1):32–40.
25. Bennett KJ, Vaeyens R, Fransen J. Creating a framework for talent identification and development in emerging football nations. Sci Med Footb. 2019; 3(1):36–42.
26. Allison R, Barranco R. 'A rich white kid sport?' Hometown socioeconomic, racial, and geographic composition among US women's professional soccer players. Soccer Soc. 2021; 22(5):457–469.
27. Ford PR, Bordonau JLD, Bonanno D, Tavares J, Groenendijk C, Fink C, Gualtieri D, Gregson W, Varley MC, Weston M, Lolli L, Platt D, Di Salvo V. A survey of talent identification and development processes in the youth academies of professional soccer clubs from around the world. J Sports Sci. 2020; 38(11–12):1269–1278.
28. Korgaokar AD, Farley RS, Fuller DK, Caputo JL. Relative age effect among elite youth female soccer players across the United States. Sport Mont. 2018; 16(3):37–41.

29. Romann M, Javet M, Fuchslocher J. Coaches' eye as a valid method to assess biological maturation in youth elite soccer. Tal Dev Excel. 2017; 9(1):3–13.
30. Smith KL, Scarfone S, Chittle L, Horton S, Dixon JC. Confusion reigns: An analysis of responses to US soccer age cut-off date policy change. Front Sports Act Living. 2021; 3:635195.
31. Padrón-Cabo A, Rey E, García-Soidán JL, Penedo-Jamardo E. Large scale analysis of relative age effect on professional soccer players in FIFA designated zones. Int J Perform Anal Sport. 2016; 16(1):332–346.
32. Cohen J. Quantitative methods in psychology: A power primer. Psychol Bull. 1992; 112:1155–1159.
33. Augste C, Lames M. The relative age effect and success in German elite U-17 soccer teams. J Sports Sci. 2011; 29(9):983–987.
34. Pedersen AV, Aune TK, Dalen T, Lorås H. Variations in the relative age effect with age and sex, and over time-elite-level data from international soccer world cups. PLoS One. 2022; 17(4):e0264813.
35. Vincent J, Glamser FD. Gender differences in the relative age effect among US Olympic Development Program youth soccer players. J Sports Sci. 2006; 24(4):405–413.
36. Ginés HJ, Huertas F, García Calvo T, Ponce-Bordón JC, Figueiredo AJ, Ballester R. Age and maturation matter in youth elite soccer, but depending on competitive level and gender. Int J Environ Res Public Health. 2023; 20(3):2015.
37. Sullivan J, Roberts SJ, Mckeown J, Littlewood M, McLaren-Towlson C, Andrew M, Enright K. Methods to predict the timing and status of biological maturation in male adolescent soccer players: A narrative systematic review. PLoS One. 2023; 18(9):e0286768.
38. Meylan C, Cronin J, Oliver J, Hughes M. Talent identification in soccer: The role of maturity status on physical, physiological and technical characteristics. Int J Sports Sci Coach. 2010; 5(4):571–592.
39. Sweeney L, Cummin SP, MacNamara Á, Horan D. The selection advantages associated with advanced biological maturation vary according to playing position in national-level youth soccer. Biol Sport. 2023; 40(3):715–722.
40. Cripps AJ, Hopper LS, Joyce C. Coaches' perceptions of long-term potential are biased by maturational variation. Int J Sports Sci Coach. 2016; 11(4):478–481.
41. Malina RM, Martinho DV, Valente-dos-Santos J, Coelho-e-Silva MJ, Kozieł SM. Growth and maturity status of female soccer players: A narrative review. Int J Environ Res Public Health. 2021; 18(4):1448.
42. Kelly AL, Wilson MR, Gough LA, Knapman H, Morgan P, Cole M, Jackson DT, Williams CA. A longitudinal investigation into the relative age effect in an English professional football club: Exploring the 'underdog hypothesis'. Sci Med Footb. 2020; 4(2):111–118.
43. Wattie N, Cobley S, Baker J. Towards a unified understanding of relative age effects. J Sports Sci. 2008; 26(13):1403–1409.
44. Votteler A, Höner O. The relative age effect in the German football tid programme: Biases in motor performance diagnostics and effects on single motor abilities and skills in groups of selected players. Eur J Sport Sci. 2014; 14(5):433–442.
45. Webdale K, Baker J, Schorer J, Wattie N. Solving sport's 'relative age' problem: A systematic review of proposed solutions. Int Rev Sport Exerc Psychol. 2020; 13(1):187–204.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.132995
© Institute of Sport – National Research Institute

Exercise intensity and reliability during recreational team handball training for 50–77-year-old unexperienced women

AUTHORS: Rita Pereira[1,2], Peter Krustrup[3,4,5,6], Carlo Castagna[3,7], Carlos Resende[8], Ivone Carneiro[9], José Magalhães[1], Susana Póvoas[3,9]

[1] Laboratory of Metabolism and Exercise (LaMetEx), Research Centre in Physical Activity, Health and Leisure (CIAFEL), Faculty of Sport, University of Porto, Porto, Portugal
[2] University of Maia, Maia, Portugal
[3] Department of Sports Science and Clinical Biomechanics, SDU Sport and Health Sciences Cluster (SHSC), University of Southern Denmark, Odense, Denmark
[4] Danish Institute for Advanced Study (DIAS), University of Southern Denmark, Odense, Denmark
[5] Sport and Health Sciences, University of Exeter, Exeter, UK
[6] Shanghai University of Sport (SUS), Shanghai, China
[7] Department of Biomolecular Sciences, School of Exercise and Health Sciences, Carlo Bo Urbino University, Urbino, Italy
[8] Centre of Research, Education, Innovation and Intervention in Sport (CIFID), Faculty of Sport, University of Porto, Porto, Portugal
[9] Research Center in Sports Sciences, Health Sciences and Human Development (CIDESD), University of Maia, Maia, Portugal

ABSTRACT: This study analyzed the physiological and physical demands of recreational team handball (RTH) and the training sessions' (matches) intensity variability in 50–77-year-old postmenopausal women (n = 20) without prior experience with the sport. Heart rate (HR), blood lactate, rating of perceived exertion (RPE), distance covered, time spent in different locomotor categories, accelerations, decelerations, Player Load (PL), game actions and fun levels were evaluated in 245 matches, played indoor (n = 130) or outdoor (n = 115), as small-sided games (3 × 15-min periods). Mean and peak HRs were 79 and 88% of maximal HR (%HR_{max}), showing reliable values across the training sessions, with time spent in the HR zones showing excellent relative reliability, though poor absolute reliability. Time spent > 80 and > 90%HR_{max} was 48% and 14% of total match time, respectively. Mean and peak blood lactate values were 2.6 ± 0.8 and 2.9 ± 0.9 mmol·l^{-1}, respectively. RPE was 5.5 ± 1.5, showing good relative though poor absolute reliability, and fun levels were 8.4 ± 1.1 (0–10 scale). Total distance covered was 1878 ± 333 m and the participants spent 54%, 3% and < 1% of total match time walking, fast running and sprinting, respectively. Total PL was 224 ± 41 (AU), with 67% of total match time being spent in low-intensity zones. Participants performed a total of 38 specific high-demanding actions per match, mainly throws (10.6 ± 5.8) and stops (11.0 ± 3.6). RTH training, played as small-sided games, is a high-intensity exercise training mode with high aerobic and anaerobic demands, low RPE and high fun levels for 50–77-year-old women without prior experience with the sport. Average cardiovascular demands were consistent across the training sessions.

CITATION: Pereira R, Krustrup P, Castagna C et al. Exercise intensity and reliability during recreational team handball training for 50–77-year-old unexperienced women. Biol Sport. 2024;41(4):253–261.

Received: 2023-05-31; Reviewed: 2023-08-12; Re-submitted: 2023-11-13; Accepted: 2023-11-13; Published: 2024-05-17.

Corresponding author:
Susana Póvoas
Research Center in Sports Sciences, Health Sciences and Human Development (CIDESD), University of Maia, Maia, Portugal.
E-mail: spovoas@umaia.pt

ORCID:
Rita Pereira
0000-0002-8284-8237

Peter Krustrup
0000-0002-1461-9838

Carlo Castagna
0000-0002-8320-6404

Carlos Resende
0000-0001-8380-5928

Ivone Carneiro
0000-0001-5558-1082

José Magalhães
0000-0003-4808-8374

Susana Póvoas
0000-0002-6661-3673

Key words:
Team sports
Intermittent training
Activity profile
Global positioning system
Cardiovascular response

INTRODUCTION

Although the unequivocal positive health effects of physical activity (PA) and exercise, physical inactivity levels in Europe are high, particularly in over 55-year-old men and women [1]. Lack of motivation and interest is one of the main barriers to exercise or play sport, while enjoyment and fun have been reported as motives for being physically active [1, 2]. Thus, the World Health Organization (WHO) has made a call for innovative, health-enhancing exercise options, highlighting the role of sport in counteracting physical inactivity, and improving health by setting promotion of sport for all as a central policy recommendation in the WHO Global Action Plan on PA 2018–2030 [3]. In fact, team sports seem to meet the population's interests, based on the estimated high number of participants [4]. Football, team handball (TH), floorball, basketball, touch rugby and futsal have been adapted to its recreational versions (i.e., involving lower number of players, smaller areas, limited body contact, simpler rules) to be used in exercise interventions aiming at health

enhancements [4]. Team sports are an example of multicomponent exercise modalities, casuistically and intermittently combining low to high-intensity locomotion activities and high-demanding specific actions (e.g., jumps, accelerations, decelerations, changes of direction and stops) [4]. Therefore, the physical demands of team sports are aligned with the PA guidelines for adults and older adults that focus on moderate to vigorous-intensity aerobic PA, muscle-strengthening activities and balance training, to improve cardiorespiratory and muscular fitness, bone health, functional balance and preventing falls [5]. Exercise interventions using recreational team sports usually entail 2 weekly sessions of 40–60 min (i.e., 80–120 min/week), with mean heart rates (HRs) ranging from 71–85% of maximal HR (HR_{max}) [4]. Hence, team sports practice under these conditions (volume and intensity) meets part of the PA guidelines [5]. Moreover, ball games and team sports have been reported to be a motivating exercise mode [6], thus counteracting one of the main barriers to exercise [1, 2].

Recreational team handball (RTH) has shown to induce several health benefits, namely by improving cardiovascular, bone and metabolic health and physical fitness of different populations [7–12]. Particularly in postmenopausal women, RTH practice showed to improve peak oxygen uptake (VO_{2peak}), aerobic performance, bone mineral density (BMD) and content (BMC), bone turnover markers, postural balance, body mass, body fat, and total and low-density lipoprotein cholesterol [11, 12]. This is a population of interest considering the deleterious broad-spectrum impact of menopause on women's health [13], and that physical inactivity levels increase with age, and are higher in women than in men [1]. Nonetheless, even though the health benefits of RTH practice in this population have been described, its working demands have not been addressed in detail so far. Information on the external and internal load experienced during small-sided RTH games will result of great practical interest as it may explain the reasons underlying the observed health adaptations and allow for training prescription accuracy. Moreover, due to the casuistic nature of this exercise modality, it is of importance to know how the cardiovascular stress (HR) varies between training sessions that are based on RTH matches.

Therefore, the aim of this study is to examine the physiological (internal load) and physical demands (external load) induced by the most frequently used small-sided RTH games (i.e., 4v4 to 6v6) in postmenopausal women without prior experience with the sport and to analyze the intensity (HR) variability between training sessions (matches). Based on the results of previous studies [14, 15], we hypothesized that small-sided RTH games are a vigorous exercise activity, comprising high-intensity specific actions able to improve the cardiovascular and musculoskeletal systems of postmenopausal women. We also hypothesized that there is variability in the intensity (HR) among training sessions, although the cardiovascular stress is high on average, providing stimulus in the range to induce positive cardiovascular health adaptations.

MATERIALS AND METHODS

Participants

Recruitment started one month before the beginning of the trial. Twenty 50–77-year-old postmenopausal women (mean age 64 ± 7 years, stature 158 ± 7 cm, body mass 65.5 ± 10.9 kg, fat mass 36.0 ± 6.4%, VO_{2peak} 25.7 ± 3.4 $mL \cdot min \cdot kg^{-1}$) volunteered to participate in this study. Inclusion criteria were: women with menopause for at least 3 years and inactive (i.e., not complying with the PA guidelines for the last 6 months). Exclusion criteria were: participants that presented any contraindication to perform moderate-to-vigorous PA or incapacity to run or grip a ball.

All participants were informed verbally and in written about the purpose, potential risks, and benefits of the study and that they could withdraw at any time without penalty and signed a written informed consent. The study was carried out in accordance with the Declaration of Helsinki and ethical approval was provided by the local Ethics Committee (CEFADE 20 2019).

Experimental design

Internal and external load markers and fun levels evaluations were performed at the beginning of a RTH-based exercise intervention. Detailed description of the study is provided elsewhere [11, 12]. The participants randomly performed RTH matches (played as 4v4, 5v5 and 6v6), preceded by a standardized warm-up, in indoor (n = 130) and outdoor conditions (n = 115), organized in 3 × 15-min periods interspersed by 2-min breaks, and with at least 48 h of rest between matches. The matches were carried out on a regular TH court (40 × 20 m) adjusted in length and width to result in 34–36 m^2/player. The participants were hydrated at the beginning of the session and were allowed to drink water *ad libitum* to ensure the maintenance of proper hydration.

The participants rotated positions every 3 min in a random order, including the goalkeeper, and no exclusions or substitutions were applied. Dribbling was not allowed, and the ball was immediately put back in play by the goalkeeper after a goal. To avoid injuries, no hard tackles and physical contact were permitted, and the balls were made of soft material and lighter than the official ones.

The physiological and physical demands were analyzed considering internal [HR, blood lactate (BL), rating of perceived exertion (RPE)] and external [distance covered and time spent in different locomotor categories, accelerations, decelerations, Player Load (PL), and specific game actions] load variables and fun levels were also determined. In indoor conditions, only HR, RPE and fun levels were assessed, while in outdoor conditions all the study variables were evaluated. No differences were observed between indoor and outdoor conditions in mean and peak HR, time spent in the HR zones, RPE and fun levels (data not shown) and therefore, the data from the matches performed in these two conditions were analyzed together.

Experimental procedures

The participants were familiarized with all the procedures before the data collection. HR was evaluated using HR monitors (Firstbeat Technologies Ltd., version 4.7.2.1., Jyväskylä, Finland). Mean and peak HR are expressed as absolute ($b \cdot min^{-1}$) and relative values (%HR_{max}) and individual HR_{max} was determined according to a multiple testing approach [16]. HR zones were ≤ 60, 61–70, 71–80, 81–90 and 91–100% of individual HR_{max}. Capillary blood samples (~30 μL) were collected from the right earlobe at rest (baseline) and randomly in each match period, using a portable electroenzymatic lactate device analyzer (Lactate Pro 2 LT-1730, Arkray, Amsterdam, The Netherlands) to access BL concentrations ($mmol \cdot l^{-1}$). RPE (0–10, AU, Borg scale) [17] and fun levels (0–10, AU, visual analogic scale) [18] were evaluated at the end of the training sessions.

Distance covered (m) and time spent (s) in different locomotor categories (standing, walking, jogging, fast running and sprinting), accelerations and decelerations, and PL were measured using global positioning system (GPS) units (Catapult MinimaxX S4; Catapult Sports, Canberra, Australia), following standardized procedures. Catapult Sprint software (Catapult Innovations, Canberra, Australia, version 5.1.1) was used to export the data. The validity and reliability of the accelerometers have been described elsewhere [19]. In this study, individual speed thresholds were considered to normalize external load variables. For every participant, the mean velocity of each locomotor category over a set distance (20 m) was determined using telemetric photoelectric cells (Brower Timing System, IRD-T175, UT, USA). The mean velocity of the participants in each category was 6, 8, 12 and 13 $km \cdot h^{-1}$ for walking, jogging, fast running and sprinting, respectively. The resulting scores were used to set individual thresholds for the considered arbitrary speed categories. PL (estimated by triaxial accelerometry, measured at a 100 Hz sampling rate) was presented as total PL (AU) and percentage of time spent in PL zones (< 0.1, 0.1–0.3, 0.3–0.6, 0.6–1.0, 1.0–1.5, 1.5–2.0, > 2.0). The number of accelerations and decelerations was determined and categorized as low (1.50–2.14 $m \cdot s^{-1}$), medium (2.14–2.78 $m \cdot s^{-1}$) and high-intensity (> 2.78 $m \cdot s^{-1}$), according to manufacture settings (Catapult Sprint Version 5.1.1 software manual, Catapult Innovations, Canberra, Australia). Individual workload ($Kg \cdot m$) was calculated multiplying the total distance covered by the body mass. Qualitative analyses were performed using video recordings (SONY-DCR-SX65E, digital video camera recorder, UK) to account for game actions, namely jumps, throws, stops, changes of direction, and one-on-one situations. The external load data [i.e., total distance covered (ICC 0.59; 0.30–0.80), total PL (ICC 0.69; 0.44–0.86), time spent in fast running (ICC 0.84; 0.67–0.93) and jogging (ICC 0.75; 0.53–0.89)] demonstrated good to excellent relative reliability. The matches were held under neutral temperature (17–22°C) and humidity (50–70%) conditions.

Statistics

Data are presented as mean ± standard deviations (SD). Differences in internal and external load variables between the three periods were assessed by one-way repeated measures analysis of variance (ANOVA) with Bonferroni post hoc test. Differences in HR variables, RPE and fun in indoor and outdoor conditions were assessed by Student's paired *t*-test. Practical significance was assessed by calculating Cohen *d* and interpreted as trivial (< 0.2), small (0.2–0.5), medium (0.5–0.8) and large (> 0.8) [20]. Mean and peak HR and HR zones' absolute reliability was assessed using the typical error of measurement (TEM) and expressed as raw and as percentage of the coefficient of variation (%CV) in 3 randomly selected matches. Random errors were interpreted as good, moderate and modest to poor, if %CV and

TABLE 1. Heart rate and time spent in selected heart rate zones during each match period and total match duration of recreational team handball matches (mean ± SD)

Variables	1st period	2nd period	3rd period	Total match
Mean heart rate ($b \cdot min^{-1}$)	134 ± 15	137 ± 15*	136 ± 15	136 ± 15
Mean heart rate (%HR_{max})	77.8 ± 5.4	79.6 ± 5.5*	79.0 ± 5.8	78.8 ± 5.4
Peak heart rate ($b \cdot min^{-1}$)	151 ± 14	153 ± 15*	151 ± 15#	152 ± 14
Peak heart rate (%HR_{max})	87.5 ± 4.2	88.7 ± 4.7*	87.4 ± 5.0#	87.9 ± 4.5
Time ≤ 60%HR_{max} (%)	5.6 ± 6.3	2.8 ± 4.7*	2.9 ± 4.5*	3.8 ± 5.0
Time 61–70%HR_{max} (%)	18.7 ± 15.1	15.8 ± 12.6	17.1 ± 15.7	17.1 ± 13.5
Time 71–80%HR_{max} (%)	30.0 ± 13.1	32.2 ± 13.7	32.4 ± 13.9	31.5 ± 12.6
Time 81–90%HR_{max} (%)	33.0 ± 17.3	34.0 ± 16.6	34.0 ± 18.0	33.7 ± 16.2
Time 91–100%HR_{max} (%)	13.1 ± 16.7	15.8 ± 18.5	14.2 ± 16.5	14.4 ± 16.9
Time > 80%HR_{max} (%)	46.1 ± 26.6	49.8 ± 25.3	48.2 ± 28.7	48.1 ± 25.7

*Significantly different from the first period. #Significantly different from the second period.

TEM as %CV were ≤ 10%, > 10-20% and >20%, respectively [21]. The intraclass correlation coefficient ($ICC_{3,1}$) was used to calculate relative reliability [22, 23], with values 0.75–1.00 being considered as excellent, 0.41–0.74 as good, and 0.00–0.40 as poor [24]. Statistical Package for the Social Sciences (SPSS Inc., version 25) was used for data analysis. Statistical significance was set at $p \leq 0.05$.

RESULTS

Internal load variables and fun levels

Mean and peak HR and time spent in the HR zones during the RTH matches held in indoor and outdoor conditions are presented in Table 1. Mean HR increased from the first to the second period ($p = 0.002$; $d = 0.916$). Peak HR in the second period was higher than in the first ($p = 0.025$; $d = 0.662$) and third periods ($p = 0.005$; $d = 0.799$). Time spent ≤ 60%HR_{max} decreased from the first to the second ($p = 0.002$; $d = 1.062$) and third periods ($p = 0.034$; $d = 0.682$). No differences were found between the match periods in time spent in any other HR zones.

Baseline values and mean and peak BL values for the total match time during the RTH matches performed outdoors were 2.2 ± 0.7, 2.6 ± 0.8 and 2.9 ± 0.9 mmol·l^{-1}, respectively, with peak values being higher compared to baseline ($p = 0.047$; $d = 0.844$) and mean values ($p = 0.001$; $d = 1.717$). Mean BL was 2.6 ± 0.9, 2.4 ± 0.8 and 2.4 ± 0.6 mmol·l^{-1} for the first, second and third periods, respectively, with no differences between them and with baseline (Figure 1). Fun levels were reported as 8.4 ± 1.1 and RPE was 5.5 ± 1.5 (0–10, AU), during the RTH matches held in indoor and outdoor conditions.

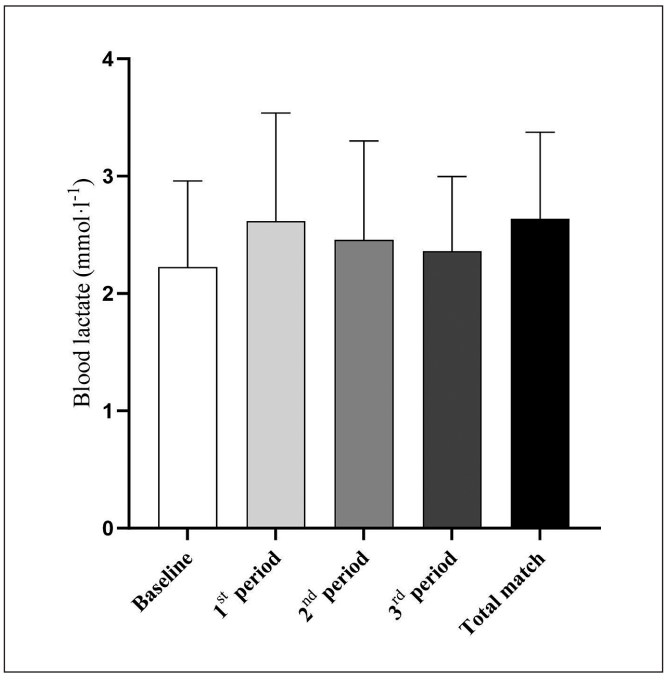


FIG. 1. Mean blood lactate at baseline and during the first, second and third periods and total match duration during recreational team handball matches.

External load variables

Distance covered, accelerations and decelerations, PL and game actions data were evaluated in outdoor matches.

Time spent and distance covered in each locomotor category, total distance covered, and individual workload are presented in Table 2. There were no differences between the match periods regarding these variables.

The number of low, medium, high and total accelerations and decelerations is presented in Table 3. Total decelerations increased from the first to the second period ($p = 0.039$; $d = 0.643$).

Time spent in PL zones and total PL are present in Table 4. No differences were found in total PL between the match periods. Time spent in PL zone 0.1–0.3 ($p = 0.015$; $d = 0.729$) increased from the first to the third period, while time spend between 0.3–0.6 ($p = 0.036$; $d = 0.630$) and 1.0–1.5 ($p = 0.010$; $d = 0.879$) decreased from the first to the third period (Table 4). Time spent between 0.6–1.0 decreased over time (from the first to the second period: -1%; $p = 0.036$; $d = 0.629$; from the first to the third period: -2%; $p < 0.001$; $d = 1.197$).

The frequency of different game actions is described in Table 5. One-on-one situations decreased from first to the third period ($p = 0.050$; $d = 0.714$). No differences were found between the match periods in any other game actions.

Internal load reliability

HR variables' absolute and relative reliability are presented in Table 6. Mean and peak HR presented good to moderate absolute reliability (TEM%CV ≤ 10%; CV% < 20%) and excellent relative reliability (ICC > 0.75). Time spent in the HR zones presented excellent relative reliability, except for time ≤ 60%HR_{max} and time 71–80%HR_{max}, which was poor and good, respectively, and poor absolute reliability. RPE showed good relative reliability and poor absolute reliability.

DISCUSSION

This is the first study analyzing the physiological and physical demands of small-sided RTH games, and the intensity variability of the training sessions (matches) in inactive 50–77-year-old women without prior experience with this sport. The main findings were that RTH is a high-intensity exercise modality, showing consistent results across the training sessions, with time spent in the HR zones presenting excellent relative reliability, though poor absolute reliability between the training sessions.

Mean HR values were > 77%HR_{max}, which corresponds to vigorous PA [25] and almost half of the match time was spent in this intensity category. Mean HR increased from the first to the second period with high values being held across the 3 × 15-min periods.

TABLE 2. Time spent and distance covered in different locomotor categories, total distance covered and individual workload during each match period and total match duration of recreational team handball matches (mean ± SD)

Variables	1st period	2nd period	3rd period	Total match
Standing				
Time (s)	348 ± 81	351 ± 79	379 ± 97	1078 ± 226
Time (%)	38 ± 9	38 ± 9	40 ± 10	38 ± 8
Walking				
Distance (m)	458 ± 79	464 ± 63	458 ± 77	1380 ± 197
Distance (%)	76 ± 9	76 ± 9	77 ± 9	76 ± 9
Time (s)	504 ± 74	509 ± 65	502 ± 79	1516 ± 196
Time (%)	55 ± 8	55 ± 7	53 ± 8	54 ± 7
Individual workload (Kg·m)	29468 ± 5511	29939 ± 5283	29663 ± 6570	89071 ± 16163
Jogging				
Distance (m)	93 ± 48	92 ± 53	89 ± 53	274 ± 148
Distance (%)	14 ± 7	14 ± 7	13 ± 7	14 ± 7
Time (s)	46 ± 24	46 ± 25	44 ± 26	135 ± 72
Time (%)	5 ± 3	5 ± 3	5 ± 3	5 ± 3
Individual workload (Kg·m)	5981 ± 3243	5931 ± 3501	5797 ± 3493	17709 ± 9900
Fast running				
Distance (m)	66 ± 65	67 ± 62	71 ± 63	205 ± 178
Distance (%)	9 ± 9	10 ± 9	9 ± 8	10 ± 8
Time (s)	26 ± 27	26 ± 26	27 ± 25	80 ± 74
Time (%)	3 ± 3	3 ± 3	3 ± 2	3 ± 3
Individual workload (Kg·m)	4329 ± 4306	4395 ± 4029	4715 ± 4368	13439 ± 12019
Sprinting				
Distance (m)	6 ± 12	7 ± 13	7 ± 15	19 ± 36
Distance (%)	1 ± 1	1 ± 1	1 ± 1	1 ± 1
Time (s)	2 ± 4	2 ± 4	2 ± 4	5 ± 10
Time (%)	0.1 ± 0.3	0.1 ± 0.4	0.2 ± 0.5	0.1 ± 0.3
Individual workload (Kg·m)	342 ± 714	429 ± 899	480 ± 1102	1252 ± 2425
Total distance covered (m)	622 ± 131	631 ± 111	626 ± 137	1878 ± 333
Total individual workload (Kg·m)	40119 ± 8940	40695 ± 8465	40656 ± 10673	121471 ± 25652

TABLE 3. Number of accelerations and decelerations during each match period and total match duration of recreational team handball matches (mean ± SD)

Variables	1st period	2nd period	3rd period	Total match
Low accelerations	6.1 ± 4.0	5.7 ± 3.5	5.8 ± 3.4	17.6 ± 10.4
Medium accelerations	3.8+ 2.2	3.8 ± 2.6	3.2 ± 2.1	10.8 ± 6.4
High accelerations	3.1+ 1.6	3.1 ± 2.2	3.1 ± 1.9	9.2 ± 5.1
Total accelerations	13.0 ± 6.9	12.6 ± 7.6	12.0 ± 6.7	37.6 ± 20.7
Low decelerations	3.5 ± 2.9	4.1 ± 2.9	3.7 ± 3.0	11.4 ± 8.5
Medium decelerations	1.4 ± 1.1	1.8 ± 1.1	1.5 ± 1.2	4.8 ± 3.1
High decelerations	0.9 ± 0.8	0.8 ± 0.6	0.7 ± 0.7	2.4 ± 1.7
Total decelerations	5.8 ± 4.4	6.7 ± 4.2*	6.0 ± 4.7	18.6 ± 13.0

*Significantly different from the first period.

TABLE 4. Time spent (%) in different Player Load zones and total Player Load during each match period and total match duration of recreational team handball matches (mean ± SD)

Variables	1st period	2nd period	3rd period	Total match
Player Load Zones				
Time <0.1 (%)	25.28 ± 6.92	25.98 ± 7.40	27.67 ± 8.25	26.31 ± 6.45
Time 0.1-0.3 (%)	39.75 ± 6.93	41.37 ± 6.69	41.84 ± 6.36*	41.01 ± 6.39
Time 0.3-0.6 (%)	17.65 ± 4.65	17.19 ± 4.45	16.29 ± 5.10*	16.92 ± 4.59
Time 0.6-1.0 (%)	10.25 ± 3.37	9.24 ± 3.16*	8.33 ± 3.29*	9.26 ± 3.18
Time 1.0-1.5 (%)	5.80 ± 3.30	5.26 ± 2.79	4.76 ± 2.54*	5.31 ± 2.78
Time 1.5-2.0 (%)	1.04 ± 1.57	0.94 ± 1.38	0.93 ± 1.41	0.98 ± 1.42
Time >2.0 (%)	0.03 ± 0.15	0.07 ± 0.21	0.06 ± 0.15	0.06 ± 0.18
Total Player Load (AU)	77 ± 16	73 ± 14	72 ± 15	224 ± 41

*Significantly different from the first period.

TABLE 5. Game actions during each match period and total match duration of the recreational team handball matches (mean ± SD)

Actions	1st period	2nd period	3rd period	Total match
Jumps	2.2 ± 2.2	1.9 ± 1.6	1.7 ± 1.3	5.9 ± 4.8
Throws	3.7 ± 2.7	3.5 ± 1.8	3.4 ± 1.9	10.6 ± 5.8
Stops	3.7 ± 1.3	3.7 ± 1.2	3.5 ± 1.6	11.0 ± 3.6
Changes of direction	2.5 ± 1.5	2.3 ± 1.2	2.1 ± 1.5	6.9 ± 3.9
One-on-one situations	1.4 ± 1.0	1.5 ± 1.4	0.9 ± 0.9*	3.8 ± 2.9

*Significantly different from the first period.

TABLE 6. Reliability of heart rate variables (mean, peak and time spent in selected heart rate zones) and rating of perceived exertion across the three analyzed training sessions

Variables	ICC	95%CI	TEM	95%CI	TEM%CV	95%CI	CV%
Mean heart rate ($b \cdot min^{-1}$)	0.93	0.84–0.98	4.82	3.71–7.00	3.6	2.8–5.3	12.25
Mean heart rate (%HR_{max})	0.82	0.60–0.94	0.45	0.35–0.66	3.6	2.8–5.3	7.74
Peak heart rate ($b \cdot min^{-1}$)	0.95	0.87–0.98	4.34	3.34–6.31	2.9	2.2–4.2	11.06
Peak heart rate (%HR_{max})	0.84	0.62–0.94	2.54	1.96–3.70	2.9	2.2–4.2	6.39
Time ≤ 60%HR_{max} (%)	0.37	-0.02–0.71	2.11	1.62–3.06	67.9	49.6–116.8	153.4
Time 61–70%HR_{max} (%)	0.78	0.52–0.92	8.74	6.73–12.70	132.6	92.7–253.6	76.70
Time 71–80%HR_{max} (%)	0.74	0.46–0.90	0.54	0.41–0.78	101.4	71.5–177.8	77.31
Time 81–90%HR_{max} (%)	0.78	0.61–0.90	0.50	0.42–0.64	70.4	54.1–111.0	56.47
Time 91–100%HR_{max} (%)	0.82	0.59–0.93	11.11	8.56–16.16	135.9	93.2–254.1	113.99
Time > 80%HR_{max} (%)	0.77	0.51–0.92	0.51	0.39–0.74	69.9	50.9-120.9	57.93
RPE (AU; 0–10)	0.72	0.48–0.87	1.02	0.82–1.39	23.7	18.6–33.7	38.66

CI - Confidence interval; CV - coefficient of variance; ICC – Intraclass Correlation Coefficient; RPE – Rating of perceived exertion; TEM – Typical Error of the Measure.

Additionally, time ≤ 60%HR_{max} (light-intensity) decreased after the first period. Thus, RTH is a vigorous-intensity exercise mode for postmenopausal women, able to be sustained over 45 min, and thereby can contribute for meeting the PA guidelines (volume and intensity). Nonetheless, the cardiovascular demands of RTH were lower for postmenopausal women than for younger populations [8–10, 14, 26], and were slightly higher than for 67-year-old men [15]. Moreover, there is consistency in mean and peak cardiovascular intensity across the training sessions, with high relative reliability, in spite of the absolute variability in the time spent in the HR zones. The collected data provide evidence for a satisfactory intra-individual consistency of the cardiovascular responses to RTH matches, despite the spontaneous nature of the considered exercise mode. However, it was evident that there is variability in the magnitude of the cardiovascular demands between training sessions, which suggests that if specific outcomes are targeted, such as a reaching a certain amount of time spent at a given cardiovascular intensity, a keen assessment and monitoring of the exercise intensity should be performed. Despite these findings, the resulting variability located the cardiorespiratory demands in the range considered helpful in producing sound health benefits in the participants [25], thus corroborating our hypothesis.

In this study, 14% of total match time was > 90%HR_{max}. Time > 90%HR_{max} has been largely correlated with changes in cardiorespiratory fitness [7]. Accordingly, increases of 14%, 11% and 7% in cardiorespiratory fitness were reported for middle-aged men [7], young men [8] and postmenopausal women [12], involved in RTH-based exercise interventions, spending 21%, 14% and 11% of total match time > 90%HR_{max}, respectively. Cardiorespiratory fitness is associated with reduced incidence of cardiovascular diseases and all-cause mortality [27], and consequently, any increase or even maintenance in $\dot{V}O_{2max}$ is relevant. Thus, exercise modalities such as RTH that have the potential to improve $\dot{V}O_{2max}$ are of the outmost importance. Nonetheless, even though postmenopausal women were shown to attain higher HRs and spend more time in higher intensity HR zones than older men, lower BL accumulation was found in comparison to their male counterparts (mean BL: 3.6–3.9 $mmol \cdot l^{-1}$; peak BL: 4.7–5.6 $mmol \cdot l^{-1}$) [15]. This is probably the result of a higher aerobic energy production and thus a lower anaerobic energy production of the considered female population during the RTH matches. However, comparison between BL concentrations across sexes should only be performed when normalizing for individual maximal values [28].

On the other side, this high-intensity physiological response contrasts with the amount of time spent in low-intensity locomotor categories. In fact, half of the total distance covered was performed walking and almost the total match time (92%) was spent standing or walking. Also in recreational football, high HRs were observed even when 70% of the match time was spent standing or walking, which suggests that other actions, besides the locomotor profile, could play a role in the match intensity [29]. Additionally, these findings highlight the relevance of HR or, in alternative, RPE being monitored in real time, to better assess and regulate exercise intensity. An increase was shown in decelerations from first to the second period and in time spent in low-intensity PL zone (0.1–0.3) from first to the third period, as well as a decrease in one-on-one situations. This decrement in external load demands was not in accordance with the high internal load demands during the matches, suggesting that external load variables pattern may not reflect changes in internal load, or vice versa, and highlights the importance of combining both measurements.

Despite all, a total of 38 accelerations (mainly low) and 19 decelerations were recorded. The number of accelerations, decelerations and total distance covered were correlated with changes in leg BMC of men with prostate cancer that participated in a recreational football exercise-based program for 12 weeks [30], being potential promoters of an osteogenic effect. Although, there are similarities between the physical demands of football and TH [31], the potential of these actions to induce skeletal muscle adaptations remains to be studied in TH. This would be of interest in future studies, as in fact, it has been previously showed that TH training results in positive bone adaptations [8, 10], namely in postmenopausal women [11]. Additionally, the frequency of different actions was also suggested as a contributor to the musculoskeletal adaptations shown in RTH players [14]. The number of actions performed by our participants was lower than that observed in other populations [8, 10, 15], which could be related, at least in part, to the inexperienced sport status of the population, and could have resulted in more ball losses and time-outs. Notwithstanding, RTH practice seems to offer a sufficient stimulus for postmenopausal women that increased lumbar spine BMD and BMC and femur BMC, and the expression of bone turnover markers after 16 weeks of practice [11].

The total distance covered by postmenopausal women was lower than that shown for younger populations playing RTH, namely young [26] and adult/middle-aged [14] men, that covered ~3 and ~6 km, respectively. However, the goalkeepers were not considered in the analysis of these studies, which can possibly explain the differences shown, as in our study the participants rotated positions, namely as outfield players and goalkeepers. Nonetheless, even when compared with 67-year-old men that covered ~5 km when playing RTH in 5v5 to 7v7 formats alternating between outfield and goalkeeper positions, postmenopausal women covered less than half the total distance [15]. The lower total distance covered per player in our study may have been the result of the lower area per player used in our study compared with the previous RTH mentioned studies (34–36 m^2 per player vs. 57, 57–80 and 66–100 m^2 per player [14],[15],[26]). In fact, an increase in the area per player resulted in an increase in the distance covered in recreational football players [32]. These particularities are of the most importance when the aim is to increase the external load imposed by exercise.

RPE was reported as 5.5 (hard; 0–10 AU), which is partly in accordance with other recreational team sport studies (range:

3.9–5.4) [26]. A higher RPE was expected, due to the vigorous intensity of the activity. Former TH players playing this sport recreational version reported a RPE of 7.6 (very hard) during RTH matches [14], which could reflect their ability to accurately evaluate the exercise intensity based on their training and competing experience. Nonetheless, a high level of fun (8.4, 0–10 AU) was reported by the participants. This finding is of the most importance, since lack of motivation is one of the main barriers to exercise, and thus RTH practice can potentially contribute for reducing the levels of physical inactivity shown in this population.

This study addresses the gap in the literature regarding the characterization of RTH in postmenopausal women without prior experience with the sport. It showed that exercise intensity is high and can be sustained during the total match duration (45 min), contributing to attain the PA guidelines. Moreover, due to its multicomponent nature, a feature recommended by PA guidelines, RTH-based programs can offer an alternative option to conventional exercise programs available for older populations. A strength of this study is the detailed characterization of the physical and physiological demands of RTH in this population, with the results supporting our study hypothesis, and also proving insights on the reasons that may explain the physical fitness, cardiovascular and musculoskeletal adaptations. Moreover, RTH showed to be a versatile exercise modality that can be played in different settings (indoor/outdoor), being thus adaptable to different contexts. Nonetheless, although there were no differences in internal load variables between indoor and outdoor conditions, it would be relevant to compare external load variables in these conditions, in order to better ascertain the physical characteristics of RTH practice in different settings. So, the lack of information about the external load demands in indoor conditions is a limitation of this study. Future studies should analyze the differences in the working demands of different game formats in this population, as well as for older populations with experience with the sport.

CONCLUSIONS

Recreational TH training, played as small-sided games, is a high-intensity exercise training mode, showing cardiovascular intensity consistency across training sessions with high aerobic and anaerobic demands, low RPE and high levels of fun for 50–77-year-old women without prior experience with the sport. These results are in line with previous studies using RTH with other populations and support the positive cardiorespiratory fitness, metabolic and musculoskeletal health effects of RTH practice shown in this population. Given the variability reported across matches, preliminary and or sustained activity demands control, i.e., HR monitoring and field testing, is suggested to optimize training responses.

Acknowledgments

RP (SFRH/BD/136789/2018) and IC (SFRH/BD/144132/2019) are supported by grants from the Portuguese Foundation for Science and Technology. This work was funded by National Funds by FCT - Foundation for Science and Technology under the following project UIDB04045/2020 (https://doi.org/10.54499/UIDB/04045/2020). This study is part of the Handball for Health project, which has the support of the Portuguese Handball Federation, the European Handball Federation and Gaia City Hall. We would like to thank all the participants for their committed participation.

Conflict of interests

The authors declare that they have no competing interests.

REFERENCES

1. European Comission. Special Eurobarometer 525: Sport and Physical Activity. European Comission; 2022.
2. Pedersen MRL, Hansen AF, Elmose-Østerlund K. Motives and Barriers Related to Physical Activity and Sport across Social Backgrounds: Implications for Health Promotion. Int J Environ Res Public Health. 2021; 18(11).
3. World Health Organization. Global action plan on physical activity 2018–2030: more active people for a healthier world. Geneva: World Health Organization; 2018.
4. Castagna C, Krustrup P, Póvoas S. Cardiovascular fitness and health effects of various types of team sports for adult and elderly inactive individuals – a brief narrative review. Prog Cardiovasc Dis. 2020; 63(6):709–22.
5. World Health Organization. WHO guidelines on physical activity and sedentary behaviour. Geneva: World Health Organization; 2020.
6. Pedersen MT, Vorup J, Nistrup A, Wikman JM, Alstrøm JM, Melcher PS, et al. Effect of team sports and resistance training on physical function, quality of life, and motivation in older adults. Scand J Med Sci Sports. 2017; 27(8):852–64.
7. Póvoas SCA, Castagna C, Resende C, Coelho EF, Silva P, Santos R, et al. Effects of a Short-Term Recreational Team Handball-Based Programme on Physical Fitness and Cardiovascular and Metabolic Health of 33–55-Year-Old Men: A Pilot Study. Biomed Res Int. 2018; 2018:4109796.
8. Hornstrup T, Løwenstein FT, Larsen MA, Helge EW, Póvoas S, Helge JW, et al. Cardiovascular, muscular, and skeletal adaptations to recreational team handball training: a randomized controlled trial with young adult untrained men. Eur J Appl Physiol. 2019; 119(2):561–73.
9. Hornstrup T, Póvoas S, Helge JW, Melcher PS, Fristrup B, Andersen JL, et al. Cardiovascular and metabolic health effects of team handball training in overweight women: Impact of prior experience. Scand J Med Sci Sports. 2020; 30(2):281–94.
10. Hornstrup T, Wikman JM, Fristrup B, Póvoas S, Helge EW, Nielsen SH, et al. Fitness and health benefits of team handball training for young untrained women-A cross-disciplinary RCT on physiological adaptations and motivational aspects. J Sport Health Sci. 2018; 7(2):139–48.
11. Pereira R, Krustrup P, Castagna C, Coelho E, Santos R, Helge EW, et al. Effects of recreational team handball on bone health, postural balance and body composition in inactive postmenopausal women – A randomised controlled trial. Bone. 2021; 145:115847.
12. Pereira R, Krustrup P, Castagna C, Coelho E, Santos R, Martins S, et al. Effects of a 16-week recreational team handball intervention on aerobic performance and cardiometabolic fitness markers in postmenopausal women: A randomized controlled trial. Prog Cardiovasc Dis. 2020; 63(6):800–6.

13. El Khoudary SR, Greendale G, Crawford SL, Avis NE, Brooks MM, Thurston RC, et al. The menopause transition and women's health at midlife: a progress report from the Study of Women's Health Across the Nation (SWAN). Menopause. 2019; 26(10):1213–27.
14. Póvoas SCA, Castagna C, Resende C, Coelho EF, Silva P, Santos R, et al. Physical and Physiological Demands of Recreational Team Handball for Adult Untrained Men. BioMed Research International. 2017; 2017:6204603.
15. Carneiro I, Krustrup P, Castagna C, Pereira R, Coelho E, Póvoas S. Acute physiological response to different recreational team handball game formats in over 60-year-old inactive men. PLoS One. 2022; 17(10):e0275483.
16. Póvoas S, Krustrup P, Castagna C. Submaximal field testing validity for aerobic fitness assessment in recreational football. Scand J Med Sci Sports. 2020; 30(4):680–9.
17. Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, et al. A new approach to monitoring exercise training. J Strength Cond Res. 2001; 15(1):109–15.
18. Grant S, Aitchison T, Henderson E, Christie J, Zare S, McMurray J, et al. A comparison of the reproducibility and the sensitivity to change of visual analogue scales, Borg scales, and Likert scales in normal subjects during submaximal exercise. Chest. 1999; 116(5):1208–17.
19. Boyd LJ, Ball K, Aughey RJ. The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. Int J Sports Physiol Perform. 2011; 6(3):311–21.
20. Cohen J. Statistical Power Analysis for the Behaviour Sciences. Hillsdale, NJ: LawrenceErlbaum Associates; 1988.
21. Stokes M. Reliability and Repeatability of Methods for Measuring Muscle in Physiotherapy. Physiotherapy Practice. 1985; 1(2):71–6.
22. Hopkins WG. Measures of reliability in sports medicine and science. Sports Medicine. 2000; 30(1):1–15.
23. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. Journal of strength and conditioning research / National Strength & Conditioning Association. 2005; 19(1):231–40.
24. Fleiss JL. Reliability of measurements: The design and analysis of clinical experiments. New York, NY: Wiley; 1986.
25. Pescatello LSA, R. Riebe, D. Thompson, P. D. ACSM's Guidelines for Exercise Testing and Prescription 9th ed. Philadelphia: Lippincott Williams & Wilkins; 2014.
26. Stojiljković N, Scanlan A, Dalbo V, Stankovic R, Milanović Z, Stojanović E. Physiological responses and activity demands remain consistent irrespective of team size in recreational handball. Biol Sport. 2020; 37(1):69–78.
27. Al-Mallah MH, Sakr S, Al-Qunaibet A. Cardiorespiratory Fitness and Cardiovascular Disease Prevention: an Update. Current Atherosclerosis Reports. 2018; 20(1):1.
28. Castagna C, Francini L, Póvoas SCA, D'Ottavio S. Long-Sprint Abilities in Soccer: Ball Versus Running Drills. Int J Sports Physiol Perform. 2017; 12(9):1256–63.
29. Randers MB, Nybo L, Petersen J, Nielsen JJ, Christiansen L, Bendiksen M, et al. Activity profile and physiological response to football training for untrained males and females, elderly and youngsters: influence of the number of players. Scand J Med Sci Sports. 2010; 20 Suppl 1:14–23.
30. Uth J, Hornstrup T, Christensen JF, Christensen KB, Jørgensen NR, Helge EW, et al. Football training in men with prostate cancer undergoing androgen deprivation therapy: activity profile and short-term skeletal and postural balance adaptations. Eur J Appl Physiol. 2016; 116(3):471–80.
31. Randers MB, Nielsen JJ, Bangsbo J, Krustrup P. Physiological response and activity profile in recreational small-sided football: no effect of the number of players. Scand J Med Sci Sports. 2014; 24 Suppl 1:130–7.
32. Randers MB, Ørntoft C, Hagman M, Nielsen JJ, Krustrup P. Movement pattern and physiological response in recreational small-sided football – effect of number of players with a fixed pitch size. J Sports Sci. 2018; 36(13):1549–56.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Review Paper DOI: https://doi.org/10.5114/biolsport.2024.133665
© Institute of Sport – National Research Institute

Effects of lower-limb intermittent pneumatic compression on sports recovery: A systematic review and meta-analysis

AUTHORS: Filipe Maia[1,2], Fábio Yuzo Nakamura[1,2], Hugo Sarmento[3], Rui Marcelino[2,4,5], João Ribeiro[1,2,5,7]

[1] Research Center in Sports Sciences, Health Sciences and Human Development (CIDESD), Maia, Portugal
[2] University of Maia, Maia, Portugal
[3] Research Unit for Sport and Physical Activity (CIDAF), Faculty of Sport Sciences and Physical Education, University of Coimbra, Coimbra, Portugal
[4] Research Center in Sports Sciences, Health Sciences and Human Development (CIDESD), CreativeLab Research Community, Vila Real, Portugal
[5] Portugal Football School, Portuguese Football Federation, Oeiras, Portugal
[6] Department of Performance Optimization (GOD), Sporting Clube de Braga SAD, Braga, Portugal
[7] SC Braga Education, Braga, Portugal

ABSTRACT: Intermittent pneumatic compression (IPC) applied to lower limbs is becoming a popular post-exercise recovery technique; however, it still lacks strong scientific support. The purpose of this systematic review and meta-analysis was to analyse the effects of lower-limb IPC on sports recovery, as well as to identify the most used protocols to optimize it. A systematic search was conducted across athletic and healthy populations, following the PRISMA guidelines, covering the databases: PubMed, Web of Science, SportDiscus, Academic Search Complete, and Science Direct; using the search terms: ("Pneumatic compression" OR "Intermittent pneumatic compression" OR "Recov* boot*") AND (Recover*). Data was extracted, and standardized mean differences were calculated with 95% confidence and prediction interval. The pooled data analysis was conducted using a random-effects model, with heterogeneity assessed using I^2. A total of 17 studies (319 participants) were included. The studies' methodological quality was assessed using the PEDro scale, ranging from fair to good. Results indicate a trivial to small benefit towards lower-limb IPC in enhancing muscular function, as well as a trivial to moderate effect for pain and soreness measurements, and a highly variable effect on muscle damage markers. Moreover, protocols of about 20 to 30 minutes and pressures of about 80 mmHg appear to be the most used option to optimize recovery. In summary, lower-limb IPC might be a method with potential effects for recovery in sports, mainly reducing perceived soreness.

CITATION: Maia F, Nakamura FY, Sarmento H et al. Effects of lower-limb intermittent pneumatic compression on sports recovery: A systematic review and meta-analysis. Biol Sport. 2024;41(4):263–275.

Received: 2022-12-20; Reviewed: 2023-06-29; Re-submitted: 2023-08-11; Accepted: 2023-12-02; Published: 2024-06-17.

Corresponding author:
Filipe Maia
Research Center in Sports Sciences, Health Sciences and Human Development (CIDESD), Maia, Portugal
E-mail: fm.filipemaia@gmail.com

ORCID:
Filipe Maia
0000-0002-4026-3804

Fábio Yuzo Nakamura
0000-0002-5336-3652

Hugo Sarmento
0000-0001-8681-0642

Rui Marcelino
0000-0001-8717-3243

João Ribeiro
0000-0002-7658-4837

Key words:
Athletic Performance
Physical exercise
Fatigue
Compression Therapy
Sports

INTRODUCTION

Physical capacities are fundamental to perform in sports [1]. In fact, athletes' physical readiness influences technical and tactical behaviours, which, in turn, determine the final outcome [2, 3]. Over the last years, it is noticeable that competitive sports are becoming more and more demanding: e.g., total covered distances, as well as high-intensity actions tend to increase in competitive team sports [4]. Moreover, athletes are experiencing higher loads due to the increase in competitive density (i.e., congested fixtures) [3, 5, 6]. This fact might increase the risk of overuse and non-contact musculoskeletal injuries [7, 8]. Injuries usually force athletes to withdraw from competitions and disturb or interrupt training routines, causing a loss in physical performance [9]. Aiming to moderate constraints associated with reduced physical capacity and incidence of injuries, the need for post-match and post-training recovery strategies is increasing, imposing an optimization of the associated processes [10].

Recovery is considered a multifaceted restorative process relative to time, disturbed by internal and external factors, and dependent on reducing, altering, or breaking down from stress [11, 12]. The use of post-exercise recovery strategies is particularly required when there is a need to limit the severity of fatigue and shorten its duration [13, 14]. For instance, in sports such as swimming, track and field, or powerlifting, athletes typically participate in more than one event in the same session or day, separated by minutes or hours, while multiday races characterize sports like road cycling or ultra-marathon [15–17]. On the other hand, in sports such as soccer, basketball or baseball, athletes typically compete in congested calendars [18]. Recovery modalities are highly trendy and not always fully

supported by scientific literature with regard to their purported effects [19]. Intermittent Pneumatic Compression (IPC) is an emerging method, grown in popularity among practitioners and athletes over the past few years [20]. This method consists of pumped inflation and deflation pressure cycles of air bladders, usually applied on the lower limbs. Lower-limb IPC is performed using sleeves that cover the feet, calves, or whole thighs and legs. These cycles can be performed uniformly or in sequence, at different pressures and cycle rates [21].

Despite being novel in sports, this technology has been used in medical care units since 1970 [22]. In this area, IPC is widely utilized to prevent stasis and deep vein thrombosis, and to treat lymphedema and leg ulcers [23–28]. Although these devices are shared between sport and medical areas, the applied protocols tend to vary, mainly in pressure and duration of application [29]. In sports science, this method remains controversial, with the majority of studies reporting either advantages [20, 30, 31] or a neutral effect [32, 33] for different recovery parameters of muscular function, perceptual measures and physiological markers. The effect of compression provided by these devices would, in theory, increase local blood flow, which is associated with an acceleration of the removal rate (outflow) of metabolic by-products that could adversely affect physical performance [34]. Additionally, the induced compression may also assist in reducing oedema, through the limitation of the space available for swelling to form, therefore restricting the inflammatory and muscle damage responses [35]. Intermittent pneumatic compression devices are lightweight and thus highly portable and do not require additional human resources (i.e., it can be performed by the athletes themselves), simplifying and making the intervention more accessible [36]. Therefore, IPC may be a promising practical solution for recovery in sports, if it proves to be effective.

Although the organization and systematization of the evidence concerning the use of this recovery method is incipient, athletes seem to have embraced IPC by regularly using it [37, 38]. Therefore, it becomes important to elucidate its effects and search for the most effective recovery conditions. The purpose of this study is to address this important gap in the scientific evidence by systematically and meta-analytically reviewing the effects of lower-limb IPC, in the context of sports recovery, on muscular function, subjective measures, and physiological markers, as well as explore the most used recovery protocols.

MATERIALS AND METHODS

Search Strategy: Databases and inclusion criteria

This systematic literature review with meta-analysis was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [39]. The study protocol was registered at the International Prospective Register of Systematic Reviews (PROSPERO) under the code CRD42021273598 (Figure 1).

The extensive literature search covered the following electronic databases: PubMed, Web of Science (all databases), SportDiscus, Academic Search Complete, and Science Direct. All articles published until 1st November 2022 were considered. The searched keywords were: ("Pneumatic compression" OR "Intermittent pneumatic compression" OR "Recov* boot*") AND (Recover*).

The criteria of selection were established according to the PICOS strategy, as follows:

- *Participants:* Adults (age ≥ 18); male and female; healthy and physically active or athletes.
- *Intervention:* Articles that reported a fatiguing activity, a recovery protocol using IPC, and subsequent measurements of recovery.
- *Comparator*: Studies comparing the use of IPC with placebos or passive rest conditions.
- *Outcomes:* Recovery parameters: neuromuscular function (e.g., time trial performance, maximal voluntary contraction), subjective measures (e.g., perceived fatigue, perceived soreness), or physiological markers (e.g., creatine kinase, blood lactate) of recovery, measured up to 96 hours after the fatiguing protocol.
- *Study Design:* Randomized controlled trials (with parallel groups or crossover designs).

Articles were excluded if they: (i) reported IPC treatments after surgery, recovery from diseases, or injuries treatment; (ii) reported results of unhealthy populations; (iii) animal studies; (iv) reported results unrelated to practical post-exercise recovery strategies; (v) reported upper limbs IPC interventions; (vi) poster presentations, articles composed only by abstracts or review studies; and (vii) studies written in a language other than English. After excluding articles by title, the second screening for the inclusion of studies was conducted based on abstract analysis and full text versions. This process was conducted by two investigators independently (FM, JR), and discrepancies were solved by a third investigator (FYN).

Quality of Studies and Risk of Bias

Two investigators (FM, HS) assessed the overall studies' methodological quality independently, following the criteria of the Physiotherapy Evidence Database (PEDro) scale. The scale consists of 11 items encompassing external validity (item 1), internal validity (items 2 to 9), and statistical reporting (items 10 to 11) [40].

Publication bias was assessed by visually analysing funnel plots and formal testing for funnel plot asymmetries using the "trim and fill" algorithm [41, 42].

Data extraction and analysis

All meta-analysis calculations and graphical designs were conducted using the software IBM SPSS Statistics for Windows, version 28 (IBM Corp., Armonk, N.Y., USA). General characteristics and results of the individual studies were extracted independently by two authors (FM, JR). In case of a lack of information, the statistics were extrapolated from the published figures and graphs, through the GetData Graph Digitizer software for Windows, version 2.26.0.20 [43]. A meta-analysis with a random-effects model was

performed using the restricted maximum-likelihood estimation, to examine the effects of lower-limb IPC on functional, pain and soreness and muscle damage measurements. Summary effect sizes (ES) were presented for each study using standardized mean difference (SMD) to compare the effects between lower-limb IPC and control conditions. The ES are expressed as Hedges' g, to account for possible overestimation of the true population ES in small studies. The magnitude of ES was interpreted according to the following scale: < 0.20 = negligible effect, 0.20–0.49 = small effect, 0.50–0.79 = moderate effect, > 0.80 = large effect [44]. A *p*-value of 0.05 was considered statistically significant for all analyses and a 95% confidence interval (CI) and prediction interval (PI) were assumed. To combine results from parallel-group and crossover trials, appropriate formulae was used for standardized mean ES and standard errors [45]. For the purposes of meta-analysis, the direction of change for some measures was reversed to ensure consistency of directionality across the tests (e.g., reduced time trial times indicate improvement in recovery, whereas higher jump height also indicates improved recovery). When dealing with multiple outcomes for each subgroup, the recommendations of Moeyaert et al. [46] were followed. Heterogeneity was assessed using the I^2 statistic, which describes the percentage of variability in effect estimates attributable to heterogeneity rather than chance [47]. I^2 values of 25%, 50% and 75% can be considered to reflect small, moderate and large degrees of heterogeneity [48]. To provide some criterion of temporal echo-coherence consistency, subgroup analysis was carried out, grouping studies into the following time points: 0–2, 24, 48, 72 and 96 hours post IPC protocol.

RESULTS

Search, Selection, and Inclusion of Publications

The initial search identified 6040 articles that were exported to the citation manager software EndNote™20 (Clarivate Analytics, Philadelphia, PA). Duplicate references were removed (n=266), resulting in 5774 articles. Those remaining manuscripts were screened by title (excluding 5724). From the 50 articles left, the analyses of the abstract and full text (except one not retrieved) were carried out. A total of 17 articles were included in the systematic review, and from those 14 were included in meta-analysis. All excluded records did not match the inclusion criteria previously described or were not retrieved.

Quality assessment

The quality of the 17 studies included in this review ranged from a score of 5 to 8, according to PEDro scale, with a mean of 6.29 and a standard deviation of 0.67, indicating an overall good methodological quality [40]. As illustrated in Table 1, all studies adequately

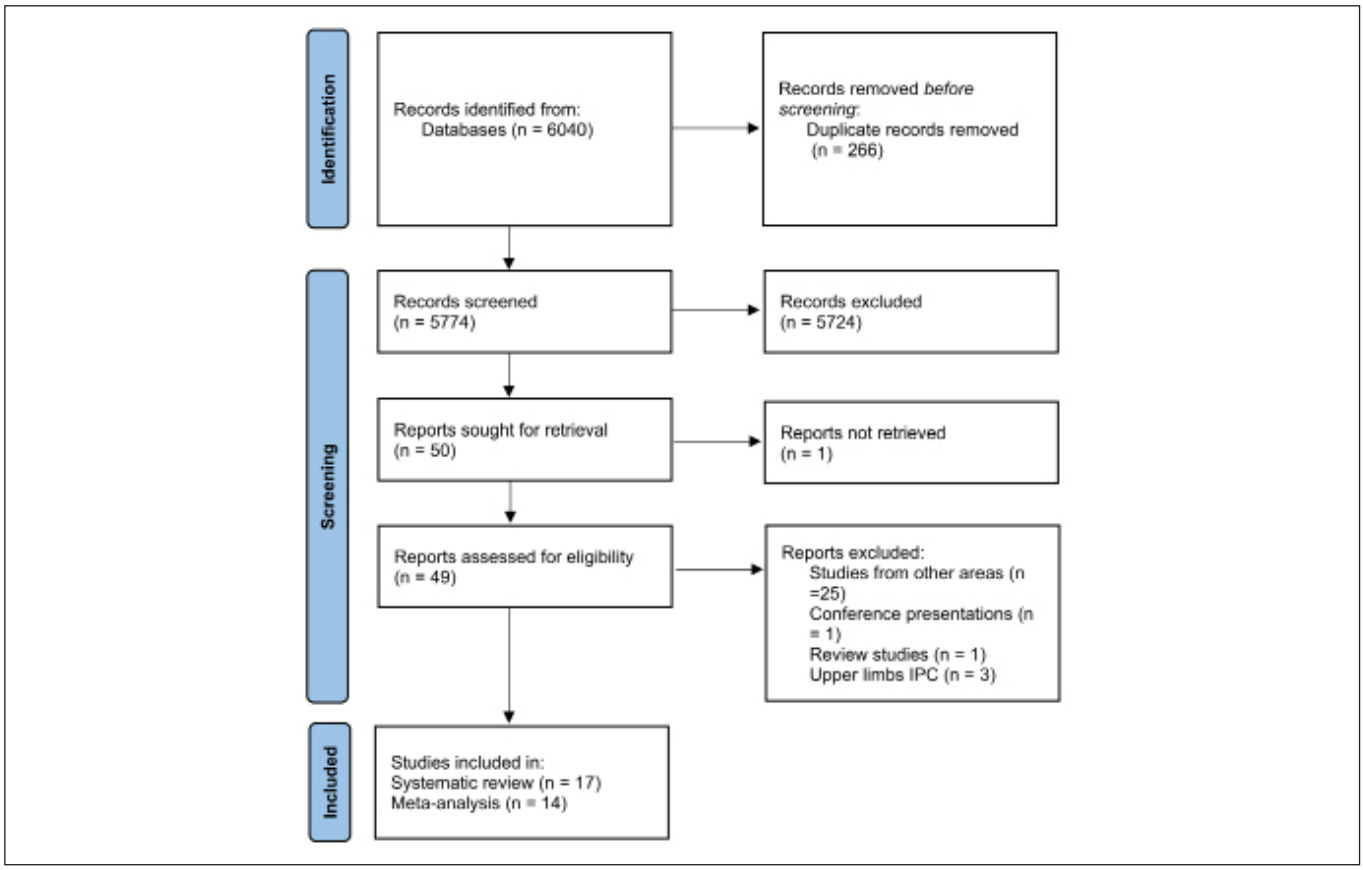


FIG. 1. PRISMA Flow Diagram of the procedures used for the articles search.

TABLE 1. Study quality according to Physiotherapy Evidence Database (PEDro) scale.

Study	Eligibility criteria and source	Random allocation	Concealed allocation	Baseline comparability	Blinding of participants	Blinding of therapists	Blinding of assessors	Adequate follow-up	Intention-to-treat analysis	Between-group statistical comparisons	Reporting of point and variability measures	Total*
Wiecha et al. [49]	1	1	1	1	1	0	0	1	1	1	1	8 (Good)
Khan, Ahmad and Hussain [50]	1	1	0	1	1	0	0	1	1	1	1	7 (Good)
Draper et al. [33]	1	1	0	1	0	0	0	1	1	1	1	6 (Good)
Collins et al. [51]	1	1	0	1	0	0	0	1	1	1	1	6 (Good)
Marcello, Fortini and Greer [52]	1	0	0	1	1	0	0	1	1	1	1	6 (Good)
Heapy et al. [30]	1	1	0	1	0	0	0	1	1	1	1	6 (Good)
Northey et al. [53]	1	1	0	1	0	0	0	1	1	1	1	6 (Good)
Overmayer and Driller [54]	1	1	0	1	0	0	0	1	1	1	1	6 (Good)
Haun et al. [55]	1	1	0	1	1	0	0	1	1	1	1	7 (Good)
Haun et al. [56]	1	1	0	1	1	0	0	1	1	1	1	7 (Good)
Hoffman et al. [20]	1	1	0	1	0	0	0	1	1	1	1	6 (Good)
Keck et al. [57]	1	1	0	1	0	0	0	1	1	1	1	6 (Good)
Martin et al. [58]	1	1	0	1	1	0	0	1	1	1	1	7 (Good)
O'Donnell and Driller [32]	1	1	0	1	0	0	0	1	1	1	1	6 (Good)
Sands et al. [31]	1	1	0	1	0	0	0	1	1	1	1	6 (Good)
Cochrane et al. [59]	1	1	0	1	0	0	0	1	1	1	1	6 (Good)
Waller, Caine and Morris [21]	1	0	0	1	0	0	0	1	1	1	1	5 (Fair)

* Total score from a possible maximum of ten. Scores of: < 4 are considered 'poor'; 4 to 5 are considered 'fair'; 6 to 8 are considered 'good' and 9 to 10 are considered 'excellent' [40].

TABLE 2. Summary of the randomized controlled trials included in the review.

Study	Age, Sport/ Condition and sex	Design	N	Experimental design	Main results
Wiecha et al. [49]	Age: 22.05 ± 3.3 yrs Population: Healthy active Sex; Male	Parallel group	30	Exercise 5 × 20 box drops with vertical jump. Recovery protocol: 30 min peristaltic IPC at 80 mmHg. Recovery parameters: Physiological (muscle damage via serum Ck), subjective (perceived pain), and functional measures (range of motion and muscle strength – 5 series knee extension and flexion (0°–90°), at $60^{o} \cdot s^{-1}$).	IPC had no influence on DOMS, ROM, strength and muscle damage markers (CK).
Khan, Ahmad and Hussain [50]	Age: 18 to 25 yrs Population: Collegiate basketball players Sex: Male	Crossover	16	Exercise: Submaximal treadmill running Recovery protocol: 15 min peristaltic IPC at 80 mmHg Recovery parameters: Physiological (HR)	IPC is effective in lowering the heart rate during the first minute of recovery after submaximal exercise.
Draper et al. [33]	Age: 38.7 ± 11.2 yrs Population: Distance runners Sex: Male and female	Crossover	10	Exercise: 20-mile run at 70% or more of $\dot{V}O_{2max}$. Recovery Protocol: 1 h sequential IPC from 90 mmHg to 100 mmHg of pressure. Recovery Parameters: Physiological (inflammation via CRP) and subjective measures (perceived pain).	IPC offered little to no benefit in recovery from a prolonged bout of running. No effect of treatment on CRP.
Collins et al. [51]	Age: 21.6 ± 3.4 Population: Team sport athletes Sex: Male	Parallel group	21	Exercise: Cycles of maximal CMJ, a '20-metre sprint out' and a '20-metre sprint back' Recovery protocol: 20 minutes sequential at 235 mmHg Recovery Parameters: Functional (CMJ, dynamometry – 4 maximal extensions at 60, 120 and 180 °/s, with 2 min of rest separating each velocity + 2 maximal extensions and 2 flexions were completed isometrically), subjective (perceived muscle soreness), physiological (CK)	Following high-intensity exercise, IPC has potentially beneficial effects upon biomarkers of recovery, without affecting the neuromuscular function.

TABLE 2. Continue.

Study	Age, Sport/ Condition and sex	Design	N	Experimental design	Main results
Marcello, Fortini and Greer [52]	Age: 16 to 60 yrs Population: Cyclists Sex: Male and female	Crossover	10	Exercise: 2 × 60 minute steady state rides and 30 minutes recovery period between rides. Recovery Protocol: ∼25 minutes peristaltic IPC at 80 mmHg. Recovery Parameters: Physiological (HR and BLa).	No influence on HR and cadence. IPC promoted either an increase in lactate production or an impairment in clearance.
Heapy et al. [30]	41 ± 8 yrs Population: Ultra-marathon runners Sex: Male and female	Parallel group	37	Exercise: Ultra-marathon competitive event. Recovery Protocol:20 min lower extremity treatment and peristaltic compression up to 80 mmHg. Recovery Parameters: Subjective (lower body muscle pain, soreness rating and overall muscular fatigue score) and functional measurements (400 m runs).	IPC resulted in improvements in overall muscular fatigue. IPC provided some immediate subjective improvements in muscle fatigue, pain and soreness. No effect neither in 400 m run time nor both functional and subjective measures of fatigue and soreness after 96 hours.
Overmayer and Driller [54]	Male age: 40 ± 14 yrs Female age: 29 ± 12 yrs Population: Trained cyclists	Crossover	21	Exercise: 20 min TT on cycle ergometer. Recovery Protocol: 30 min peristaltic IPC treatment at 80 mmHg). Recovery Parameters: Subjective (perceived recovery, RPE), physiological (Max HR, BLa), and function (4 min TT) measures.	MaxHR was higher in IPC at the 4-min TT. IPC had no effect on performance or recovery, mean HR, RPE and average power. Unclear effect for pre to post recovery BLa concentration. IPC enhanced TQR.
Haun et al. [55]	Age: 21.6 ± 2.4 yrs Population: Healthy endurance trained Sex: Male	Parallel group	18	Exercise: HIIT (22.5 min in duration -15 rounds running for 45 s and walking for 45 s). Recovery Protocol: 1 h peristaltic EPC treatment at ∼70 mmHg. Recovery Parameters: Functional (6 km run time trial and flexibility), physiological (muscle damage via serum CK; inflammation via CRP and oxidative stress via 8-isoprostane) and subjective measures (muscle soreness via PPT).	No significant differences in 6 km TT, flexibility, muscle damage, oxidative stress and inflammation markers, and muscular soreness. EPC treatment of the lower limbs reduced markers of oxidative stress in skeletal muscle tissue.
Haun et al. [56]	Age: 22.5 ± 0.8 yrs Population: Healthy resistance-trained males Sex: Male	Parallel group	20	Exercise: 3 consecutive days of heavy and high-volume RT. Recovery Protocol: 1 h peristaltic EPC at 70 mmHg. Recovery Parameters: Functional (1RM, flexibility), subjective (PPT), and physiological measures (muscle damage via CK, inflammation via IL-6 and CRP, and RNA expression).	EPC improved flexibility and reduced PPT on days 3–7. No effect on lifting volume and CK. Larger reduction on CRP and IL6. EPC reduced muscle proteolysis, oxidative stress, and muscle soreness.
Hoffman et al. [20]	Age: 43 ± 8 yrs Population: Ultra-marathon runners Sex: Male and female	Parallel group	47	Exercise: Ultra-marathon competitive event. Recovery Protocol: 20 min interventions with peristaltic compression of 80 mmHg. Recovery Parameters: Subjective (lower body muscle pain, soreness rating and overall muscular fatigue) and functional measures (400 m runs).	IPC provided some immediate subjective benefits. IPC improved overall muscular fatigue score. No effect on functional measures.
Northey et al. [53]	Age: 24 ± 6.3 yrs Popuation: Strength trained participants Sex: Male	Crossover	12	Exercise: 10 sets with 10 repetitions of back squats at 70% 1 repetition maximum with 3-minute rest between sets Recovery Protocol: 45-minute sequential IPC at 80 mmHg. Recovery parameters: Functional (peak torque – 5 maximal voluntary contractions at $30^{o} \cdot s^{-1}$, with 30 s of rest, CMJ and SJ), and subjective (perceived soreness and recovery)	There were no significant differences between conditions for any of the postexercise measures
Keck et al. [57]	Age: 28.1 ± 7.3 yrs Population: Cyclists Sex: Male	Crossover	10	Exercise: 90-minute cycling session (warm up + 10 intervals (2 minutes at 80% watt max followed by 4 minutes at 50% watt max) + cool down). Recovery Protocol: 2 × 60 min (1 h apart) of peristaltic IPC at 70 mmHg. Recovery Parameters: Physiological biomarkers (muscle glycogen, blood glucose, insulin, and BLa) an HR measures.	No effect on muscle glycogen, plasma glucose, plasma insulin, BLa and heart rate
Martin et al. [58]	Age: 22.73 ± 4.05 yrs Population: Healthy active participants Sex: Male and female	Crossover	14	Exercise: 2 Wingate Anaerobic test (3 minutes rest) + Recovery + 1 Wingate Anaerobic test. Recovery Protocol: 30 minutes peristaltic EPC at ∼70 mmHg Recovery Parameters: Functional (peak power, mean power, and fatigue index – Wingate Anaerobic test), and physiological (HR and BLa).	EPC improved BLa clearance. No effect on HR and performance parameters. No significant effect on anaerobic performance.

TABLE 2. Continue.

Study	Age, Sport/ Condition and sex	Design	N	Experimental design	Main results
O'Donnell and Driller [32]	Age: 29 ± 9 yrs Population: Triathletes Sex: Male	Crossover	10	Exercise: Participants performed a cycling HIIT session – Recovery – 5 km TT run. Recovery Protocol: 30 minutes peristaltic IPC device at 80 mmHg. Recovery Parameters: Subjective (TQR and RPE), physiological (HR and BLa) and functional measures (5 km run TT).	No effect/trivial on performance. No differences in blood lactate. Unclear results on TQR.
Sands et al. [31]	Age: 18–40 yrs Population: Internationally competitive athletes Sex: Male and female	Parallel group	24	Exercise: Morning and afternoon practice. Recovery Protocol: 15 minutes peristaltic IPC treatment at a pressure ranging from 70 mmHg to 80 mmHg. Treatment performed between morning and afternoon practice. Recovery Parameters: Subjective measures (PPT).	IPC seemed to enhance recovery by the reduction of muscle tenderness. IPC resulted in increased values of PPT.
Cochrane et al. [59]	Age: 21.0 ± 1.7 yrs Population: Healthy and physically activity individuals Sex: Male	Crossover	10	Exercise: Muscle Dynamometry – 3 × 100 ECC contractions. Recovery Protocol: 30 minutes peristaltic IPC from 60 to 80 mmHg. Recovery Parameters: Physiological (muscle damage via CK), and functional (single leg VJ and muscle dynamometry – eccentric, concentric, and isometric: 3 RM were separated by 10 s rest and a 2-min rest between contraction type).	No differences were observed in dynamometry and VJ, muscle recovery, and force loss in isokinetic contractions.
Waller, Caine and Morris [21]	Age: 25.2 ± 1.72 yrs Population: Healthy participants Sex: Male	Crossover	9	Exercise: Set of shuttle runs for one hour. Recovery Protocol: 1 h sequential IPC (70:65:60 mmHg). Recovery Parameters: Functional (VJ) and subjective measures (soreness diagram).	IPC treatment produced a smaller reduction on VJ. Perceived soreness was reduced by IPC until 48 hours. No effect on calf and thigh circumferences.

Notes: BLa – Blood lactate; CK – Creatine Kinase; CMJ – Countermovement jump; CRP – C Reactive Protein; DOMS – Delayed Onset of Muscle Soreness; ECC – eccentric; EPC – External Pneumatic Compression; HIIT – High Intensity Interval Training; HR – Heart Rate; IL-6 – Interleukin 6; IPC – Intermittent Pneumatic Compression; mmHg – millimetre(s) of mercury; PPT – Pressure Pain Threshold; RM – Maximum Repetition; RPE – Rated Perceived Exertion; RT – Resistance training; SJ – Squat jump; TQR – Total Quality Recovery; TT – Time Trial; VJ – Vertical Jump; $\dot{V}O_{2max}$ – Maximal Oxygen Uptake.

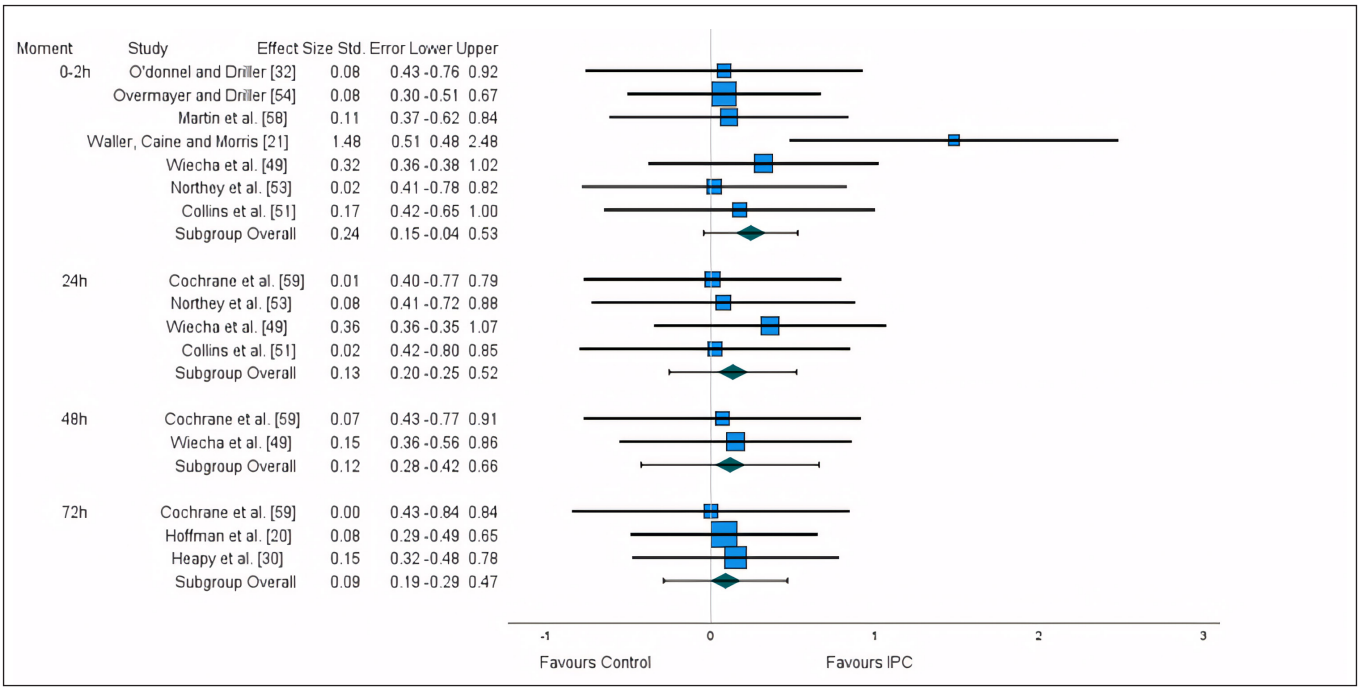


FIG. 2. Forest plot illustrating the effect of IPC on functional measures.

reported a baseline comparison, provided adequate follow-ups (considering dropouts ratio), intention to treat analysis, between groups statistical comparisons, and reported point and variability measures. Additionally, most of the studies reported a random allocation (88%), and few reported the blinding of participants to procedures (35%). Finally, none of the studies reported allocation concealment, as well as blinding to therapists and assessors.

General description of the studies

From the 17 studies included in this review, 12 assessed muscular function and performance parameters [20, 21, 30, 32, 49, 51, 53–56, 58, 59], 12 assessed subjective measures [20, 21, 30–33, 49, 51, 53–56], and 12 assessed physiological markers [32, 33, 49–52, 54–59] (Table 2). The synthesis of the meta-analysis results is displayed in Table 3.

Effects on functional and performance measures

Functional measures are particularly important, as they are directly related to the athletes' performance. For this purpose, and considering the reduced number of studies, a variety of measures of similar nature were grouped: time trial [20, 30, 54], maximum voluntary contraction (MVC) [49, 51, 53, 56, 59], and power output [21, 51, 53, 58, 59]. A non-significant small effect was found for the first 2 hours (ES:0.243). A trivial effect was found for 24 h (ES: 0.134), 48 h (ES: 0.117), and 72 h (ES: 0.089) (Figure 2). After the application of the trim and fill method, the adjusted values remained unaltered.

Flexibility and range of motion (ROM) were not considered for meta-analytical purposes, as these variables highly differ from the remaining. From the three studies [49, 55, 56] assessing the effects of lower-limb IPC on these measures, two studies reported a lack of significant differences [49, 55], while one detected a moderate effect favouring the use of lower-limb IPC [56].

Effects on subjective measures

From the 12 studies assessing subjective measures, 10 reported outcomes of pain and soreness [20, 21, 30, 31, 33, 49, 51, 53, 55, 56]. The vast majority of studies measured pain and soreness daily, immediately after the recovery protocol and at least for 96 h [20, 30, 33, 60]. However, two studies started the measurements of pain and soreness at the 48 h time point [55, 56], two measured these variables within 48 h [21, 49], two within

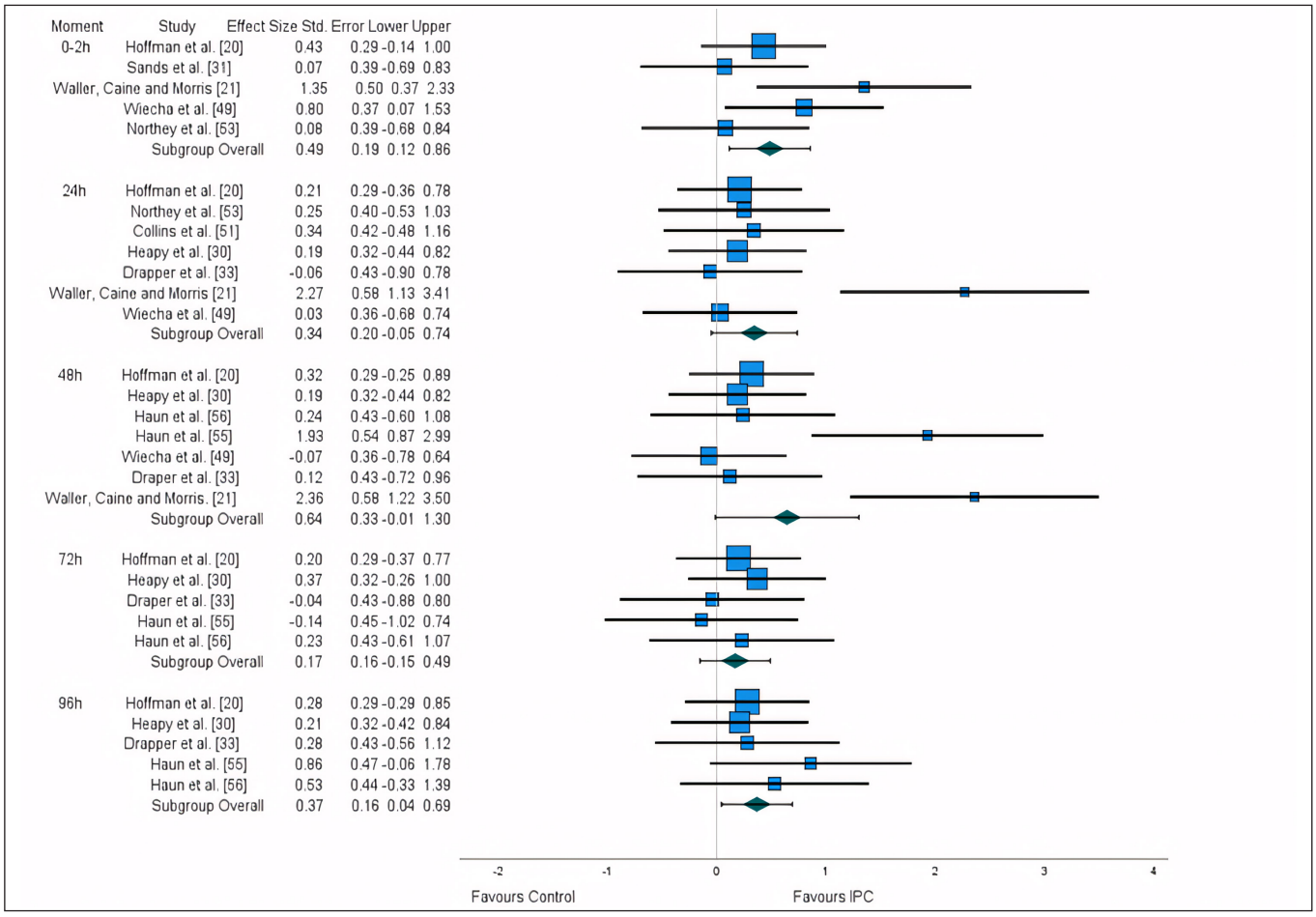


FIG. 3. Forest plot of the meta-analysis illustrating the effect of IPC on pain and soreness.

TABLE 3. Meta-analysis summary.

Outcome	SMD (95% CI)	95% PI	p-value	Z	Std. Error	I^2
Muscle function 0–2 h	0.243 (-0.43; 0.528)	-0.134; 0.620	0.096	1.665	0.146	0.2%
Muscle function 24 h	0.134 (-0.253; 0.521)	-0.716; 0.984	0.498	0.678	0.198	0%
Muscle function 48 h	0.117 (-0.424; 0.658)	-*	0.672	0.424	0.276	0%
Muscle function 72 h	0.089 (-0.287; 0.466)	-2.353; 2.532	0.642	0.464	0.192	0%
Pain and Soreness 0–2 h	0.486 (0.117; 0.855)	-0.367; 1.339	0.010	2.580	0.188	20.4%
Pain and Soreness 24 h	0.344 (-0.048;0.736)	-0.711; 1.399	0.085	1.720	0.200	47.0%
Pain and Soreness 48 h	0.644 (-0.012; 1.300)	-1.536; 2.824	0.055	1.923	0.335	79.6%
Pain and Soreness 72 h	0.169 (-0.151; 0.490)	-0.351; 0.689	0.301	1.035	0.164	0%
Pain and Soreness 96 h	0.368 (0.045; 0.691)	-0.157; 0.893	0.026	2.231	0.165	0%
CK 24 h	-0.203 (-0.655; 0.249)	-3.134; 2.728	0.378	-0.882	0.231	0%
CK 48 h	0.873 (-0.427; 2.173)	-5.169; 6.914	0.188	1.316	0.663	88.3%
CK 72 h	0.100 (-0.996; 1.197)	-12.894; 13.095	0.329	0.179	0.559	78.1%

SMD – Standardized Mean Difference; 95% CI – 95% Confidence Interval; 95% PI – 95% Prediction Interval; Std. Error – Standard Error; * to calculate the prediction interval, a minimum of 3 studies are required.

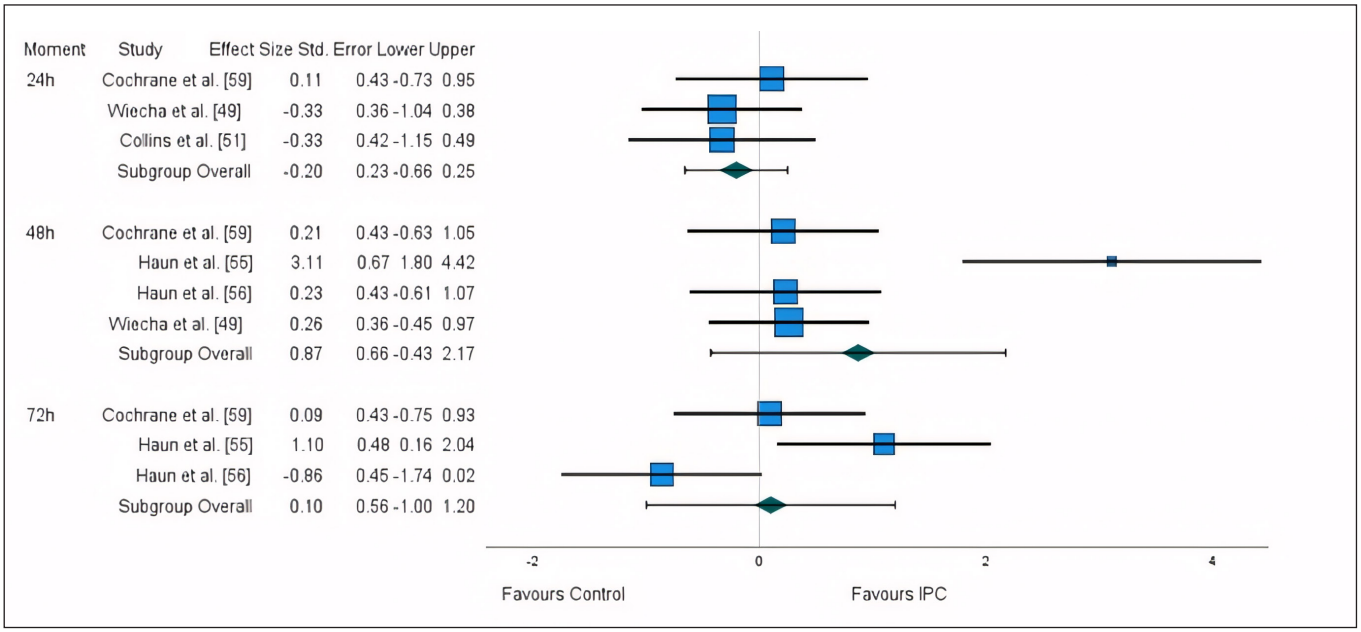


FIG. 4. Forest plot illustrating the effect of IPC on creatine-kinase concentrations.

24 h [51, 53], and one only presented results immediately after the recovery protocol [31].

A significant small effect was observed for the 0–2 h time interval (ES: 0.486), as well as for the 96 h time frame (ES:0.368). A non-significant small effect was also observed for the 24 h time point (ES: 0.344), a moderate effect for the 48-hour (ES: 0.644), and a trivial effect for the 72 h (ES:0.169). After the application of the trim and fill method, the adjusted values remained unaltered (Figure 3).

Two studies assessed perceived fatigue [20, 30], which was measured using a visual analogue scale, and three assessed perceived recovery [32, 53, 54], using the Total Quality Recovery scale. In this regard, the use of lower-limb IPC seems to provide trivial to small benefits enhancing the perception of recovery, as well as trivial effects reducing the perception of fatigue.

Effects on physiological markers

A great number of different physiological measures were analysed across the studies. For this reason, to ensure consistency of measures, we only considered muscle damage markers (CK) for meta-analytical purposes, along with inflammation (CRP, IL-6), anaerobic metabolism marker (BLa) and heart rate (HR) as part of the review.

Five studies measured CK: three at the 24 h time point [49, 51, 59], four at the 48 h [49, 55, 56, 59], and three at the 72 h [55, 56, 59]. A large disparity in results was identified, with studies reporting both advantages and disadvantages. A non-significant negative small

effect (ES: -0.203) was observed for the first 24 h, while a large positive effect (ES: 0.873) was observed for the 48 h time point. Lastly, for the 72 h time point, a trivial non-significant effect (ES: 0.10) was identified (Figure 4). After the application of the trim and fill method, the adjusted values remained unaltered.

Inflammation markers were addressed by three studies, using two different biomarkers: CRP [33, 55, 56] and IL-6 [55, 56]. The measurements took place immediately after the recovery protocol [33, 56], and at 24 h until at least 96 h, on a daily basis [33, 55, 56]. The results also showed to be conflicting, with studies reporting advantages and disadvantages considering the use of lower-limb IPC. With the available results, no further extrapolations can be obtained.

BLa was typically measured during the recovery period, testing the ability of lower-limb IPC to improve its clearance, with two studies reporting advantages [32, 58] and two a neutral effect [54, 57], even after using similar recovery protocols. Additionally, one study [52] measured BLa on subsequent efforts, where IPC either promoted an increased production or an impairment in clearance.

Two studies [52, 54] addressed measures of mean and maximum heart rate on exercise performed after the recovery protocol, also demonstrating no significant differences. Finally, one study [50] assessed the capability of IPC to restore baseline HR values, in which a positive effect was only detected for the first minute of IPC protocol.

Recovery protocols

Regarding the recovery protocols, a great heterogeneity was observed when considering duration, pressure, and type of application. The protocols used ranged from 15 [31] to 60 minutes [21, 33, 55–57], and the applied pressure ranged from 60 mmHg [21, 59] to approximately 235 mmHg [51]. Finally, considering the type of application, four studies [21, 33, 51, 53] applied a sequential program (i.e., air bladders inflate and deflate one at a time), while the remaining chose a peristaltic program (i.e., air bladders inflate one at a time, keeping the pressure for the whole cycle, and deflate all together).

DISCUSSION

Competitive sports involve high levels of physiological stress, especially during in-season periods [61]. Additionally, the margins between winning and losing have been narrowing over the last decades [62]. Therefore, marginal performance gains may translate into significantly improved competitive outcomes [62]. In this sense, to improve the chances of succeeding, the recovery process plays an important role in athletic performance [59, 61]. Practical post-exercise recovery techniques are expected to produce small, but meaningful additional benefits to athletes' recovery states, and their use should be seen as a complement to the "natural" (e.g., sleep hygiene, ordinary food) recovery process [63, 64]. The current study used a systematic review and meta-analysis approach to provide insights into the use of lower-limb IPC as a sports recovery tool.

Functional measurements

One of the primary sought recovery outcomes while implementing recovery methods is the attenuation of post-exercise losses in athletes' physical capacities [11, 65]. A variety of physical measures were considered in the current study, including aerobic and anaerobic power performance, muscular strength and jump height. From those, recovery with IPC devices seemed to provide non-significant small benefits on parameters associated with muscular function (e.g., peak power) on short-term (i.e., first two hours). These could be explained by the positive effect of augmenting blood flow (the theoretical benefit of IPC) on subsequent performance, as previously reported in scientific literature [35, 66]. Moreover, IPC provides mechanical pressure to the limbs, which is hypothesized to help reduce muscular stiffness and improve muscle compliance, therefore enhancing functional capacity [67]. There are other strategies with similar acting mechanisms, such as the use of compression garments or massage treatments [68–70]. Two studies compared the recovery kinetics of ultramarathon participants using IPC, a control condition, and massage treatments [20, 30], finding similar effects between IPC and massage. Additionally, one study [60] compared the use of IPC to compression garments, finding greater recovery benefits for the IPC group. More studies directly comparing IPC with similar recovery techniques could help clarify the real effectiveness of this recovery strategy. Associated with the lack of significant effect, due to the risk of bias regarding blinding procedures, and the reduced number of studies and participants, it is not certain that these results represent the "true" effects of lower-limb IPC, at this point. Future research should consider this critical aspect to reduce biases and limitations that can influence the outcomes, and test the effectiveness of IPC on functional parameters using more robust study methods.

Subjective measures

It is recognized that subjective and objective measures of athletes' recovery do not necessarily follow the same trend and time courses [71]. The subjective parameters seemed to be the most benefited from the use of IPC devices. Nevertheless, it should be noted that the use of a placebo condition is fundamental to limit the interference of psychological factors associated with participants' beliefs and expectations [72]. From the 17 studies included in this review, only six were conducted using a placebo condition [49, 51, 52, 55, 56, 58]; therefore, these results should be cautiously considered.

Regarding pain and soreness measurements, the effect sizes were shown to be higher at 48 h post-exercise. This coincides with the peak values of DOMS [73] and may indicate the higher efficacy of lower-limb IPC on the reduction of pain and soreness in this specific time frame. The mechanism behind the advantages provided by lower-limb IPC on perceptions of pain and soreness could be associated with a reduction in neuromuscular excitability, achieved by stimulating sensory receptors and decreasing the level of muscular tension [67].

It is important to highlight that athletes appear to perceive similar effectiveness between compression garments and IPC; however,

they adhere more to the former, possibly due to the easier access to compression garments considering their portability and cost [37, 38]. The reviews about compression garments reveal that this method is also able to reduce post-exercise muscle soreness within 24 and 96 hours [74, 75].

Perceived recovery was assessed in three studies, revealing either small positive [32, 53] or trivial effects [54]. Accordingly, the results of the two included studies that assessed perceived fatigue reported trivial advantages towards the use of IPC [20, 30]. There is some evidence suggesting that lower-limb IPC may not expressively affect the perceptions of physical fatigue and may provide some small additional benefits concerning perceived recovery; however, we expect that future studies further investigate whether recovery perceptions are improved by this intervention while controlling for the placebo effect.

Physiological markers

Creatine kinase is a marker of muscle damage, highly variable inter- and intra-individually, usually peaking approximately 48 h after high-intensity exercise [56, 76, 77]. This feature leads to some limitations in our results considering that they are based only in five studies (addressing this measure), across different observation points. It should be noted that results could have been influenced by participants' training status: physically active participants typically show a lower level of muscle damage markers compared to untrained subjects [78]. From the studies included in the CK analysis, three analysed trained participants [51, 55, 56], and two reported results of recreationally active healthy subjects [49, 59]. Moreover, participants were subjected to different exercise interventions; therefore, it is likely that different levels of muscle damage were induced, which inevitably would have generated different kinetics of serum-CK. For instance, some fatigue-inducing interventions may not have been sufficiently intense to produce expressive levels of muscle damage, which partially helps to explain the inconsistent results. Overall, since results are generally variable, with wide confidence intervals encompassing both negative and positive effects, it is unlikely that lower-limb IPC affects this marker. By the effects of lower-limb IPC on CK, it appears that post-exercise inflammation markers (CRP, IL-6) are also not affected by the use of this strategy [33, 55, 56]. More studies should take these biomarkers into consideration, to fully explore the effects of lower-limb IPC, especially after more damaging events (e.g., downhill running).

In addition, the use of lower-limb IPC seems not to affect BLa clearance. Nevertheless, it has been suggested that BLa clearance does not necessarily translate into better performances during subsequent exercise [13]. Interestingly, one study [52] reported that the use of IPC caused higher concentrations of BLa during subsequent performance, which may suggest an impairment in the clearance capacity or an improvement in the production capacity. Finally, it was expected that HR measures would kept unaltered after IPC since the former is not necessarily associated with changes in blood flow [35]. However, it is important to note that there is no clear association between HR reduction and recovery of performance indices. It is suggested that globally IPC does not affect HR responses. Regarding BLa, it is important to show in future studies whether higher values during the subsequent exercise are beneficial or not to anaerobic performance.

Recovery protocols

The protocols applied in the included studies varied substantially regarding duration and pressure. Preliminary evidence suggests that a single bout of 20 to 30 minutes may be sufficient to provide immediate and mid-term benefits [20, 30]. The pressure used also varies across studies: it is suggested that a low-pressure treatment offers fewer benefits than high-pressure, but greater effects when compared to passive rest [21]. The results indicate that lower-limb IPC pressures of approximately 80 mmHg, sustained for 20 to 30 minutes seem to be the most used option to recover muscle mechanical functions and reduce perceptions of pain and soreness. To obtain strong and consistent evidence regarding the most contributory recovery options, future studies should consider this critical aspect by comparing and controlling the recovery kinetics following different IPC protocols.

Quality of Evidence and Limitations

The majority of studies revealed a good methodological quality; however, the risk of bias is evident when it is not possible to blind the participants and conceal the treatment allocation [79]. In addition, a limitation of crossover trials is the carryover effect [45]. The power of the selected studies was mainly small, considering sample sizes. Moreover, the best results were found for subjective measures. Although general well-being is recognized as important for athletic performance [80], these measures are more susceptible to biases. This susceptibility arises from various factors, including the participant's belief in the recovery technique [54], familiarity with the assessment scales [81], among others. In this regard, some of the scales assessed still lack proper scientific validation [82]. The choice of different exercise interventions, followed by different recovery protocols considering time, pressure, type of application and moment turn different results expected to occur. Moreover, given the scarcity of research on this recovery technique, it was not possible to cluster the results according to exercise interventions. To address this limitation, more studies on the topic are required. Finally, sex, competitive level or sports differences were not considered, which could limit the validity of our conclusions.

Despite the limitations acknowledged, this study provides reliable results about lower-limb IPC in the context of sports recovery, providing information that may be useful to assist coaches, athletes, and support staff when considering lower-limb IPC as a recovery tool.

CONCLUSIONS

Performance outcomes of elite sport are discussed in the tiny detail, therefore, marginal additions to athletes' readiness to compete may be of capital importance, considering the chances to succeed [62, 83]. The results of the present study indicate that lower-limb IPC provides (at best) moderate beneficial effects concerning perceptions of pain and soreness, as well as small, however non-significative effects on the recovery of muscle mechanical functions. Variable and unclear results were found on the clearance of muscle damage and inflammation markers, while HR and BLa removal rates seem to be unaltered with the use of lower-limb IPC. Finally, the most used recovery protocols appear to last from 20 to 30 minutes with an applied pressure of about 80 mmHg.

Future research recommendations

Intermittent Pneumatic Compression is still in an embryonic phase of scientific evidence, which is demonstrated by the different protocols applied, and the reduced number of original studies analysing this recovery technique as a practical post-exercise strategy. The exercise intervention may be fundamental to determine the recovery response since the type of exercise (e.g., intermittent and continuous efforts) promotes different fatigue effects [84–86]. In addition, valid subjective scales, functional tests, and physiological analyses should be addressed to fully explore the potentialities of IPC. Finally, larger sample sizes, consistent follow-up timings, the use of placebo conditions, and the blinding of procedures to therapists and assessors may help prevent biases in studies assessing the effects of practical post-exercise recovery strategies.

Protocol and Registration

The study protocol was registered at the International Prospective Register of Systematic Reviews (PROSPERO) under the code CRD42021273598.

Conflicts of Interests

The authors declare that they have no conflicting interests.

Funding

Filipe Maia is supported by an individual doctoral grant awarded by Portuguese Foundation for Science and Technology (FCT: 2022.09686.BD). The author Rui Marcelino has received a grant by FCT – Fundação para a Ciência e a Tecnologia, I.P., within the scope of the project "2021.02330.CEECIND", with the DOI 10.54499/2021.02330.CEECIND/CP1699/CT0001.

This work was funded by National Funds by FCT - Foundation for Science and Technology under the following project UIDB/04045/2020 (https://doi.org/10.54499/UIDB/04045/2020).

Ethics approval

Not applicable.

Author contributions

All the authors contributed to the manuscript, including the conception and design of the study, analysis, and interpretation of the data, drafting and critical revision of the manuscript. All authors read and approved the final manuscript.

REFERENCES

1. Mooney M, O'Brien B, Cormack S, Coutts A, Berry J, Young W. The relationship between physical capacity and match performance in elite Australian football: a mediation approach. J Sci Med Sport. 2011; 14(5):447–452.
2. Stølen T, Chamari K, Castagna C, Wisløff U. Physiology of soccer: an update. Sports Med. 2005; 35(6):501–536.
3. Altarriba-Bartes A, Peña J, Vicens-Bordas J, Milà-Villaroel R, Calleja-González J. Post-competition recovery strategies in elite male soccer players. Effects on performance: A systematic review and meta-analysis. PloS One. 2020; 15(10):e0240135.
4. Wallace J, Norton K. Evolution of World Cup soccer final games 1966–2010: Game structure, speed and play patterns. J Sci Med Sport. 2014; 17(2):223–228.
5. Lago-Peñas C, Rey E, Lago-Ballesteros J, Casáis L, Domínguez E. The influence of a congested calendar on physical performance in elite soccer. J Strength Cond Res. 2011; 25(8):2111–2117.
6. Soligard T, Schwellnus M, Alonso J, Bahr R, Clarsen B, Dijkstra H, Gabbett T, Gleeson M, Hägglund M, Hutchinson M, Janse van Rensburg C, Khan K, Meeusen R, Orchard J, Pluim B, Raftery M, Budgett R, Engebretsen L. How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. Br J Sports Med. 2016; 50(17):1030–1041.
7. Paterno M, Taylor-Haas J, Myer G, Hewett T. Prevention of Overuse Sports Injuries in the Young Athlete. Orthop Clin North Am. 2013; 44(4):553–564.
8. Laux P, Krumm B, Diers M, Flor H. Recovery–stress balance and injury risk in professional football players: a prospective study. J Sports Sci. 2015; 33(20):2140–2148.
9. Ekstrand J, Hagglund M, Walden M. Injury incidence and injury patterns in professional football: the UEFA injury study. Br J Sports Med. 2011; 45(7):553–558.
10. Bengtsson H, Ekstrand J, Hägglund M. Muscle injury rates in professional football increase with fixture congestion: an 11-year follow-up of the UEFA Champions League injury study. Br J Sports Med. 2013; 47(12):743–747.
11. Kellmann M. Preventing overtraining in athletes in high-intensity sports and stress/recovery monitoring. Scand J Med Sci Sports. 2010; 20:95–102.
12. Kellmann M, Bertollo M, Bosquet L, Brink M, Coutts AJ, Duffield R, Erlacher D, Halson SL, Hecksteden A, Heidari J, Kallus KW, Meeusen R, Mujika I, Robazza C, Skorski S, Venter R, Beckmann J. Recovery and Performance in Sport: Consensus Statement. Int J Sports Physiol Perform. 2018; 13(2):240–245.
13. Nédélec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in Soccer. Sports Med. 2013; 43(1):9–22.
14. Poppendieck W, Wegmann M, Ferrauti A, Kellmann M, Pfeiffer M, Meyer T. Massage and Performance Recovery: A Meta-Analytical Review. Sports Med. 2016; 46(2):183–204.
15. Sanders D, van Erp T. The Physical Demands and Power Profile of Professional Men's Cycling Races: An Updated Review. Int J Sports Physiol Perform. 2020; 16(1):3–12.
16. Burke L. Nutrition for Swimming. Int J Sports Nutr Exerc Metab. 2014; 24(4):360–372.

17. Burke L, Mujika I. Nutrition for recovery in aquatic sports. Int J Sport Nutr Exerc Metab. 2014; 24(4):425–436.
18. Ranchordas M, Dawson J, Russell M. Practical nutritional recovery strategies for elite soccer players when limited time separates repeated matches. J Int Soc Sports Nutr. 2017; 14(1):35.
19. Querido S, Radaelli R, Brito J, Vaz J, Freitas S. Analysis of Recovery Methods' Efficacy Applied up to 72 Hours Postmatch in Professional Football: A Systematic Review With Graded Recommendations. Int J Sports Physiol Perform. 2022; 17(9):1326–1342.
20. Hoffman M, Badowski N, Chin J, Stuempfle K. A Randomized Controlled Trial of Massage and Pneumatic Compression for Ultramarathon Recovery. J Orthop Sports Phys Ther. 2016; 46(5):320–326.
21. Waller T, Caine M, Morris R. Intermittent Pneumatic Compression Technology for Sports Recovery. Eng of Sport 6. Springer NY; 2006. 391–396.
22. Calnan J, Pflug J, Mills C. Pneumatic intermittent-compression legging simulating calf-muscle pump. Lancet. 1970; 2(7671):502–503.
23. Tran K, Argáez C. CADTH Rapid Response Reports. Intermittent Pneumatic Compression Devices for the Management of Lymphedema: A Review of Clinical Effectiveness and Guidelines. Canadian Agency for Drugs and Technologies in Health.; 2017.
24. Nelson E, Mani R, Vowden K. Intermittent pneumatic compression for treating venous leg ulcers. Cochrane Database Syst Rev. 2008; 16(2):Cd001899.
25. Tastaban E, Soyder A, Aydin E, Sendur O, Turan Y, Ture M, Bilgen M. Role of intermittent pneumatic compression in the treatment of breast cancer-related lymphoedema: a randomized controlled trial. Clin Rehabil. 2020; 34(2):220–228.
26. Sanal-Toprak C, Ozsoy-Unubol T, Bahar-Ozdemir Y, Akyuz G. The efficacy of intermittent pneumatic compression as a substitute for manual lymphatic drainage in complete decongestive therapy in the treatment of breast cancer related lymphedema. Lymphology. 2019; 52(2):82–91.
27. Lauvrak V, Hafstad E, Fure B. NIPH Systematic Reviews: Executive Summaries. Intermittent Pneumatic Compression to Prevent Venous Thromboembolism in Hospitalized Patients: Systematic Scoping Review. Oslo, Norway: Knowledge Centre for the Health Services at The Norwegian Institute of Public Health (NIPH). 2016. Report from the Norwegian Institute of Public Health No. 2016–24.
28. Wang D, Bao F, Li Q, Teng Y, Li J. Semiautomatic intermittent pneumatic compression device applied to deep vein thrombosis in major orthopedic surgery. Biomed Eng Online. 2018; 17(1):78.
29. Williams K, Babber A, Ravikumar R, Davies A. Non-Invasive Management of Peripheral Arterial Disease. Adv Exp Med Biol.; 2017; 387–406.
30. Heapy A, Hoffman M, Verhagen H, Thompson S, Dhamija P, Sandford F, Cooper M. A randomized controlled trial of manual therapy and pneumatic compression for recovery from prolonged running – an extended study. Res Sports Med. 2018; 26(3):354–364.
31. Sands W, McNeal J, Murray S, Stone M. Dynamic Compression Enhances Pressure-to-Pain Threshold in Elite Athlete Recovery: Exploratory Study. J Strength Cond Res. 2015; 29(5):1263–1272.
32. O'Donnell S, Driller M. The effect of intermittent sequential pneumatic compression on recovery between exercise bouts in well-trained triathletes. J Sci Cycl. 2015; 4(3):19–23.
33. Draper S, Kullman E, Sparks K, Little K, Thoman J. Effects of Intermittent Pneumatic Compression on Delayed Onset Muscle Soreness (DOMS) in Long Distance Runners. Int J Exerc Sci. 2020; 13(2):75–86.
34. Borne R, Hausswirth C, Bieuzen F. Relationship Between Blood Flow and Performance Recovery: A Randomized, Placebo-Controlled Study. Int J Sports Physiol Perform. 2017; 12(2):152–160.
35. Morris R, Woodcock J. Effects of supine intermittent compression on arterial inflow to the lower limb. Arch Surg. 2002; 137(11):1269–1273.
36. Brock K, Eberman L, Laird R, Elmer D, Games K. Sequential Pulse Compression's Effect on Blood Flow in the Lower-Extremity. J Sport Rehabil. 2020; 29(1):7–11.
37. Field A, Harper L, Chrismas B, Fowler P, McCall A, Paul D, Chamari K, Taylor L. The Use of Recovery Strategies in Professional Soccer: A Worldwide Survey. Int J Sports Physiol Perform. 2021; 16(12):1804–1815.
38. Leabeater A, James L, Huynh M, Vleck V, Plews D, Driller M. All the gear: The prevalence and perceived effectiveness of recovery strategies used by triathletes. Perform. Enhanc. Health. 2022:100235.
39. Page M, Moher D, Bossuyt P, Boutron I, Hoffmann T, Mulrow C, Shamseer L, Tetzlaff J, Akl E, Brennan S, Chou R, Glanville J, Grimshaw J, Hróbjartsson A, Lalu M, Li T, Loder E, Mayo-Wilson E, McDonald S, McGuinness L, Stewart L, Thomas J, Tricco A, Welch V, Whiting P, McKenzie J. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. BMJ. 2021; 372:n160.
40. Cashin A, McAuley J. Clinimetrics: Physiotherapy Evidence Database (PEDro) Scale. J Physiother. 2020; 66(1):59.
41. Egger M, Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ. 1997; 315(7109):629–634.
42. Duval S, Tweedie R. Trim and fill: A simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. Biometrics. 2000; 56(2):455–463.
43. Wojtyniak J, Britz H, Selzer D, Schwab M, Lehr T. Data Digitizing: Accurate and Precise Data Extraction for Quantitative Systems Pharmacology and Physiologically-Based Pharmacokinetic Modeling. CPT: Pharmacomet. Syst. Pharmacol.. 2020; 9(6):322–331.
44. Cohen J. A power primer. Psychol Bull. 1992; 112(1):155.
45. Curtin F. Meta-analysis combining parallel and cross-over trials with random effects. Res Synth Methods. 2017; 8(3):263–274.
46. 46. Moeyaert M, Ugille M, Natasha Beretvas S, Ferron J, Bunuan R, Van den Noortgate W. Methods for dealing with multiple outcomes in meta-analysis: a comparison between averaging effect sizes, robust variance estimation and multilevel meta-analysis. Int J Soc Res Methodol. 2017; 20(6):559–572.
47. Higgins J, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch, V. A. Cochrane handbook for systematic reviews of interventions: John Wiley & Sons; 2019.
48. Higgins J, Thompson S, Deeks J, Altman D. Measuring inconsistency in meta-analyses. BMJ. 2003; 327(7414):557–560.
49. Wiecha S, Jarocka M, Wiśniowski P, Cieśliński M, Price S, Makaruk B, Kotowska J, Drabarek D, Cieśliński I, Sacewicz T. The efficacy of intermittent pneumatic compression and negative pressure therapy on muscle function, soreness and serum indices of muscle damage: a randomized controlled trial. BMC Sports Sci Med Rehabil. 2021; 13(1):144.
50. Khan Z, Ahmad I, Hussain M. Intermittent pneumatic compression changes heart rate recovery and heart rate variability after short term submaximal exercise in collegiate basketball players: a cross-over study. Sport Sci Health. 2021; 17(2):317–326.
51. Collins R, McGrath D, Horner K, Eusebi S, Ditroilo M. Effect of External Counterpulsation on Exercise Recovery in Team Sport Athletes. Int J Sports Med. 2019; 40(8):511–518.
52. Marcello R, Fortini L, Greer B. Intermittent Pneumatic Compression Boot Use Elevates Blood Lactate During Subsequent Exercise. Int J Exerc Sci. 2019; 12(2):385–392.

53. Northey J, Rattray B, Argus C, Etxebarria N, Driller M. Vascular Occlusion and Sequential Compression for Recovery After Resistance Exercise. J Strength Cond Res. 2016; 30(2):533–539.
54. Overmayer R, Driller M. Pneumatic Compression Fails to Improve Performance Recovery in Trained Cyclists. Int J Sports Physiol Perform. 2018; 13(4):490–495.
55. Haun C, Roberts M, Romero M, Osburn S, Healy J, Moore A, Mobley C, Roberson P, Kephart W, Mumford P, Goodlett M, Pascoe D, Martin J. Concomitant external pneumatic compression treatment with consecutive days of high intensity interval training reduces markers of proteolysis. Eur J Appl Physiol. 2017; 117(12):2587–2600.
56. Haun C, Roberts M, Romero M, Osburn S, Mobley C, Anderson R, Goodlett MD, Pascoe DD, Martin JS. Does external pneumatic compression treatment between bouts of overreaching resistance training sessions exert differential effects on molecular signaling and performance-related variables compared to passive recovery? An exploratory study. PLoS One. 2017; 12(6):e0180429.
57. Keck N, Cuddy J, Hailes W, Dumke C, Ruby B. Effects of commercially available pneumatic compression on muscle glycogen recovery after exercise. J Strength Cond Res. 2015; 29(2):379–385.
58. Martin J, Friedenreich Z, Borges A, Roberts M. Acute effects of peristaltic pneumatic compression on repeated anaerobic exercise performance and blood lactate clearance. J Strength Cond Res. 2015; 29(10):2900–2906.
59. Cochrane D, Booker H, Mundel T, Barnes M. Does intermittent pneumatic leg compression enhance muscle recovery after strenuous eccentric exercise? Int J Sports Med. 2013; 34(11):969–974.
60. Winke M, Williamson S. Comparison of a Pneumatic Compression Device to a Compression Garment During Recovery from DOMS. Int J Exerc Sci. 2018; 11(3):375–383.
61. Ribeiro J, Sarmento H, Silva A, Clemente F. Practical Postexercise Recovery Strategies in Male Adult Professional Soccer Players: A Systematic Review. Strength Cond J. 2021; 43(2):7–22.
62. Marck A, Antero J, Berthelot G, Saulière G, Jancovici J-M, Masson-Delmotte V, Boeuf G, Spedding M, Le Bourg É, Toussaint J. Are we reaching the limits of homo sapiens? Front Physiol. 2017; 8:812.
63. Richard N, Koehle M. Optimizing recovery to support multi-evening cycling competition performance. Eur J Sport Sci. 2019; 19(6):811–823.
64. Rojano-Ortega D, Peña-Amaro J, Berral-Aguilar A, Berral-De La Rosa F. Quercetin supplementation promotes recovery after exercise-induced muscle damage: a systematic review and meta-analysis of randomized controlled trials. Biol Sport. 2023; 40(3):813–825.
65. Wiewelhove T, Schneider C, Döweling A, Hanakam F, Rasche C, Meyer T, Kellmann M, Pfeiffer M, Ferrauti A . Effects of different recovery strategies following a half-marathon on fatigue markers in recreational runners. PloS One. 2018; 13(11):e0207313.
66. O'Riordan S, McGregor R, Halson S, Bishop D, Broatch J. Sports compression garments improve resting markers of venous return and muscle blood flow in male basketball players. J Sport Health Sci. 2021; S2095-2546(21)00092-2.
67. Weerapong P, Hume P, Kolt G. The Mechanisms of Massage and Effects on Performance, Muscle Recovery and Injury Prevention. Sports Med. 2005; 35(3):235–256.
68. Lee D, Ali A, Sheridan S, Chan D, Wong S. Wearing compression garment enhances central hemodynamics? A systematic review and meta-analysis. J Strength Cond Res. 2020; 36(8):2349–2359.
69. Brown F, Gissane C, Howatson G, Van Someren K, Pedlar C, Hill J. Compression Garments and Recovery from Exercise: A Meta-Analysis. Sports Med. 2017; 47(11):2245–2267.
70. Guo J, Li L, Gong Y, Zhu R, Xu J, Zou J, Chen X. Massage Alleviates Delayed Onset Muscle Soreness after Strenuous Exercise: A Systematic Review and Meta-Analysis. Front Physiol. 2017; 8:747.
71. Saw A, Main L, Gastin P. Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. Br J Sports Med. 2016; 50(5):281–291.
72. Hróbjartsson A, Kaptchuk T, Miller F. Placebo effect studies are susceptible to response bias and to other types of biases. J Clin Epidemiol. 2011; 64(11):1223–1229.
73. Nosaka K, Aldayel A, Jubeau M, Chen T. Muscle damage induced by electrical stimulation. Eur J Appl Physiol. 2011; 111(10):2427–2437.
74. Hill J, Howatson G, van Someren K, Leeder J, Pedlar C. Compression garments and recovery from exercise-induced muscle damage: a meta-analysis. Br J Sports Med. 2013; 48(18):1340–1346.
75. Dupuy O, Douzi W, Theurot D, Bosquet L, Dugué B. An Evidence-Based Approach for Choosing Post-exercise Recovery Techniques to Reduce Markers of Muscle Damage, Soreness, Fatigue, and Inflammation: A Systematic Review With Meta-Analysis. Front Physiol. 2018; 9:403.
76. Ribeiro J, Gantois P, Moreira V, Miranda F, Romano N, Nakamura F. Individual-based Creatine Kinase Reference Values in Response to Soccer Match-play. Int J Sports Med. 2022; 43(6):533–537.
77. Giechaskiel B. Weight training and creatine kinase (CK) levels: a literature review. Int J Sci Res. 2020; 9(1):303–311.
78. Ertel K, Hallam J, Hillman A. The effects of training status and exercise intensity on exercise-induced muscle damage. J Sports Med Phys Fitness. 2020; 60(3):449–455.
79. Forbes D. Blinding: an essential component in decreasing risk of bias in experimental designs. Evid Based Nurs. 2013; 16(3):70–71.
80. Noon M, James R, Clarke N, Akubat I, Thake C. Perceptions of well-being and physical performance in English elite youth footballers across a season. J Sports Sci. 2015; 33(20):2106–2115.
81. Abdel-Malek D, Foley R, Wakeely F, Graham J, Delfa N. Calibrating ratings of perceived fatigue relative to objective measures of localised muscle fatigue using a feedback-based familiarisation protocol. Theor Issues Ergon Sci. 2021; 22(5):511–527.
82. Jeffries A, Wallace L, Coutts A, McLaren S, McCall A, Impellizzeri F. Athlete-Reported Outcome Measures for Monitoring Training Responses: A Systematic Review of Risk of Bias and Measurement Property Quality According to the COSMIN Guidelines. Int J Sports Physiol Perform. 2020; 15(9):1203–1215.
83. Peeling P, Binnie M, Goods P, Sim M, Burke L. Evidence-Based Supplements for the Enhancement of Athletic Performance. Int J Sport Nutr Exerc Metab. 2018; 28(2):178–187.
84. Kesisoglou A, Nicolò A, Howland L, Passfield L. Continuous Versus Intermittent Running: Acute Performance Decrement and Training Load. Int J Sports Physiol Perform. 2021; 16(12):1794–1803.
85. Kanthack T, Guillot A, Clemencon M, Debarnot U, Di Rienzo F. Effect of Physical Fatigue Elicited by Continuous and Intermittent Exercise on Motor Imagery Ability. Res Q Exerc Sport. 2020; 91(3):525–538.
86. Gharbi A, Chamari K, Kallel A, Ahmaidi S, Tabka Z, Abdelkarim Z. Lactate kinetics after intermittent and continuous exercise training. J Sports Sci Med. 2008; 7(2):279–285.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2022.106154
© Institute of Sport – National Research Institute

Effects of carob rich-polyphenols on oxidative stress markers and physical performance in taekwondo athletes

AUTHORS: Nawel Gaamouri[1,2], Hassane Zouhal[3], Katsuhiko Suzuki[4], Mehrez Hammami[1,2], Aloui Ghaith[1], El Hafedh El Mouhab[3], Anthony C. Hackney[5], Ismail Laher[6], Omar Ben Ounis[2,7]

[1] Research Unit «Sport Performance, Health & Society», Higher Institute of Sport and Physical Education of Ksar Saîd, University of "La Manouba", Tunis, Tunisia
[2] Higher Institute of Sport and Physical Education of Ksar Said, University of "La Manouba", Tunis, Tunisia
[3] Univ Rennes, M2S (Laboratoire Mouvement, Sport, Santé) – EA 1274, F-35000 Rennes, France
[4] Faculty of Sport Sciences, Waseda University, Tokorozawa 359–1192, Japan
[5] Department of Exercise & Sport Science, University of North Carolina, Chapel Hill, NC, USA
[6] Department of Anesthesiology, Pharmacology and Therapeutics, Faculty of Medicine, University of British Columbia, Vancouver, Canada
[7] Tunisian Research Laboratory ''Sport Performance Optimization'', National Center of Medicine and Science in Sports, Tunis, Tunisia

ABSTRACT: Excessive exercise can induce cell damage and impair muscle function by generating oxidative stress. Carob rich phenolic components have attracted the attention of many researchers because of their antioxidant actions. We utilized a double-blind randomized placebo-controlled design to study the putative antioxidant role of six weeks of daily polyphenol supplementation on selected blood markers of oxidative stress and performance in taekwondo athletes. We studied the effects of daily supplementation with carob (40 g/d, for six-weeks) on performance levels and antioxidant capacity in 22 taekwondo athletes (age 21.9 ± 1.2 years; height 1.66 ± 0.34 m; weight 68.3 ± 16.9 kg; women = 10, men = 12) using a randomized, double-blinded study. Participants were divided into an experimental group (EG) or placebo group (PG). All athletes performed a frequency speed of kick test mult ($FSKT_{mult}$) before and after a six-week training period. Superoxide dismutase (SOD), catalase (CAT), and malondialdehyde (MDA) were measured 5 min after a $FSKT_{mult}$. Physical performances improved significantly after six weeks in EG compared to PG for kicks number per set (from set 1 to set 5: $p = 0.032$, $d = 0.70$; $p = 0.020$, $d = 0.77$; $p = 0.001$, $d = 1.12$; $p = 0.001$, $d = 1.25$; $p = 0.003$, $d = 1.01$), total kicks number ($p = 0{,}002$, $d = 1.04$), and kick decrement index (%) ($p = 0.017$, $d = 0.13$). There were significant increases in CAT ($p = 0.001$, $d = 1.85$) and SOD ($p = 0.001$, $d = 1.98$) activities and significant decreases in MDA levels ($p = 0.002$, $d = 0.81$) in the EG. Carob supplementation during a six-week training program reduced oxidative stress and improved physical performance levels in taekwondo athletes.

CITATION: Gaamouri N, Zouhal H, Suzuki K et al. Effects of carob rich-polyphenols on oxidative stress markers and physical performance in taekwondo athletes. Biol Sport. 2024;41(4):277–284.

Received: 2020-12-22; Reviewed: 2021-02-11; Re-submitted: 2021-03-31; Accepted: 2021-03-31; Published: 2024-06-17.

Corresponding authors:
Hassane Zouhal
Sport Sciences and Physical Education Department
UFR APS
Université Rennes 2, France
E-mail:
hassane.zouhal@univ-rennes2.fr

Katsuhiko Suzuki
Faculty of Sport Sciences,
Waseda University, Tokorozawa
359–1192, Japan
E-mail: katsu.suzu@waseda.jp

ORCID:
Hassane Zouhal
0000-0001-6743-6464

Katsuhiko Suzuki
0000-0002-4149-0814

Mehrez Hammami
0000-0001-7524-4753

Anthony C. Hackney
0000-0002-6607-1472

Ismail Laher
0000-0002-3917-4417

Omar Ben Ounis
0000-0001-8490-9542

Key words:
Polyphenols
Antioxidants
Ergogenic aids
Exercise

INTRODUCTION

Excessive and poorly monitored training (including aerobic [1] and anaerobic [2] exercises), as sometimes practiced by athletes, often leads to increases in oxidative stress [3]. Sports involving combat maneuvers frequently contain intense physical activities that are dependent on both aerobic and anaerobic energy metabolism [4]. Competitions such as taekwondo involve high levels of physiological, hormonal and psychological stress [5–7]. Taekwondo competitions require athletes to be physically fit, where power is generated through aerobic and anaerobic metabolism, muscular strength, speed and agility [8]. All fights in taekwondo competitions (from qualification to finals) occur in a single day [9]. The frequency speed of kick test (FSKT10s) is the only assessment that is mainly related to the ATP-PCr energy system, due to its intense nature and short duration (10s), and which is performed intermittently (5 × 10s/10s intervals, $FSKT_{mult}$) [10]. Moreover, this test can be easily applied in the taekwondo training facility and does not require sophisticated equipment [11–13]. Additionally, the FSKT is sensitive enough to identify acute [14] and long-term performance changes [13], and is able to discriminate between international/national and state/regional female taekwondo performances [11]. Engaging in taekwondo necessitates periods of high-intensity efforts, leading to cellular generation of reactive oxygen species (ROS) [2], oxidative stress and cellular damage [15, 16]. Accumulation of ROS induces cell and skeletal muscle damage, and causes rapid muscle-fatigue and reduces exercise performance [17]. Therapeutic

interventions including massage, cryotherapy and nutritional strategies have been studied in efforts to reduce oxidative stress and improve athletic performance [18, 19]. A recent review summarized the findings of studies on the effects of natural products (e.g., vitamin C, vitamin E, β-carotene, quercetin, resveratrol, and polyphenols) either alone or in combination with other supplements on exercise-induced oxidative stress [20].

Polyphenols are natural compounds that can prevent or reduce oxidative stress, relieve muscle soreness and improve performance [21, 22, 23]. To this end, carob is rich in dietary fiber, polyphenols, and cyclitols with low amounts of fat and is gaining increasing use due to its ability to improve health and prevent numerous chronic diseases [24]. Carob has antiproliferative and apoptotic activity against cancer cells, can treat diarrhea symptoms, and possesses antihyperlipidemic and antidiabetic effects [25]. Furthermore, carob fiber has a higher antioxidant capacity than many other foods rich in polyphenols such as blueberries, grapes or red wine [26]. Only a few studies have investigated the effects of carob supplementation on physiological stress in athletes undertaking aerobic and anaerobic activities. We utilized a double-blind randomized placebo-controlled design to study the putative antioxidant role of six weeks of a daily polyphenol supplementation with carob on selected blood markers of oxidative stress [malondialdehyde (MDA), superoxide dismutase (SOD) and catalase (CAT)] and performance in taekwondo athletes. We hypothesized that carob supplementation reduced oxidative stress and improved physical performance levels in taekwondo athletes.

MATERIALS AND METHODS

Participants

Twenty-two taekwondo athletes (age: 22.7 ± 2.4 years, see Table 1) who are students at the High Institute of Sport and Physical Education of Ksar Said (Tunis, Tunisia) volunteered to participate in the current study. Participants were recruited following a poster submitted to the Institute's Sports Department. The poster included a brief description of the study, its objectives, the inclusion and exclusion criteria and the tasks required from participants. All participants were required to be at the level of black belts (first Dan or greater).

Inclusion criteria of participants were: i) they trained at least three times a week for 90 to 120 min per session, ii) if they participated at a national level for at least three years, iii) if they were not consuming antioxidants or anti-inflammatory compounds, either currently or one month prior to the study, iv) females should not be consuming any form of oral contraception and physical performance was measured during the luteal phase of the menstrual cycle. Participants were excluded if they were smokers, sustained an injury in the previous 30 days, had recent surgery, had hypertension or cardiovascular/metabolic disorders. The study procedures were explained before participants provided written informed consent, and participants were informed that they could withdraw from the study at any stage. The study was approved by the Ethical Committee on Human Research of the University of la Manouba, Tunisia (Approval Number: 2017-0396), and was carried out in accordance with the Declaration of Helsinki. The study lasted six-weeks, and during this period, athletes trained four times per week with each session lasting 90 minutes. Each training session included specific technical interval training (IT), tactical and technical training sessions (TT), technical-development training sessions and free taekwondo sparring, and was supervised by the same taekwondo coach throughout the study. The training sessions included specific technical interval training, tactical technical training sessions, technical-development training sessions and free taekwondo sparring [8].

Experimental design

We used a double-blind randomized design to study whether supplementation with carob for 6 weeks improved antioxidant capacity and physical performance of taekwondo athletes. Athletes were randomly assigned to one of two study groups: A) Supplement Group (EG: n = 11; 5 females and 6 males) and B) Placebo Group (PG: n = 11; 5 females and 6 males).

TABLE 1. Characteristics of athletes

Measures	Groups	T1	T2	P
Weight (kg)	**PG**	72.9 ± 15.2	70.3 ± 13.3	
	EG	70.8 ± 12.6	68.8 ± 12.4	> 0.05
Height (m)	**PG**	1.72 ± 0.19	1.72 ± 0.15	
	EG	1.72 ± 0.11	1.72 ± 0.07	> 0.05
BMI (kg/m^2)	**PG**	24.5 ± 4.9	23.7 ± 4.3	
	EG	23.9 ± 3.8	23.2 ± 3.7	> 0.05

Values are presented as mean ± SD. Variables were measured before (T1) and after (T2) six-weeks of carob supplementation. The data were analyzed using two-way ANOVA: two groups (EG, PG) × two time points (T1, T2). EG: experimental group, PG: placebo group.

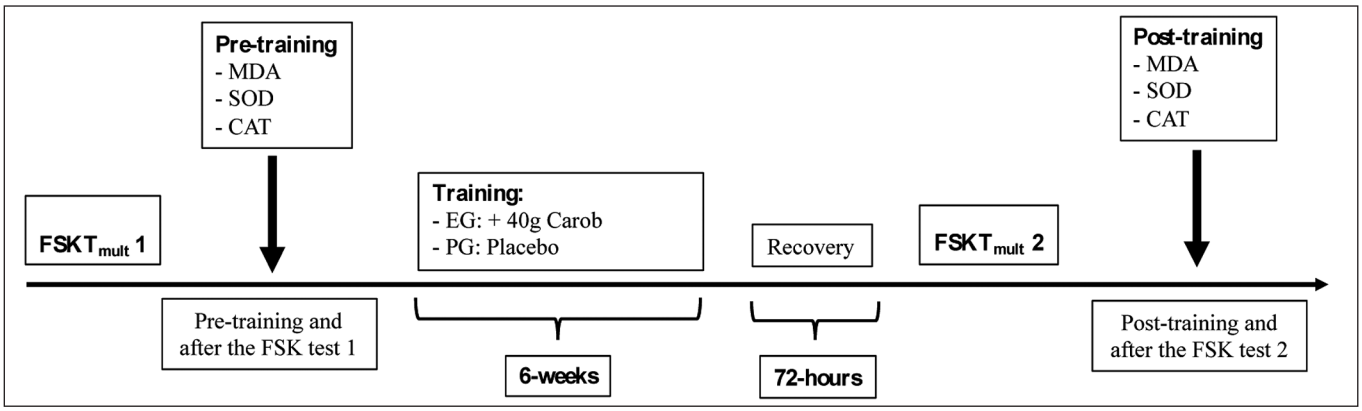


FIG. 1. Experimental design
FSK: frequency speed of kick; EG: experimental group; PG: placebo group

Participants successfully completed two familiarization trials over a two-week period before the data were collected immediately before the training period (pre- and post-exercise) and after the six-week trial (pre- and post-exercise) (Figure 1). Testing involved the frequency speed of kick test mult ($FSKT_{mult}$) protocol; the athletes all followed identical training sessions and data were recorded at the same of every day of the tests. A daily record of nutrient intake was collected from each participant seven days before starting the study; the participants were instructed in detail (written and oral explanations) on these data collection procedures. All participants continued with their usual eating habits and were instructed to be accurate with recording the amount and type of food and fluid intake. Common measures (e.g., cups and tablespoons) and quantities (e.g., grams) were provided to the participants, and individual diets were calculated using the Bilnut 4 software package (SCDA Nutrisoft, Cerelles, France) and food composition tables published by the Tunisian National Institute of Statistics in 1978. Nutrient intakes were within the reference dietary guidelines for healthy Tunisian adults.

Exercise protocol

Frequency Speed of Kick Test Mult ($FSKT_{mult}$): The Frequency Speed of Kick Test ($FSKT_{10s}$) lasts for 10 s, and during its execution each athlete is placed in front of a stand bag equipped with a simple trunk taekwondo protector. After a command, the athlete performs the maximal number of kicks possible, alternating the right and the left legs. The turning kick, known as Bandal Tchagui, is used during the test [12, 14] .The same procedures was used in the $FSKT_{10s}$ were also used during the $FSKT_{mult}$. Briefly, five FSKTs with a 10-s rest interval between repetitions were executed. Performance was determined by the total number of kicks in each set, the total number of kicks in five sets, and the kick fatigue index [10] [12]. The $FSKT_{mult}$ had a mean intraclass correlation coefficient (ICC) of 0.85 between tests and retests. The mean test and retest coefficient of variation was 3.9%. The kick decrement indicates performance decreases during the tests.

The number of kicks applied during the multiple FSKT is considered when calculating the kick decrement. The equation takes into account the results of all FSKT sets [27] .Kick decrement index (%) = [1 – (FSK test 1 + FSK test 2 + FSK test 3 + FSK test 4 + FSK test 5 / best FSK test × number of sets)] × 100.

Sample collection

Blood samples were always collected at the same time (7 to 8 AM) following an overnight (12 hr) fast. Venous blood samples were collected by the same technician at the following times: A) pre-training, after the $FSKT_{mult}$ (Pre); and B) post-training program, after the $FSKT_{mult}$ (Post). Blood samples were taken from the antecubital site and placed in EDTA tubes (Vacutainer, Becton Dickinson, Franklin Lakes, NJ, USA) after the participants were seated for 5 min immediately after the test. Blood samples were transported to the laboratory in crushed ice and then centrifuged (3500 × g at 4° C for 12 min) and stored in aliquots (-80°C) for later analysis. Inter-assay variance was minimized by analyzing samples in the same assay run; measurements were made in duplicate using an automated analyzer (Beckman Coulter UniCel® DxC 600 Synchron®, Beckman Instruments, California, USA), using reagents, standards, and controls from Randox Laboratories (Crumlin, Northern Ireland, UK). The measurements had an intra-assay coefficient of variation of less than 7%.

Oxidative stress and antioxidant enzymes

Plasma lipid peroxidation was estimated by measuring malondialdehyde (MDA) levels using a double heating method [28]. Aliquots (250 μl) from the sample were mixed with butylated hydroxytoluene –trichloroacetic acid (TCA) Q3 solution (250 μl) containing 1% BHT (m/v) dissolved in 20% TCA (m/v) and centrifuged at 1,000 × g for 5 min at 4 °C. The supernatant (400 μl) was mixed with 0.5 N HCl

(80 μl) and 120 mM thiobarbituric acid (TBA) in 26 mM Tris (320 μl) and then heated (80° C for 10 min). The absorbance of the resulting pink chromophore was measured at 532 nm using a SmartSpec 3000 Bio-Rad UV-visible spectrophotometer (Germany).

Concentrations of MDA were calculated (using an extinction coefficient of 155 $mM^{-1}cm^{-1}$ for the MDA -TRA complex) using the formula: MDA concentration (M) = absorbance at 532 nm/1.56 × 105. Superoxide dismutase (SOD) activity was determined by the epinephrine method [29], which is based on the capacity of the SOD to inhibit the auto-oxidization of the epinephrine in adrenochrome while trapping the flux of anion superoxide. The sample was mixed in a buffer of Na_2CO_3/$NaHCO_3$ (50 mM, pH = 10.2) with 10 μl of bovine CAT (0.4 U/ml) and 20 μl of epinephrine (5 mg/ml). The SOD activity was assessed by spectrophotometry. Detection was performed at 480 nm with a Bio-Rad spectrophotometer (Bio-Rad Laboratories, Philadelphia, USA).

CAT is a metalloenzyme that transforms the peroxide of hydrogen in water and molecular oxygen according to the following reaction: $2H_2O_2 \rightarrow 2H_2O + O_2$. The sample was mixed with phosphate buffer (50 mM, pH = 7). The kinetics of the CAT activity was spectrophotometrically measured at 240 nm for 3 min while measuring the decomposition of the H_2O_2. The CAT activity was calculated according to the Beer–Lambert principle.

Determination of total phenols

Extraction

A test sample of degreased vegetable material (2 g) was macerated in a mixture of acetone / water (100ml, 70/30 v/v) for 24 hours at room temperature before being vacuum filtered. The acetone / water mixture was then evaporated (45° C) to dryness under reduced pressure, and the resultant residue recovered with 3 ml methanol for later assays [30].

Dosage by Folin-Ciocalteu method

The process requires the reduction of phoshomolybdic acid in Folin-Ciocalteau reagent (a yellow acid consisting of acid polyheterocycles containing molybdenum and tungsten) by polyphenols under alkaline conditions [31]. This reaction creates a dark blue tungsten molybdenum complex, which is measured using a spectrophotometer.

Procedure

Polyphenols were measured using the method of Singleton as reported by Dogyan et al. [32]. The residue resulting from the extraction was dissolved in distilled water (5 ml), and 100 μl of this solution was diluted to 3 ml and added to 0.5 ml of Folin Ciocalteu reagent. This reaction was allowed to proceed for 3 min, after which 2 ml of 20% a sodium carbonate solution was added; the mixture was vortexed and incubated in the dark for 1 hr, and the absorbance was read at 650 nm.

Carob extract and placebo supplementation

Mature carob pods collected from the north-west of Tunisia and dried in an incubator (50° C, 72 h) and then powdered in an electric blender (Moulinex Ovatio 2, France) to yield a mixture of carob pulp (90%) and carob seeds (10%). Each 40 g sample of carob powder contained 208 mg of total polyphenol, and 14.4 mg of flavonoids. Participants in both groups were contacted by telephone to remind them to consume the supplements at the agreed times. The placebo was prepared with a carob-flavored commercial drink (250 ml) containing water, citric acid, natural flavor (carob), sweeteners (aspartame × 0.3 g/l), acesulfame K (0.16 g/l)), stabilizers (Arabic gum) and was free of antioxidants, vitamins and polyphenols. Participants in the EG consumed freshly prepared carob powder (40 g) diluted in 250 ml of water daily at breakfast for 6 weeks.

Statistical analysis

Data are reported as mean ± standard deviation (SD) and normality was verified with the Kolmogorov-Smirnov test. A two-way ANOVA (2 levels [supplementation (PG and EG) × 2 levels [training period (Pre and Post)] was used to determine the effects of carob supplementation on physical performance (FSK test) and biochemical measurements. No between sexes comparison were conducted due to the small sample numbers for men and women. The Cohen's d test was used to assess effect size (ES) under the two conditions, so that a d value of 1 indicates that the two groups differed by 1 SD.

ES were considered to be either trivial ($d < 0.2$), small ($d = 0.2–0.6$), moderate ($d = 0.6–1.2$), large ($d = 1.2–2.0$) and very large ($d = 2.0–4.0$) [33]. Relationships between parameters were assessed using the Pearson's product-moment correlation coefficient (r), which were interpreted as trivial ($r < 0.1$), small ($0.1 < r < 0.3$), moderate ($0.3 < r < 0.5$), large ($0.5 < r < 0.7$), very large ($0.7 < r < 0.9$), nearly perfect ($0.9 < r < 1$), and perfect ($r = 1$) [34]. Statistical analyses were made with a SPSS (SPSS Inc., Chicago, IL, version 20.0), and significance was set at $p < 0.05$.

RESULTS

There were no significant differences in the study groups for any of the anthropometric characteristics (Table 1). There were significant weight reductions when comparing pre- and post-interventions (~2 kg) in both PG and EG, but these were not different between the groups.

Effect of carob supplementation on oxidative stress and antioxidant enzymes

Blood levels of oxidative stress and antioxidant enzymes are shown in Table 2. MDA levels following the $FSKT_{mult}$ decreased after the supplementation period for both EG ($p < 0.01$) and PG ($p = 0.01$). The decrease was significantly higher in EG (-25.6 ± 6.1%). In addition, SOD levels increased after the supplementation period compared to values before supplementation for EG ($p < 0.01$) and PG ($p < 0.01$). Values were significantly higher in EG (+32.7 ± 5.1%).

TABLE 2. Changes in blood levels of oxidative stress markers induced by the $FSKT_{mult}$ before and after 6-week supplementation in both groups (PG and EG).

Measures	Groups	Pre-Supplementation	Post-Supplementation	MΔ ± SDΔ (%)	Cohen's d	ANOVA p-value (Cohen's d)		
						Time	Group	Time × Group
MDA (nmol/ml)	EG	0.35 ± 0.01	0.26 ± 0.01**	-25.6 ± 6.1	-6.42	0.001 (3.64)	0.001 (1.33)	0.002 (0.81)
	PG	0.35 ± 0.01	0.30 ± 0.01**	-16.1 ± 4.5	-4.75			
SOD (KL/ml)	EG	0.34 ± 0.01	0.46 ± 0.02**	32.7 ± 5.1	7.77	0.001 (5.69)	0.001 (1.36)	0.001 (1.85)
	PG	0.34 ± 0.01	0.40 ± 0.01**	17.0 ± 4.6	4.40			
CAT (Mm/ml)	EG	18.20 ± 0.25	22.04 ± 0.30**	21.0 ± 0.4	15.41	0.001 (15.78)	0.001 (0.85)	0.001 (1.98)
	PG	18.24 ± 0.27	21.17 ± 0.30**	16.1 ± 1.9	11.06			

Values are presented as mean ± SD. Blood samples were collected after the $FSKT_{mult}$, before the six-week treatment (Pre-supplementation) and after the treatment (Post-supplementation). Data were analyzed using two-way ANOVA: two groups (PG and EG) * two time points (Pre, Post). EG: experimental group, PG: placebo group; Superoxide dismutase: SOD; catalase: CAT; malondialdehyde: MDA; EG: experimental group; PG: placebo group; MΔ ± SDΔ: percentage change of blood parameters ± SD; **: $p < 0.05$.

TABLE 3. Values (mean ± SD) of $FSKT_{mult}$ parameters before (T1) and after (T2) supplementation.

Measures	Groups	T1	T2	ANOVA	
				Time × Group	Cohen's d
Set 1	PG	21.63 ± 1.12	22.18 ± 1.16	p = 0.032	0.70
	EG	21.81 ± 1.77	24.18 ± 1.25		
Set 2	PG	20.72 ± 1.19	21.18 ± 1.16	p = 0.020	0.76
	EG	21.27 ± 1.84	23.81 ± 1.40		
Set 3	PG	19.90 ± 0.83	20.18 ± 0.98	p = 0.001	1.12
	EG	20.00 ± 1.73	23.09 ± 1.51		
Set 4	PG	18.90 ± 0.94	19.54 ± 0.93	p = 0.003	1.24
	EG	19.09 ± 1.70	22.90 ± 1.57		
Set 5	PG	18.45 ± 1.29	19.18 ± 1.07	p = 0.002	1.01
	EG	18.63 ± 1.96	22.27 ± 1.55		
Total Number	PG	99.63 ± 4.58	102.27 ± 5.00	p = 0.002	1.04
	EG	100.22 ± 6.70	109.27 ± 9.26		
KDI	PG	8.18 ± 2.40	7.27 ± 2.72	p = 0.017	0.79
	EG	8.81 ± 2.67	4.27 ± 1.73		

EG: experimental group, PG: placebo group; T1: before supplementation period; T2: after supplementation period, KDI: Kick decrement index

Similarly, values of CAT increased after the supplementation period for EG ($p < 0.01$) and PG ($p < 0.01$). Values were significantly higher in EG (+21.0 ± 0.4%). There were significant differences (using ANOVA) for group × time interactions for SOD activity ($p = 0.001$, $d = 1.85$), CAT activity ($p = 0.001$, $d = 1.98$) and MDA levels ($p = 0.002$, $d = 0.81$).

Effect of carob supplementation on $FSKT_{mult}$ performance

Physical performance measured during the $FSKT_{mult}$ (i.e., set 1 to set 5, total number and F-index) after PLA and carob supplementation are shown in Table 3.

An ANOVA test revealed significant group × time effects for all parameters tested: set 1 ($p = 0.032$, $d = 0.70$), set 2 ($p = 0.020$, $d = 0.77$), set 3 ($p = 0.001$, $d = 1.12$), set 4 ($p = 0.001$, $d = 0.12$), set 5 ($p = 0.003$, $d = 1.01$), and the total number ($p = 0.002$, $d = 1.04$).

Similarly, an ANOVA test revealed significant group × time effects for the kick decrement index ($p = 0.017$, $d = 0.13$). The relationship between percentage changes of antioxidant enzymes and performance markers during the $FSKT_{mult}$ is shown in Table 4. Correlations between % changes of SOD and $FSKT_{mult}$ parameters (best, total number and kick decrement index, respectively) were either positively moderate,

TABLE 4. Relations between percentage changes of blood parameters of antioxidant enzymes and those of performance markers after the $FSKT_{mult}$ both before and after the training program.

		% changes of blood parameters of oxidative stress		
		SOD	**CAT**	**MDA**
Performance parameters changes during $FSKT_{mult}$ (%)	**Best**	r = 0.48** (moderate)	r = 0.52** (large)	r = - 0.21** (small)
	Total number	r = 0.72** (very large)	r = 0.80** (very large)	r = - 0.46** (moderate)
	KDI	r = - 0.63** (large)	r = - 0.72** (very large)	r = 0.72** (very large)

**: $p < 0.05$. Superoxide dismutase: SOD; catalase: CAT; Malondialdehyde: MDA; EG: experimental group; PG: placebo group KDI: Kick decrement index.

positively very large and negatively large between % changes of SOD and $FSKT_{mult}$ parameters (best, total number and kick decrement index, respectively). There were negative small correlations, negative moderate correlations and positive very large correlations between % changes of MDA and $FSKT_{mult}$ parameters (best, total number and kick decrement index, respectively).

DISCUSSION

The results of our study indicate that performance in a six-week taekwondo training program was improved by carob supplementation in both treatment (EG) and placebo (PG) groups. Our finding that carob improved aerobic performance in taekwondo athletes supports previous studies reporting improved physiological effects of polyphenols on athletes. Polyphenols reportedly augment vasodilation by increasing endothelial nitric oxide synthesis [35, 36], which improves tissue perfusion of both oxygen and other substrates to active muscles during exercise, and so enhances exercise performance [37, 38]. The low levels of fatigue index shown in the EG reinforced the notion that the direct effects of polyphenols may involve the reduction of muscle fatigue at the level of contractile function [39]. Thus, according to Kashi et al. [40], the ergogenic effects of fruit-derived polyphenols may be associated with improved vascular function, enhanced muscle perfusion and enhance oxygen extraction, and improved physical work capacity.

Our study indicates that carob supplementation improved antioxidant status in athletes, likely due to augmented activities of SOD and CAT. Furthermore, six weeks of daily supplementation with carob significantly decreased MDA levels and enhanced physical performance. Acute consumption of cocoa rich polyphenol reduces oxidative stress and muscle damage induced by exercise [41], while chronic intake of dark chocolate reduces oxidative stress and muscle damage biomarkers in elite football players undergoing intensive physical training [26, 42]. The beneficial effects of dark chocolate support the hypothesis that polyphenols, particularly epicatechin, may be responsible for this effect [42] .The ability of carob to increase antioxidant (SOD and CAT) activities may be related to inhibition of NADPH-oxidase activity and reduced superoxide anion overproduction [43].

Our study also examined the effects of carob supplementation on antioxidant parameters in response to intense exercise. The % change of performance was correlated with the % change of antioxidant enzyme (SOD and CAT) and MDA levels for the most part. Some authors describe the antioxidant capacity conferred by supplementation with fruit-derived polyphenols as being ergogenic [40]. In addition, aqueous extracts of carob protect cells from lipid peroxidation induced damage. Our results are in agreement with the findings of Al-Olayan et al. [44] who suggested that carob prevents liver glutathione depletion and stabilizes membrane permeability by inhibiting MDA formation and reducing lipid peroxidation in mice.

The efficacy of the carob preparation may be related to its high content of polyphenols, which have antioxidant effects [45]. Other studies reported that supplementation with such antioxidants accelerates recovery from physical fatigue [46] and prevents exercise-induced tissue damage by limiting exercise-induced muscular and oxidative damage, inflammation, and the consequences of reduced muscle force capacity [47]. Carob supplementation also reduce tissue oedema and/or the accumulation of metabolic by-products [48].

Limitations and Implications for future Research

Taekwondo is an intermittent combat sport and competition rules require that athletes recover quickly between fights, and all contests (from qualification to finals) occur in a single day. To our knowledge, this is the first study to evaluate carob supplementation on antioxidant capacities and physical performance in taekwondo athletes. However, our study has a number of limitations that should be addressed. First is the relatively small sample size of our study groups and the limited number of measurement time points. Hence studies with larger sample sizes are needed to verify these findings. Secondly, we

measured only three markers of oxidative stress; measuring other biomarkers of antioxidant activity such as Ferric-reducing ability of plasma (FRAP), total antioxidant status (TAS), 2.2'-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid (ABTS) would have added to our findings. Lastly, we did not measure nitric oxide biomarkers (e.g., plasma nitrate, nitrite and L-citrulline levels) which could have validated the results obtained in performance tests [51]. Finally, we did not address the mechanistic basis of the biological benefits of supplementation with carob, for example by measuring skeletal muscle eNOS activity [51]. Hence, a causal role for the benefits of carob use can only be claimed after additional studies are performed.

Practical Applications

The decrease of oxidative stress which improved physical performance should interest taekwondo coaches, as it is relatively easy to incorporate, it is easily possible to incorporate 40 g of carob in the diet of an athlete for at least six-weeks before a competition.

CONCLUSIONS

The intense muscle-endurance tests used in this study induced oxidative stress, muscle damage and fatigue in taekwondo athletes. The results of our study indicate that daily supplementation with 40 g of carob-rich polyphenol for six-weeks prevents oxidative stress as induced by high-intensity exercise and improves physical performance in taekwondo athletes.

Funding

No funds were received for this study.

Acknowledgments

The authors thank all the athletes for their participation in the current study.

Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. Vollaard NB, Shearman JP, Cooper CE. Exercise-induced oxidative stress: myths, realities and physiological relevance. Sports Med. 2005;35(12):1045–1062.
2. Bloomer RJ, Goldfarb AH. Anaerobic exercise and oxidative stress: a review. Can J Appl Physiol. 2004; 29(3):245–263.
3. Fisher-Wellman K, Bloomer RJ. Acute exercise and oxidative stress: a 30 year history. Dyn Med. 2009;8:1.
4. Campos FA, Bertuzzi R, Dourado AC, Santos VGF. Energy demands in taekwondo athletes during combat simulation. Eur J Appl Physiol. 2012;112(4):1221–1228.
5. Pesce M, Fratta IL, Ialenti V, Patruno A, Ferrone A, Franceschelli S, Rizzuto A, Tatangelo R, Campagna G, Speranza L, Felaco M, Grilli A. Emotions, immunity and sport: Winner and loser athlete's profile of fighting sport. Brain Behav Immun. 2015;46:261–269.
6. Slimani M, Davis P, Franchini E, Moalla W. Rating of perceived exertion for quantification of training and combat loads during combat sport specific activities: a short review. J Strength Cond Res. 2017;31(10):2889–2902.
7. Slimani M, Miarka M, Briki W, Cheour F. Comparison of mental toughness and power tests performances in high-level kickboxers by competitive success. Asian J Sports Med. 2016;7:30840.
8. Gaamouri N, Zouhal H, Hammami M, Hackney AC, Abderrahman AB, Saeidi A, El Hage R, Ben Ounis O. Effects of polyphenol (carob) supplementation on body composition and aerobic capacity in taekwondo athletes. Physiol Behav. 2019;205:22–28.
9. World Taekwondo Federation. Competition Rules & Interpretation. Seoul, Korea, December 2016.
10. Santos JFS, Franchini, E. Is frequency speed of kick test responsive to training? A study with taekwondo athletes. Sport Sci Health. 2016;12:377–382.
11. Santos JFS, Franchini, E. Frequency Speed of Kick Test Performance Comparison Between Female Taekwondo Athletes of Different Competitive Levels. J Strength Cond Res. 2018; 32(10):2934–2938.
12. Santos JFS, Loturco I, Franchini E. Relationship between frequency speed of kick test performance, optimal load, and anthropometric variables in black-belt taekwondo athletes. J Martial Arts Anthrop. 2018;18(1):39–44.
13. da Silva Santos JF, Takito MY, Artioli GG, Franchini E. Weight loss practices in Taekwondo athletes of different competitive levels. J Exerc Rehabil. 2016;12(3):202–208.
14. Santos JF, Valenzuela TH, Franchini E. Can different conditioning activities and rest intervals affect the acute performance of taekwondo turning kick? J Strength Cond Res. 2015; 29(6):1640–1647.
15. Wang CH, Wu SB, Wu YT, Wei YH. Oxidative stress response elicited by mitochondrial dysfunction: implication in the pathophysiology of aging. Exp Biol Med. 2013;238(5):450–460.
16. El Abed K, Rebai H, Bloomer RJ, Trabelsi K, Masmoudi L, Zbidi A, Sahnoun Z, Hakim A, Tabka Z. Antioxidant status and oxidative stress at rest and in response to acute exercise in judokas and sedentary men. J Strength Cond Res. 2011; 25(9):2400–2409.
17. Lamprecht M, Greilberger JF, Schwaberger G, Hofmann P, Oettl K. Single bouts of exercise affect albumin redox state and carbonyl groups on plasma protein of trained men in a workload-dependent manner. J Appl Physiol. 2008;104(6):1611–1617.
18. Dupuy O, Douzi W, Theurot D, Bosquet L, Dugué B. An Evidence-Based Approach for Choosing Post-exercise Recovery Techniques to Reduce Markers of Muscle Damage, Soreness, Fatigue, and Inflammation: A Systematic Review With Meta-Analysis. Front Physiol. 2018; 9:403.
19. Peake J, Neubauer O, Gatta PD, Nosaka K. Muscle damage and inflammation during recovery from exercise. J Appl Physiol. 2016; 122(3):559–570.
20. Taherkhani S, Suzuki K, Castell L. A Short Overview of Changes in Inflammatory Cytokines and Oxidative Stress in Response to Physical Activity and Antioxidant Supplementation. Antioxidants. 2020; 9(9):886.
21. Vassalle C, Pingitore A, De Giuseppe R, Vigna L, Bamonti F. Biomarkers Part II: Biomarkers to Estimate Bioefficacy of Dietary/Supplemental Antioxidants in Sport. Antioxidants in Sport Nutrition. Boca Raton (FL): CRC Press/Taylor & Francis. 2015;Chapter 16.
22. Pingitore A, Lima GP, Mastorci F, Quinones A, Iervasi G, Vassalle C. Exercise and oxidative stress: potential effects of antioxidant dietary strategies in sports. Nutrition. 2015;31:916–922.
23. Wu C, Zhao W, Yu J, Li S, Lin L, Chen X. Induction of ferroptosis and mitochondrial dysfunction by oxidative stress in PC12 cells. Sci Rep. 2018;8(1):574.
24. Papaefstathiou E, Agapiou A, Giannopoulos S, Kokkinofta R. Nutritional characterization of carobs and traditional carob products. Food Sci Nutr. 2018;6(8):2151–2161.

25. Theophilou IC, Neophytou C, Kakas AC, Constantinou AI. Carob and its Components in the Management of Gastrointestinal Disorders. J Hepatol Gastroenterol. 2017;1:005.
26. Durazzo A, Turfani V, Narducci V, Azzini E, Maiani G, Carcea M. Nutritional characterisation and bioactive components of commercial carobs flours. Food Chem. 2014;153:109–113.
27. Girard O, Mendez-Villanueva A, Bishop D. Repeated sprint ability-part I: factors contributing to fatigue. Sports Med. 2011;41(8):673–694.
28. Draper HH, Hadley M. Malondialdehyde determination as index of lipid peroxidation. Methods Enzymol. 1990; 186:421–431.
29. Misra HP, Fridovich I. The role of superoxide anion in the autoxidation of epinephrine and a simple assay for superoxide dismutase. J Biol Chem. 1972;247(10):3170–3175.
30. Yu Z, Dahlgren RA. Evaluation of methods for measuring polyphenols in copper foliage. J Chem Ecol. 2000;26(9):2119–2140.
31. Catalano L, Franco I, Nobili MD, Leita L. Polyphenols in olive mill waste waters and their depuration plant effluents: a comparison of the Folin-Ciocalteau and HPLC methods. Agrochimica 1999;43:193–205.
32. Dogan S, Turan Y, Erturk H, Arslan O. Characterization and purification of polyphenol oxidase from artichoke (Cynara scolymus L.). J Agric Food Chem. 2005;53(3):776–785.
33. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009;41(1):3–13.
34. Hopkins WG. Measures of reliability in sports medicine and science. Sports Med. 2000;30(1):1–15.
35. Fisher ND, Hughes M, Gerhard-Herman M, Hollenberg NA. Flavanol-rich cocoa induces nitric-oxide-dependent vasodilation in healthy humans. J Hypertens. 2003;21(12):2281–2286.
36. Kim JA, Formoso G, Li Y, Potenza MA, Marasciulo FL, Montagnani M, Quon MJ. Epigallocatechin gallate, a green tea polyphenol, mediates NO-dependent vasodilation using signaling pathways in vascular endothelium requiring reactive oxygen species and Fyn. J Biol Chem. 2007;282(18):13736–13745.
37. Kingwell BA. Nitric oxide-mediated metabolic regulation during exercise: effects of training in health and cardiovascular disease. FASEB J. 2000;14(12):1685–1696.
38. Roberts CK, Barnard RJ, Jasman A, Balon TW. Acute exercise increases nitric oxide synthase activity in skeletal muscle. Am J Physiol. 1999;277(2):390–394.
39. Myburgh KH . Polyphenol supplementation: benefits for exercise performance or oxidative stress? Sports Med. 2014;44(1):57–70.
40. Kashi DS, Shabir A, Da Boit M, Bailey SJ, Higgins MF. The Efficacy of Administering Fruit-Derived Polyphenols to Improve Health Biomarkers, Exercise Performance and Related Physiological Responses. Nutrients. 2019;11(10):2389.
41. Gonzalez-Garrido JA, Garcia-Sanchez JR, Garrido-Llanos S, Olivares-Corichi IM. An association of cocoa consumption with improved physical fitness and decreased muscle damage and oxidative stress in athletes. J Sports Med Phys Fitness. 2017;57(4):441–447.
42. Cavarretta E, Peruzzi M, Del Vescovo R, Di Pilla F, Gobbi G, Serdoz A, Ferrara R, Schirone L, Sciarretta S, Nocella C, De Falco E, Schiavon S, Biondi-Zoccai G, Frati G, Carnevale R. Dark Chocolate Intake Positively Modulates Redox Status and Markers of Muscular Damage in Elite Football Athletes: A Randomized Controlled Study. Oxid Med Cell Longev. 2018; 4061901.
43. Rtibi K, Jabri MA, Selmi S, Souli A, Sebai H, El-Benna J, Amri M, Marzouki L. Carob pods (Ceratonia siliqua L.) inhibit human neutrophils myeloperoxidase and in vitro ROS-scavenging activity. RSC Adv. 2015;5:84207–84215.
44. Al-Olayan EM, El-Khadragy MF, Alajmi RA, Othman MS, Bauomy AA, Ibrahim SR, Abdel-Moneim AE. Ceratonia siliqua pod extract ameliorates Schistosoma mansoni-induced liver fibrosis and oxidative stress. BMC Complement Altern Med. 2016; 16(1):434.
45. Manach C, Scalbert A, Morand C, Remesy C, Jimenez L. Polyphenols: food sources and bioavailability. Am J Clin Nutr. 2004;79(5):727–747.
46. Banerjee AK, Mandal A, Chanda D, Chakraborti S. Oxidant, antioxidant and physical exercise. Mol Cell Biochem. 2003;253:307–312.
47. Jowko E, Dlugolecka B, Makaruk B, Cieslinski I. The effect of green tea extract supplementation on exercise-induced oxidative stress parameters in male sprinters. Eur J Nutr. 2015; 54(5):783–791.
48. Cheung K, Hume P, Maxwell L. Delayed onset muscle soreness : treatment strategies and performance factors. Sports Med. 2003;33(2):145–164.
49. Trombold JR, Reinfeld AS, Casler JR, Coyle EF. The effect of pomegranate juice supplementation on strength and soreness after eccentric exercise. J Strength Cond Res. 2011; 25(7):1782–1788.
50. Machin DR, Christmas KM, Chou TH, Sarah CH, Douglas WVP, Justin RT, Edward FC . Effects of differing dosages of pomegranate juice supplementation after eccentric exercise. J Physiol. 2014:1–7.
51. Nemes R, Koltai E, Taylor AW, Suzuki K, Gyori F, Radak Z. Reactive Oxygen and Nitrogen Species Regulate Key Metabolic, Anabolic, and Catabolic Pathways in Skeletal Muscle. Antioxidants. 2018; 7(7):85.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.141064
© Institute of Sport – National Research Institute

Changes in muscle quality and biomarkers of neuromuscular junctions and muscle protein turnover following 12 weeks of resistance training in older men

AUTHORS: Andrzej Mastalerz[1], Bizhan Hooshmand-Moghadam[2], Shadi Moazamigoudarzi[3], Fateme Golestani[4], Babak Hooshmand-Moghadam[2], Monika Johne[1], Krzysztof Maćkała[5], Katarzyna Lorenz[1], Ewelina Maculewicz[1]

[1] Faculty of Physical Education, Jozef Pilsudski University of Physical Education in Warsaw, Warsaw, Poland
[2] Department of Exercise Physiology, Faculty of Sport Sciences, Ferdowsi University of Mashhad, Mashhad, Iran
[3] Department of Sciences for Quality of Life, University of Bologna, Rimini, Italy
[4] Department of Exercise Physiology, University of Birjand, Birjand, Iran
[5] Department of Track and Field, Wroclaw University of Health and Sport Sciences, Wrocław, Poland

ABSTRACT: The present study aimed to investigate the effects of 12 weeks of resistance training (RT) on body composition [fat mass (FM), lean body mass (LBM)], muscle quality upper and lower (MQU, MQL), muscle size [cross sectional area (CSA), quadriceps cross-sectional area (QCSA)], biomarkers of neuromuscular junctions [C-terminal agrin fragment (CAF)], and muscle protein turnover [N-terminal peptide (P3NP), 3-methylhistidine (3MH), skeletal muscle-specific isoform of troponin T (sTnT)] in older men. Thirty elderly men (age 66.23 ± 0.57 years) were randomly divided into two groups: resistance training group (RT, n=15) and control group (CON, n=15). Participants in RT performed resistance training protocols with the intensity of 60% one-repetition maximum (3 ×/week, 4 sets of the six exercise circuits). Blood samples were assessed before (pre-test) and after (post-test) a 12-week intervention. The ANCOVA (2 × 2; group × time; with the baseline variable as the covariate) revealed significant interaction effects; the greater increases for LBM ($P < 0.001$), CSA ($P < 0.001$), QCSA ($P < 0.001$), MQU ($P < 0.05$), MQL ($P < 0.01$), 3MH ($P < 0.05$) were noted in RT than CON, and greater decreases for FM ($P < 0.001$) and CAF ($P < 0.001$) in RT than CON. No interaction effect was found for P3NP and sTnT. The time effect was found for all variables besides P3NP in RT, but no time effect was revealed in CON. The 12-week RT was an effective strategy for improving the concentrations of neuromuscular junction biomarkers such as 3-MH and CAF in older adults, and may lead to favourable changes in body composition, muscle quality, and muscle size.

CITATION: Mastalerz A, Hooshmand-Moghadam B, Moazamigoudarzi S et al. Changes in muscle quality and biomarkers of neuromuscular junctions and muscle protein turnover following 12 weeks of resistance training in older men. Biol Sport. 2024;41(4):285–292.

Received:2023-10-13; Reviewed: 2024-05-10; Re-submitted: 2024-05-27; Accepted: 2024-06-10; Published: 2024-07-08.

Corresponding author:
Monika Johne
Faculty of Physical Education
Jozef Pilsudski University
of Physical Education in Warsaw
Warsaw, Poland

ORCID:
Andrzej Mastalerz
0000-0003-2031-5563
Bizhan Hooshmand-Moghadam
0000-0002-7055-9040
Shadi Moazamigoudarzi
0000-0001-7010-6044
Fateme Golestani
0000-0001-7596-5761
Babak Hooshmand-Moghadam
0000-0002-2036-9492
Krzysztof Maćkała
0000-0001-6750-4316
Monika Johne
0000-0002-7066-8909
Katarzyna Lorenz
0000-0003-2719-2789
Ewelina Maculewicz
0000-0002-3122-3085

Key words:
Resistance Training
Muscle Quality
Neuromuscular Junctions
Protein Turnover
Elderly

INTRODUCTION

The aging population is a growing concern worldwide which exposes individuals to the increased risk of a debilitating musculoskeletal condition [1]. The main characteristic of ageing is a notable lack and weakness in muscle mass and strength [2]. Recently, it has gained credence that neurophysiological processes are important in maintaining skeletal muscle health with advancing age [3]. Neuromuscular junction (NMJ) is essential for nerve-to-muscle crosstalk [4]. During the ageing process, NMJ undergoes significant remodelling, whereby the precise alignment between pre-and postsynaptic structures is reduced, leading to a progressive accumulation of denervated muscle fibres [4]. Hence, biomarkers of NMJ stability have been suggested as indicators of skeletal muscle disorder [4].

C-terminal agrin fragment (CAF) concentrations have been recognized as a key contributing factor of skeletal muscle deterioration [3]. Agrin is a proteoglycan heparin sulfate involved in the

Abbreviation	Explanation
1RM	One-repetition maximum
3MH	3-methylhistidine
AMPK	AMP-Activated Protein kinase
BMI	Body mass index
CAF	C-terminal agrin fragment
CON	Control group
CSA	Cross sectional area;
QCSA	Quadriceps cross sectional area
FM	Fat mass
LBM	Lean body mass
MQ	Muscle quality
MQU	Muscle quality upper
MQL	Muscle quality lower
mTOR	Mammalian target of rapamycin complex 1
P3NP	N-terminal peptide
sTnT	Skeletal muscle-specific isoform of troponin T
RT	Resistance training
NMJ	Neuromuscular junction
PKB	protein kinase B

development and maintenance of NMJ [4]. It has been reported that higher concentrations of CAF may adversely affect skeletal muscle quality and NMJ. According to previous evidence, older adults with higher concentrations of CAF experienced lower muscle mass and strength [3]. Type III collagen is a subgroup of collagen found in skeletal muscle and synthesized from procollagen type III molecule during cleavage of C and N terminals. During this process, N-terminal propeptide (P3NP) is cleaved and released into the bloodstream [5]. P3NP is recognized as a biomarker for the investigation of skeletal muscle remodelling [5]. Additionally, 3-methylhistidine (3MH) indicates myofibrillar breakdown and is formed by post-translational methylation of specific histidine residues in the myofibrillar protein actin and myosin [6]. 3-MH concentrations can also be a key factor indicating high levels of Protein turnover [7]. 3-MH concentrations are formed in the muscle through the Post-translational methylation of histidine residues in actin and myosin. During muscle breakdown, 3-MH is released and found in urine [7]. The troponin complex composed of three subunits, is at the centre of Ca^{2+} regulation of muscle contraction including troponin C is the Ca^{2+}-binding subunit, the inhibitory subunit is troponin I, and the tropomyosin binding subunit troponin T (TnT) [8, 9]. Since troponins are not normally found in the blood, older adults are more likely to elevate serum concentration of sTnT associated with loss of muscle function and strength [10].

Physical activity promotes muscle remodelling and muscle mass and strength due to mechanical tension on intramuscular connective tissue which increases the activity of satellite cells and changes in collagen synthesis [11]. Resistance training (RT) increases mechanical tension on muscle tissue and its connective tissue [12]. RT can also improve the neuromuscular and functional performance of elderly adults [13]. Pieces of evidence suggested that there is a positive correlation between RT and improvement in NMJ [14]. However, to the best of the authors' knowledge, limited and contradictory studies have investigated the role of RT on neuromuscular biomarkers and muscle-specific biomarkers [11]. Consequently, considering the effect of RT on active muscle secretions in training and the change of muscle biomarkers due to exercise in the elderly and the availability of these biomarkers, we investigate the effect of resistance training on serum concentrations of CAF, P3NP, 3MH, sTnT in elderly men. Also, we evaluated changes in body composition and muscle size [cross-sectional area (CSA), quadriceps cross-sectional area (Quadriceps CSA)], and muscle quality upper and lower (MQU, MQL) in elderly men.

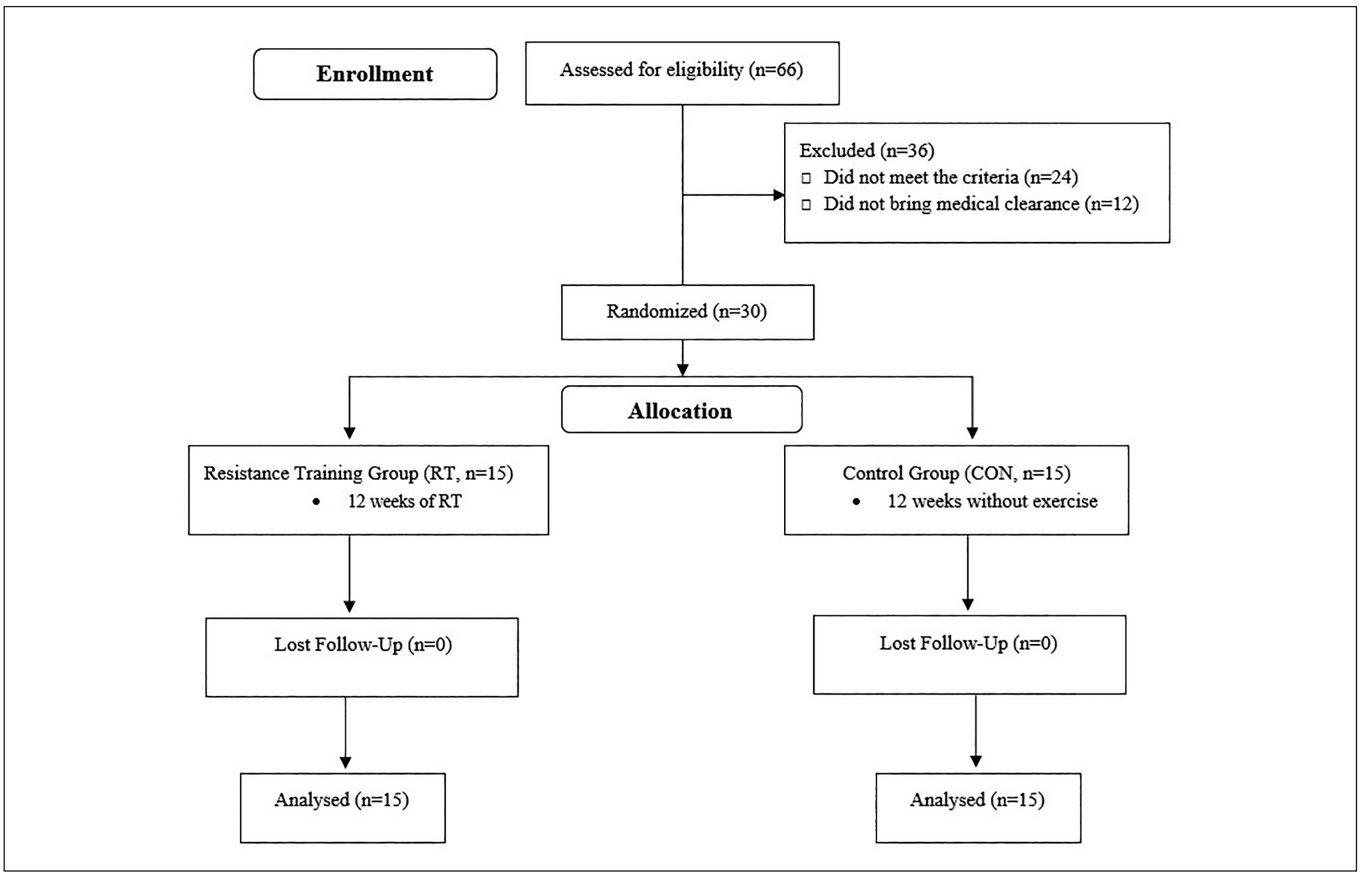


FIG. 1. Flowchart of the study.

MATERIALS AND METHODS

Participants

Thirty elderly men (age 66.23 ± 0.57 years) volunteered to partake in this study. Figure 1 shows the flowchart of this study. Inclusion criteria included: age between 60–80 years, any diseases, no smoking and alcohol, any medication and nutritional supplements, and any history of regular physical activity at least in the past year. Exclusion criteria included having more than three absences during the training sessions, unwillingness to continue cooperation, the presence of diseases, smoking, alcohol consumption, and use of medication or supplementation. Information about the physical activity level and health condition of all the participants was collected via questionnaire. Subjects were fully informed of the procedures and possible risks of the investigation and gave their informed written consent to participate. The study was approved by the ethics committee of the sports science research institution of Iran (code number: IR.SSRC.REC.1398.062, 07/09/2019) and carried out in agreement with the latest version of the Declaration of Helsinki.

Study design

This was a semi-experimental study with a pre- and post-test design. After completing the informed consent form, the subjects were randomly divided into two groups of resistance training group (RT, N = 15) and the control group (CON, N = 15). The subjects in the RT participated in a 12-week training program based on the recommendation of the American College of Sports Medicine. Participants of CON were asked to maintain their normal daily activities during the study period. Measurements were collected at two time points, baseline and after 12 weeks, during the same time of day (± 1 hr) and under the same environmental conditions (~20°C and ~55% humidity) in the morning following an overnight fast and abstinence from caffeinated drinks, alcohol, and approximately 48 hr after the last training session. Randomization was performed by using a digital tool available at www.randomizer.org. Also, the calculation of the sample size was carried out using G*Powers software (Heinrich-Heine-Universität, Düsseldorf, Germany).

Training intervention: The exercise group participated in the 12-week RT intervention (3 sessions/ week). Table 1 shows the RT program in this study. First, participants of RET warmed-up about 10 minutes of low-intensity treadmill walking. Then, they performed the RT program which contained Leg Press, Chest Press, Seated Row, Leg Extension, Lat Pulldown, and Tricep Dips; and included 15 tempo repetitions of one exercise in 60-sec and 30-sec rest before the start of the next exercise. Participants performed four sets of the six exercise circuits in each session for RT. They started the RT with ~60% of 1RM, but when an exercise was comfortably completed in 60 sec, an ~5% increment was added for the next training session to ensure that a gradual overload was provided during the training intervention. Finally, at the end of RT, participants performed 10 10-minute cool down. All training sessions were conducted between 4 and 6 PM under the supervision of RT specialists. The periodized protocols were adapted from previous studies [13].

Serum parameters: At two stages, 48 h before the start of the study (pretest) and 48 h after the last training session (post-test), 10 mL blood was obtained by venipuncture (in a heparinized tube) from a cubital vein. In both stages, sampling was carried out after approximately 12 hours of fasting. Blood samples were then centrifuged (at 3000 rpm for 10 min), and serum was extracted and stored at -80°C until the final measurement. Serum levels of CAF (MyBioSource Co, sensitivity: < 28.125 pg/ml), P3NP (Cusabio Co, sensitivity: 0.078 ng/ml), 3MH (MyBioSource Co, sensitivity: < 3.75 nmol/ml), and sTnT (Cusabio Co, sensitivity: 0.039 ng/ml), were determined using ELISA human kit. Intra and inter-assay CV for all blood markers were less than 8% and 10%, respectively.

Body Composition measurements: Participants were instructed to complete an overnight fast of 12 hours, attempt to sleep for at least 8 hours and refrain from physical activity for 48 hours before the test. Upon arriving at the laboratory, participants were asked to void completely within 30 min of the test. Height was measured by using a wall-mounted stadiometer (SECA, Germany). Body mass was evaluated by the digital SECA scale (Germany). Fat mass (FM) and lean body mass (LBM) were measured by a multi-frequency bioelectrical impedance device (Jawon Medical X Contact-356, South Korea. The test-retest reliability of the bioelectrical impedance method is high (R = 0.95 to 0.99) [15].

Muscle size measurements: Computed tomography (CT) was used to calculate the cross-sectional area and mass of the knee extensor muscle. Imaging was done by a Siemens 64-slice scanner (Somatom Definition AS; Siemens medical solution, Forchhim,

TABLE 1. Resistance training program (RT)

	Training structure
Sessions per week	3
Warm-up	10 min treadmill running/ low density
Resistance training	**Exercise:** Leg Press, Chest Press, Seated Row, Leg Extension, Lat Pulldown, Tricep Dips **Intensity:** 60% 1RM **Volume:** 1 min per exercise, 30 sec recovery per exercise **Repetition:** Repeat × 4 sets
Cool-down	10 min

Germany). Subjects laid in the supine position with legs extended. Images were taken at the midpoint between the lateral femoral condyle and the greater trochanter to calculate the lean mass of the knee extensor (middle of the thigh). To calculate lean mass, cross-sectional area images were taken from 1-mm thickness and 0-mm distance from knee to hip. Then, the cross-sectional area and lean mass of the knee extensor were analyzed by Singo software (Singo Leonardo, Siemens, Medical system, Germany) [16]. Lab specialists performed all the measurements.

Muscle quality: MQ was determined as the ratio of muscle strength or power and muscle mass as suggested previously [17]. The MQ score of upper extremities was calculated based on handgrip strength measured by hand dynamometer (kg) divided by muscle mass calculated using the BIA equation of Janssen et al. [18]. To calculate power for MQ of lower extremities the equation for peak power (W) [$-715.218 + 13.915 \times$ body weight (kg) $+ 33.425 \times$ stand in 20 s] of Smith et al. [19] predicting lower-body muscle power in older adults using a 30-s chair stand test was used. The calculated power was then divided by muscle mass.

Nutrition and dietary analysis: All subjects were encouraged to adhere to their normal and similar dietary patterns throughout the study. Subjects were required to submit 3-day (2 weekdays and 1 weekend) food records three times (Before and at the end of week 6 and week 12). Each food item was individually entered into the nutritionist software v.4 and total energy consumption, as well as the amount of energy derived from proteins, fats, and carbohydrates, were analyzed [13].

Statistical analysis: The normality of data distribution was evaluated by the Shapiro–Wilk test. Analysis of covariance (ANCOVA with the baseline variable as the covariate) was applied to examine the intra- and inter-group differences, respectively. A paired-sample t-test was applied to examine post-hoc effects. Statistical significance was set at $P \leq 0.05$. Statistical significance was set at $P \leq 0.05$. All statistical procedures were analyzed using the statistical package for social sciences (SPSS Inc., Chicago, IL, USA) software version 22 and were expressed as means ± SD and all the figures were prepared in Graphpad Prism (version 8.0.2).

RESULTS

Dietary Intake Monitoring and Compliance with Exercise Training: There were no reports of an adverse event from our training interventions. The mean demographic characteristics of the two groups are summarized in Table 2. Dietary analysis showed, there were no significant differences between energy intake, proteins, fats, and carbohydrates consumed between RT and CON (Table 3). Overall adherence to exercise training was 100%.

Body Composition, Muscle size and Muscle quality: Results indicated a significant decrease for FM ($P < 0.001$) (Figure A) in RT group vs. pretest. In addition, there were significant increases for LBM ($P < 0.001$) (Figure B), CSA ($P = 0.008$) (Figure C), quadriceps CSA ($P = 0.013$) (Figure D), MQU ($P < 0.001$) (Figure E), and MQL ($P < 0.001$) (Figure F) in RT group vs. pretest. Based on the results of the present study, there were significant alterations in RT group vs. CON group for FM ($P < 0.001$), LBM ($P < 0.001$), CSA ($P < 0.001$), quadriceps CSA ($P < 0.001$), MQU ($P = 0.034$), and MQL ($P = 0.003$) (Figure 2 A, B, C, D, E, and F, respectively).

Blood Markers: Results of the present study found a significant reduction in serum concentrations of CAF ($P < 0.001$) (Figure G), 3MH ($P < 0.001$) (Figure I), and sTnT ($P = 0.004$) (Figure J) in the RT group vs. pretest. RT group showed significant differences in serum concentrations of CAF ($P < 0.001$) and 3MH ($P = 0.012$) vs. CON group (Figure G and I, respectively). There were insignificant changes between RT group vs. CON group in serum concentrations of sTnT ($P = 0.079$) (Figure J). However, serum concentrations of P3NP observed neither a within-group nor a between-group significant alterations after 12 weeks of intervention ($P > 0.05$) (Figure H).

DISCUSSION

In this semi-experimental study, we evaluated the effects of 12 weeks of RT on biomarkers of neuromuscular junctions, muscle size, muscle quality upper and lower, and body composition in older adult men. The main findings of the present study indicated that 12 weeks of RT induced meaningful alterations in serum concentrations of CAF and 3MH in older adult men. Furthermore, results showed insignificant inter-group and intra-group differences in serum concentrations of P3NP in older adult men. In addition, the results indicated a significant effect of RT on improving body FM, LBM, CSA, quadriceps CSA, MQU, and MQL in older adult men.

Based on our results, we found a significant reduction in serum concentrations of CAF after 12 weeks of RT in elderly men. By ageing, NMJ decline occurs in both animal and human models [20]. Recently, higher circulating concentrations of CAF have emerged as a potential biomarker of skeletal muscle deterioration, due to its inverse relationship with NMJ health [4]. There are limited studies carried out on the effect of RT on CAF concentrations. In the present study, the observed significant reduction in CAF was in agreement with the study of Bigdeli et al. [11] which showed that six weeks of functional training with blood flow restriction induced a significant reduction in serum concentrations of CAF in older adult men.

TABLE 2. Demographic data of participants

Variable	CON group (n=15)	RT group (n=15)
Age (year)	66.13 ± 3.04	66.33 ± 3.35
Height (cm)	168.25 ± 3.33	167.93 ± 3.59
Weight (kg)	61.85 ± 3.79	64.85 ± 3.74

Abbreviation: Values are presented as Mean ± SD; CON: control; RT: resistance training.

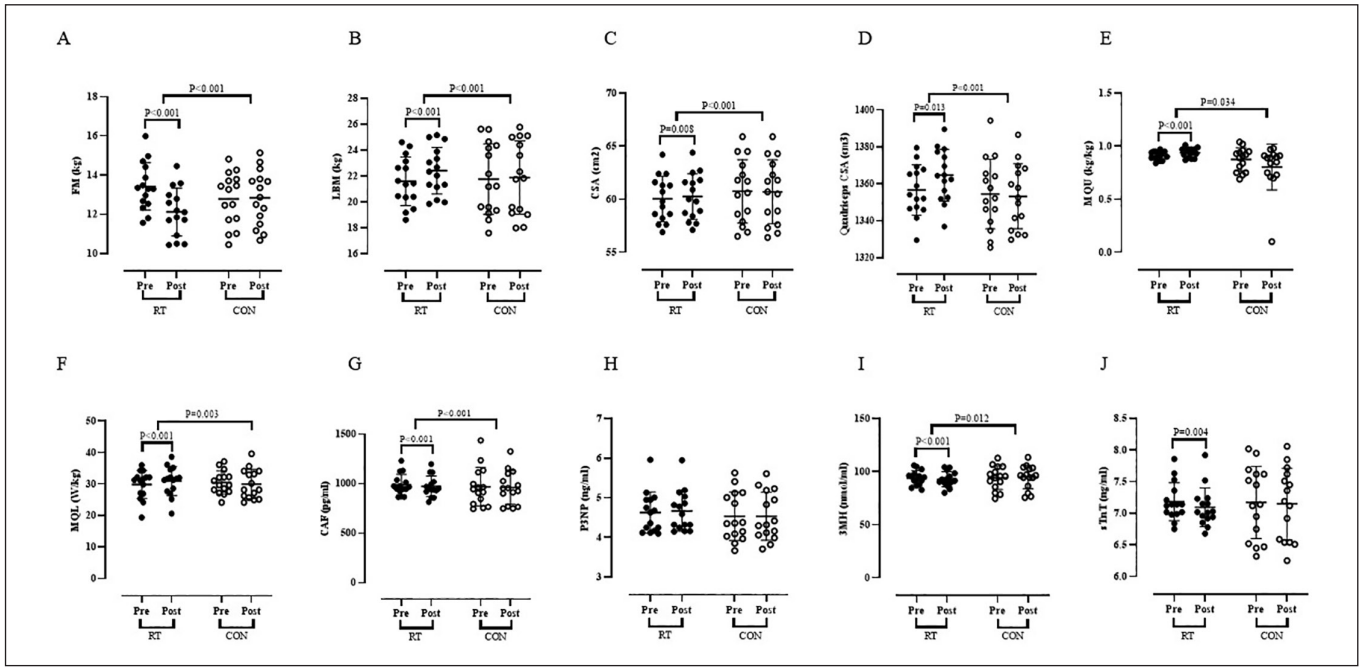


FIG. 2. Body composition, muscle size, muscle quality and blood markers before (Pre) and after 12 weeks of intervention (Post) in control (CON; white circles) and resistance training groups (RT; black circles). Abbreviation: A – fat mass, FM; B – lean body mass, LBM; C – cross sectional area, CSA; D – quadriceps cross sectional area; E – muscle quality upper, MQU; F – muscle quality lower, MQL; G – C-terminal agrin fragment, CAF; H – N-terminal peptide, P3NP; I – 3-methylhistidine, 3MH and J – skeletal muscle-specific isoform of troponin T, sTnT.

TABLE 3. Energy and macronutrients at the before and at the end of week 6 and week 12. Values are Mean ± SD

	Group	Baseline	6 weeks	12 weeks	Group differences (P)
Energy (kcal/day)	CON	1800.00 ± 75.26	1774.53 ± 53.92	1771.46 ± 46.66	0.58
	RT	1773.33 ± 49.77	1799.46 ± 54.10	1792.80 ± 56.85	
Protein (g/day)	CON	77.66 ± 4.28	79.06 ± 5.32	80.20 ± 5.26	0.30
	RT	80.40 ± 7.47	82.53 ± 6.86	77.80 ± 4.72	
Carbohydrate (g/day)	CON	244.53 ± 9.19	247.26 ± 7.86	246.26 ± 6.72	0.68
	RT	242.93 ± 6.95	247.33 ± 7.94	249.80 ± 6.85	
Fat (g/day)	CON	56.80 ± 8.04	52.13 ± 3.48	51.73 ± 3.08	0.89
	RT	53.33 ± 2.76	53.33 ± 3.17	53.60 ± 3.71	

Abbreviation: CON – control; RT – resistance training. P– statistical significance of differences between resistance training (RT) and control (CON) groups.

Drey et al. [21] showed a significant reduction in serum CAF concentrations following 20 weeks of power and strength training in older adults. However, Bigdeli et al. [11] reported that a 6-week functional and blood flow restriction training could not decrease the serum concentrations of CAF in healthy older men. Our results are contradictory to the findings of Fragala et al. [12] who reported that a 6-week RT with 70% 1-RM induced a significant increase in serum concentrations of CAF in older adult men and women. Perhaps, intensity, duration, and type of exercise could explain the contradictory agreements in literature to our findings. Although the mechanisms responsible for the reduction of CAF following 12 weeks of RT remain unknown. Also, it is well demonstrated that neuromuscular adaptation which occurs in the early stage of RT results in a reduction of serum concentration CAF [11]. Neural adaptation is explained by an increase in agonist activation, motor unit recruitment, and firing frequency against NMJ fragmentation [22]. Based on the results of Deschenes et al. [23] who suggested NMJ fragmentation may decrease by neuromuscular activity and against age-related NMJ degradation. In the present study, along with a significant reduction in serum concentrations of CAF, LBM significantly increased in RT group. Based on the previous evidence, there is a tightly inverse correlation between the circulating of CAF and

LBM [24]. Therefore, based on our results, one possible explanation is that the reduction in serum concentrations of CAF was dependent on subsequent changes in LBM. Overall, RT appears to be an effective and well-tolerated strategy for improving markers of CAF in older adult men.

In terms of effect of RT on P3NP, our findings showed an insignificant increase in serum concentrations of P3PN following of 12 weeks of RT group vs. CON in adult men. There are limited studies carried out on the effect of RT on P3NP. In agreement with our finding, Fragala et al. [5] showed an insignificant increase in serum concentrations of P3NP following six weeks of RT. However, our findings were contradictory to the results of Bhasin et al. [25] who reported a significant enhancement in serum concentrations of P3NP following four weeks of anabolic treatment of testosterone and recombinant growth hormones in older men. Pieces of evidence indicated that concentrations of P3NP are responsive to exercise, testosterone, and growth hormone (GH) [25]. Also, an increase in P3NP concentrations depends on enhancement in concentrations of GH and testosterone following exercise training [26]. However, serum concentrations of testosterone and GH have not been evaluated in the present study, perhaps due to the age of participants who had lower levels of testosterone. During Type III collagen synthesis, the P3NP is cleaved and released into circulation in direct proportion to type III collagen synthesis [5]. The cleaved P3NP results from the proteolytic cleavage in the synthesis of skeletal muscle that can be measured in the blood [5]. Since it is a product of synthetic pathways, P3NP is reflective of actual tissue remodelling [5]. On the other hand, increases in concentrations of P3NP are depended on type III collagen peptide which contributes to the growth of myoblasts and muscle formation and is caused by muscle hypertrophy [27]. Perhaps the intensity or duration recruited in the present study was not sufficient for the synthesis of structural proteins.

Based on previous studies, circulations of 3-MH are associated with the reduction of LBM and enhancement of FM in older adults [7]. The present study demonstrated a significantly greater decrease in serum concentrations of 3-MH in the RT group compared to the CON group. Results from previous studies have been inconsistent in the study of Yarasheski et al. [28] in which reported that no significant alterations in urinary concentrations of 3-MH after 12-week RT in healthy older individuals. Frontera et al. [29] showed that 12 weeks of RT increased urinary concentrations of 3-MH in older adults. Maybe the method of exercise, intensity and duration of intervention, and the type of participants are contradictory reasons to our results. Additionally, a reduction in serum concentrations of 3-MH may have been associated with an increase in LBM, MQ, and CSA which supported previous pieces of evidence in which showed high concentrations of 3-MH associated with notable lack and weakness in muscle mass [7]. Based on the results of the previous research, it has been indicated that RT lead to an increase in muscle protein fractional synthesis and breakdown which increases in muscle fibre type of I and II and ultimately muscle hypertrophy [29]. Therefore, in the present study, RT may lead to the maintenance of positive net protein balance which is against the age-related loss of skeletal muscle protein.

sTnT is one of the proteins of contractile machinery which may be used as a marker for sarcomere dysfunction and muscle wasting [8]. Serum levels of sTnT can leak out to the blood following the aging process as well as a skeletal muscle injury [10]. Concentrations of sTnT can used as an index for evaluating the effect of physical exercise on muscle function [30]. King et al. [31] illustrated that there was an association between the increase in strength and a drop in serum concentrations of sTnT. Based on to the best of authors' knowledge, the present study was the first one that investigated the effect of 12 weeks of RT in serum concentration of sTnT in elderly adult men. In this respect, Banitalebi et al. [32] reported no significant changes in serum concentrations of sTnT in women with osteosarcopenic obesity after performing 12 weeks of elastic band resistance training. Huxley and Simmons reported that 10-week strength training elicited a substantial decrease in serum concentrations of sTnT, paralleled by improvements in physical performance and muscle strength in older community-dwellers [33]. In the present study, despite significant enhancement in MQ and LBM, no significant changes were observed in serum concentrations of sTnT. In connection with the different results in our study versus previous studies, there was a possibility that the response of sTnT may be different depending on the intensity or type of exercise training. The participants in this study performed RT program with an intensity of 60% 1RM which was not sufficient for changes in the serum concentration of sTnT.

Data from the present study also showed that participants in RT group experienced significant improvement in LBM and MQ (both upper and lower) after 12 weeks of intervention. Similarly, Brooks et al. [34] reported that 16 weeks of strength training significantly improved MQ and type II fibre cross-sectional area in older adults with type 2 diabetes. In another study by Vikberg et al. [35] it was demonstrated that 10 weeks of functional training in older men led to an increase in LBM and muscle function. Additionally, Murlasits et al. [36] reported eight weeks of RT significantly increased LBM and MQ in women and men. Exercise training has been widely indicated as a useful treatment to counter or attenuate ageing-related impairments in LBM and MQ [37]. The main mechanisms through which RT may improve LBM and MQ are complex. However, qualitative improvements in muscle appear to account for neuromuscular adaptation more than muscle hypertrophy. More specifically, RT increases the major contractile protein synthesis such as myosin heavy chain (MHC) and actin, and also shifts the expression of MHC isoforms from MHC IIb to MHC IIa [38].

The findings of the present study demonstrated significant improvement in CSA and quadriceps CSA in RT group vs. CON group. These results are in agreement with the findings of Luciano et al. [39] who showed that quadriceps CSA were significantly increased following 12 weeks of three models of RT (endurance RT, strength RT, and

hypertrophy RT) in Wistar rats. Also, Nilwik et al. [40] demonstrated that 6 months of resistance training-induced significant improvement in quadriceps muscle CSA both in young and elderly men. RT results in high activation of protein kinase B (PKB), which is responsible for the phosphorylation of TSC2 at the Thr1462 site, resulting in TSC2 inactivation and consequently promoting mammalian target of rapamycin complex 1 (mTOR) activation [39]. It is known that this pathway is necessary for inducing muscle hypertrophy once the inhibition by rapamycin induces muscle atrophy [39]. It has been demonstrated that energy production during RT increases the activation of adenosine monophosphate-activated protein kinase and eukaryotic translation initiation factor-4E-binding protein 1 (4E-BP1) which (mTORC1) signalling; a potential kinase stimulates muscle hypertrophy [39]. So, the increase in CSA and quadriceps CSA after 12 weeks of RT intervention might be due to the mTORC1 signalling cascade.

We acknowledged that the current study had methodological limitations. Only a single 48-h collection was analyzed under each condition; due to the different time course of the change in muscle-specific biomarkers and non-muscle-specific biomarkers, more research is needed. Moreover, since ethical considerations in human samples (older adults), the variables were measured through blood samples and it was not possible to measure the variables by biopsy. Therefore, further studies are recommended to generalize the results due to the limitations of this study.

CONCLUSIONS

According to the results of the present study, RT was an effective strategy for improving concentrations of neuromuscular junction biomarkers such as 3-MH and CAF in older adults and may lead to favorable changes in body composition, muscle quality, and muscle size. Our results provide early insights into responses of circulating neuromuscular junction biomarkers to intervention and also support further research efforts to better elucidate potential responses and clinical.

Acknowledgements

This research was funded by the Ministry of Education and Science in 2023/2024 as part of the University Research Project of the University of Physical Education in Warsaw – UPB No. 1.

Conflict of interest declaration

The authors declare no conflict of interest.

Ethics approval and consent to participate

The study was approved by the ethics committee of the sports science research institution of Iran (code number: IR.SSRC.REC.1398.062) and carried out in agreement with the latest version of the Declaration of Helsinki.

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request. Some data may not be made available because of privacy or ethical restrictions.

Competing interests

The authors declare that they have no conflict of interest.

Author contributions

All authors contributed to the study conception and design, material preparation, data collection and analysis. All authors read and approved the final manuscript.

REFERENCES

1. Cruz-Jentoft AJ, Landi F, Schneider SM, Zúñiga C, Arai H, Boirie Y, Chen LK, Fielding RA, Martin FC, Michel J, Sieber C, Stout JR, Studenski SA, Vellas B, Woo J, Zamboni M, Cederholm T. Prevalence of and interventions for sarcopenia in ageing adults: A systematic review. Report of the International Sarcopenia Initiative (EWGSOP and IWGS). Age Ageing. 2014; 43(6):48–759.
2. Vandervoort AA, Symons TB. Functional and metabolic consequences of sarcopenia. Can. J. Appl. Physiol. 2001; 26(1):90–101.
3. Bondoc I, Cochrane SK, Church TS, Dahinden P, Hettwer S, Hsu FC, Stafford RS, Pahor M, Buford TW, Blair SN, Church T, Ashmore JA, Frierson G, Jordan AN, Morss G, Rodarte RQ, Wallace JM, Guralnik JM, Hadley EC, Romashkan S, King AC, Haskell WL, Pruitt LA, Abbott-Pilolla K, Bolen K, Fortmann S, Laws A, Prosak C, Wallace K, Fielding R, Nelson M, Kaplan RM, Groessl EJ, Pahor M, Perri M, Caudle C, Crump L, Hayden S, Holmes L, Maraldi C, Quirin C, Newman AB, Studenski S, Goodpaster BH, Glynn NW, Aiken EK, Anthony S, Kadosh J, Kost P, Newman M, Taylor CA, Vincent P, Kritchevsky SB, Brubaker P, Demons J, Furberg C, Katula JA, Marsh A, Nicklas BJ, Williamson JD, Fries R, Kennedy K, Murphy KM, Nagaria S, Wickley-Krupel K, Miller ME, Espeland M, Hsu FC, Rejeski WJ, Babcock DP, Costanza L, Harvin LN, Kaltenbach L, Lang W, Roberson WA, Rushing J, Rushing S, Walkup MP, Gill TM. Effects of a one-year physical activity program on serum C-terminal Agrin Fragment (CAF) concentrations among mobility-limited older adults. J Nutr Health Aging. 2015; 19(9):922–7.
4. Pratt J, De Vito G, Narici M, Segurado R, Pessanha L, Dolan J, Conroy J, Boreham C. Plasma C-Terminal Agrin Fragment as an Early Biomarker for Sarcopenia: Results from the GenoFit Study. J Gerontol A Biol Sci Med Sci . 2021; 76(12):2090–6.
5. Fragala MS, Jajtner AR, Beyer KS, Townsend JR, Emerson NS, Scanlon TC, Oliveira LP, Hoffman JR, Stout JR. Biomarkers of muscle quality: N-terminal propeptide of type III procollagen and C-terminal agrin fragment responses to resistance exercise training in older adults. J Cachexia Sarcopenia Muscle. 2014; 5(2):139–48.
6. Young VR, Munro HN. N (τ)-Methylhistidine (3-methylhistidine) and muscle protein turnover: an overview. Fed Proc. 1978; 37(9):2291–300.
7. Kochlik B, Stuetz W, Pérès K, Féart C, Tegner J, Rodriguez-Mañas L, Grune T,

Weber D. Associations of plasma 3-methylhistidine with frailty status in french cohorts of the FRAILOMIC initiative. J Clin Med. 2019; 8(7):1010.
8. Brotto MA, Biesiadecki BJ, Brotto LS, Nosek TM, Jin JP. Coupled expression of troponin T and troponin I isoforms in single skeletal muscle fibers correlates with contractility. Am J Physiol Cell Physiol. 2006; 290(2):C567.
9. Clause KC, Tchao J, Powell MC, Liu LJ, Huard J, Keller BB, Tobita K. Developing cardiac and skeletal muscle share fast-skeletal myosin heavy chain and cardiac troponin-I expression. PLoS One. 2012 Jul 10; 7(7):e40725.
10. Calvani R, Marini F, Cesari M, Tosato M, Anker SD, Von Haehling S, Miller RR, Bernabei R, Landi F, Marzetti E. Biomarkers for physical frailty and sarcopenia: State of the science and future developments. J Cachexia Sarcopenia Muscle. 2015; 6(4):278–86.
11. Bigdeli S, Dehghaniyan MH, Amani-Shalamzari S, Rajabi H, Gahreman DE. Functional training with blood occlusion influences muscle quality indices in older adults. Arch Gerontol Geriatr. 2020; 90:104110.
12. Fragala MS, Fukuda DH, Stout JR, Townsend JR, Emerson NS, Boone CH, Beyer KS, Oliveira LP, Hoffman JR. Muscle quality index improves with resistance exercise training in older adults. Exp Gerontol. 2014; 53:1–6.
13. Hooshmand-Moghadam B, Eskandari M, Golestani F, Rezae S, Mahmoudi N, Gaeini AA. The effect of 12-week resistance exercise training on serum levels of cellular aging process parameters in elderly men. Exp Gerontol. 2020; 141:111090.
14. Pratt J, De Vito G, Narici M, Boreham C. Neuromuscular Junction Aging: A Role for Biomarkers and Exercise. J Gerontol A Biol Sci Med Sci. 2021; 76(4):576–85.
15. Ling CHY, de Craen AJM, Slagboom PE, Gunn DA, Stokkel MPM, Westendorp RGJ, Maier AB. Accuracy of direct segmental multi-frequency bioimpedance analysis in the assessment of total body and segmental body composition in middle-aged adult population. Clinical Nutrition. 2011; 30(5):610–5.
16. Herda AA, Herda TJ, Costa PB, Ryan ED, Stout JR, Cramer J. Muscle performance, size, and safety responses after eight weeks of resistance training and protein supplementation: A randomized, double-blinded, placebo-controlled clinical trial. J Strength Cond Res. 2013; 27(11):3091–100.
17. Barbat-Artigas S, Rolland Y, Zamboni M, Aubertin-Leheudre M. How to assess functional status: A new muscle quality index. J Nutr Health Aging. 2012; 16(1):67–77.
18. Janssen I, Heymsfield SB, Baumgartner RN, Ross R. Estimation of skeletal muscle mass by bioelectrical impedance analysis. J Appl Physiol. 2000; 89(2):465–71.
19. Smith WN, Del Rossi G, Adams JB, Abderlarahman KZ, Asfour SA, Roos BA, Signorile JF. Simple equations to predict concentric lower-body muscle power in older adults using the 30-second chair-rise test: a pilot study. Clin Interv Aging. 2010; 5:173–80.
20. Li L, Xiong WC, Mei L. Neuromuscular Junction Formation, Aging, and Disorders. Annu Rev Physiol. 2018; 80:159–88.
21. Drey M, Sieber CC, Bauer JM, Uter W, Dahinden P, Fariello RG, Vrijbloed JW, Zech A, Freiberger E, Pfeifer K, Bertsch T. C-terminal Agrin Fragment as a potential marker for sarcopenia caused by degeneration of the neuromuscular junction. Exp Gerontol. 2013; 48(1):76–80.
22. Walker S, HäKkinen K. Similar increases in strength after short-term resistance training due to different neuromuscular adaptations in young and older men. J Strength Cond Res. 2014; 28(11):3041–8.
23. Deschenes MR, Roby MA, Eason MK, Harris MB. Remodeling of the neuromuscular junction precedes sarcopenia related alterations in myofibers. Exp Gerontol. 2010; 45(5):389–93.
24. Stout JR, Fragala MS, Hoffman JR, Robinson EH, Mccormack WP, Townsend JR, Jatjner AR, Emerson NS, Oliveira LP, Fukuda DH. C-terminal agrin fragment is inversely related to neuromuscular fatigue in older men. Muscle Nerve. 2015; 51(1):132–3.
25. Bhasin S, He EJ, Kawakubo M, Schroeder ET, Yarasheski K, Opiteck GJ, Reicin A, Chen F, Lam R, Tsou JA, Castaneda-Sceppa C, Binder EF, Azen SP, Sattler FR. N-terminal propeptide of type III procollagen as a biomarker of anabolic response to recombinant human GH and testosterone. J Clin Endocrinol Metab . 2009; 94(11):4224–33.
26. Nelson AE, Meinhardt U, Hansen JL, Walker IH, Stone G, Howe CJ, Leung KC, Seibel MJ, Baxter RC, Handelsman DJ, Kazlauskas R, Ho KKY. Pharmacodynamics of growth hormone abuse biomarkers and the influence of gender and testosterone: A randomized double-blind placebo-controlled study in young recreational athletes. J Clin Endocrinol Metab. 2008; 93(6):2213–22.
27. Foldvari M, Clark M, Laviolette LC, Bernstein MA, Kaliton D, Castaneda C, Pu CT, Hausdorff JM, Fielding RA, Fiatarone Singh MA. Association of muscle power with functional status in community-dwelling elderly women. J Gerontol A Biol Sci Med Sci. 2000; 55(4):M192–9.
28. Yarasheski KE, Zachwieja JJ, Campbell JA, Bier DM. Effect of growth hormone and resistance exercise on muscle growth and strength in older men. Am J Physiol Endocrinol Metab. 1995; 268(2 31–2):E268–76.
29. Frontera WR, Meredith CN, O'Reilly KP, Knuttgen HG, Evans WJ. Strength conditioning in older men: Skeletal muscle hypertrophy and improved function. J Appl Physiol. 1988; 64(3):1038–44.
30. Kalinkovich A, Livshits G. Sarcopenia – The search for emerging biomarkers. Ageing Res Rev. 2015; 22:58–71.
31. King GW, Abreu EL, An-Cheng L, Chertoff KK, Brotto L, Kelly PJ, Brotto M. A multimodal assessment of balance in elderly and young adults. Oncotarget. 2016; 7(12):13297–306.
32. Banitalebi E, Faramarzi M, Ghahfarokhi MM, SavariNikoo F, Soltani N, Bahramzadeh A. Osteosarcopenic obesity markers following elastic band resistance training: A randomized controlled trial. Exp Gerontol. 2020; 135:110884.
33. Huxley AF, Simmons RM. Proposed mechanism of force generation in striated muscle. Nature. 1971; 233(5321):533–8.
34. Brooks N, Layne JE, Gordon PL, Roubenoff R, Nelson ME, Castaneda-Sceppa C. Strength training improves muscle quality and insulin sensitivity in Hispanic older adults with type 2 diabetes. Int J Med Sci. 2007; 4(1):19–27.
35. Vikberg S, Sörlén N, Brandén L, Johansson J, Nordström A, Hult A, Nordström P. Effects of Resistance Training on Functional Strength and Muscle Mass in 70-Year-Old Individuals With Pre-sarcopenia: A Randomized Controlled Trial. J Am Med Dir Assoc. 2019; 20(1):28–34.
36. Murlasits Z, Reed J, Wells K. Effect of resistance training frequency on physiological adaptations in older adults. J Exerc Sci Fit. 2012; 10(1):28–32.
37. Radaelli R, Taaffe DR, Newton RU, Galvão DA, Lopez P. Exercise effects on muscle quality in older adults: a systematic review and meta-analysis. Sci Rep. 2021; 11(1):21085.
38. Fragala MS, Fukuda DH, Stout JR, Townsend JR, Emerson NS, Boone CH, Beyer KS, Oliveira LP, Hoffman JR. Muscle quality index improves with resistance exercise training in older adults. Exp Gerontol. 2014; 53:1–6.
39. Luciano TF, Marques SO, Pieri BL, De Souza DR, Araújo L V., Nesi RT, Scheffer DL, Comin VH, Pinho RA, Muller AP, de Souza CT. Responses of skeletal muscle hypertrophy in wistar rats to different resistance exercise models. Physiol Res. 2017; 66(2):317–23.
40. Nilwik R, Snijders T, Leenders M, Groen BBL, van Kranenburg J, Verdijk LB, Van Loon LJC. The decline in skeletal muscle mass with aging is mainly attributed to a reduction in type II muscle fiber size. Exp Gerontol. 2013; 48(5):492–8.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2025.139855
© Institute of Sport – National Research Institute

Limb-belt resisted sprint training improves physical fitness and ball-throw velocity in pubertal handball players

AUTHORS: Emna Makni[1], Firas Zghal[2], Raouf Hammami[2], Mohamed Abdelkader[3], Raghad Tarwneh[4], Mohamed Elloumi[4]

[1] University of Sousse, Research Laboratory of Exercise Physiology and Pathophysiology (LR19ES09), Faculty of Medicine of Sousse. Sousse, Tunisia
[2] Research Laboratory ''Education, Motor Skills, Sports and Health (EM2S, LR15JS01)'', Higher Institute of Sport and Physical Education of Sfax, University of Sfax, Sfax, Tunisia
[3] Department of Statistics and Operations Research, Faculty of Sciences, King Saud University, Riyadh, Saudi Arabia
[4] Sport Sciences and Diagnostics Research Group, GSD-HPE Department, Prince Sultan University, Riyadh, Saudi Arabia

ABSTRACT: The study assessed the effect of six weeks of biweekly upper and lower limbs' weighted-belt resisted sprint training (BRST) and weighted-vest resisted sprint training (VRST), or normal sprint training (NST) on muscle strength, speed, change of direction and handball-throwing velocity in young handball players. Twenty-seven pubertal male handball players aged 14.4 years were randomly assigned into BRST (n = 9), VRST (n = 8), and NST (n = 8) groups. Sprint ability (10-m and 30-m), squat jump (SJ), countermovement jump (CMJ), free-arm countermovement jump (CMJFA), standing long jump (SLJ), Five-jump test (FJT), change of direction and handball-throw velocity were assessed before and after a 6-week training in-season program. Within-group interactions showed that BRST improved all tests' performances (moderate-to-large). VRST improved sprint, SLJ, FJT and handball-throw velocity performances (small-to-large). NST improved only the change of direction performances (moderate). Between-groups comparison revealed that BRST improved all testing performances, except change of direction, compared with NST (large) and improved 30-m sprint, CMJFA, FJT and handball-throw velocity performance compared with VRST (moderate-to-large). In addition, VRST improved 30-m sprint, SJ and handball-throw velocity performances compared with NST (moderate-to-large). Throwing performance changes correlated with changes in sprint time and horizontal and vertical jump abilities ($r = 0.40$ to $r = 0.69$; $p < 0.01$). We conclude that while both resisted sprint training improved players' sprint, jumping and handball-throw performances, substantial improvements were recorded with the BRST compared to VRST and NST. Thus, BRST could be recommended to male U15 handball players as a valuable training method for developing physical fitness and skill performances.

CITATION: Makni E, Zghal F, Hammami R et al. Limb-belt resisted sprint training improves physical fitness and ball-throw velocity in pubertal handball players. Biol Sport. 2024;41(4):293–304.

Received: 2023-09-18; Reviewed: 2023-11-03; Re-submitted: 2023-12-19; Accepted: 2024-04-23; Published: 2024-07-08.

Corresponding author:
Mohamed Elloumi
Sport Sciences and Diagnostics Research Group, GSD-HPE Department, Prince Sultan University, Riyadh, Saudi Arabia Kingdom
Tel: +96611494857
E-mail: melloumi@psu.edu.sa

ORCID:
Firas Zghal
0000-0003-0440-2907

Raouf Hammami
0000-0001-6240-7162

Mohamed Abdelkader
0000-0001-5660-555X

Mohamed Elloumi
0000-0003-3751-2125

Key words:
Resisted training
Distributed load
Vertical load
Performance
Handball

INTRODUCTION

Handball is an intermittent team sport characterized by frequent body contact and the need for repeated explosive muscular contractions, including jumping, acceleration, sprinting, turning, changing pace and direction, and handball-throw velocity [1]. To achieve success at the highest level, a well-developed and comprehensive training program oriented toward the sport's specificities is crucial. The principle of training specificity requires that exercises should aim to replicate the demands of the respective activity. Therefore, coaches and practitioners need to identify the physical and physiological demands of handball to improve performance through targeted training programs. Numerous studies have highlighted the importance of jumping, sprinting, and change of direction abilities as vital performance components in high-level handball [2, 3]. Furthermore, it was pointed out that ball-throw velocity performances in handball are related to upper and lower limb strength and power as well as sprint performance [1, 4]. To this end, various training strategies have been effectively implemented to improve these performance components, including but not limited to strength, plyometric, and elastic bands in young handball players [1, 5, 6].

In recent years, there has been an increasing interest in the use of resisted sprint training among coaches and sports scientists in the training process or research studies for a variety of team sports [7–11]. This training modality involves performing sprint exercises with additional loads such as weight vests, belts, sledges, parachutes, partner

towing, uphill running, or on sand. This training aims to increase neural activation and lower limb strength, which in turn enhances sprint velocity without negatively affecting sprint and gestural techniques [12]. Moreover, it has been argued that resisted sprint training allows for more efficient transfer to specific movements [13, 14]. This includes incorporating it into various comprehensive sports training regimens and different sports fitness programs [7–10, 15]. This training modality has been widely studied and applied in various sports, including handball, to improve physical performance and direction abilities in young athletes. Nevertheless, previously published studies are conflicting and inconclusive regarding the effect of resisted sprint training on sprinting, jumping and change of direction performance in different team sports [7, 8, 10]. While some studies have reported positive effects of resisted sprint training on these abilities in different team sports [9–11], others have not found significant improvement [7, 8]. In this context, only a limited number of studies have investigated the effects of resisted sprint training on sprint performance and muscle architecture in female handball players [16]. In addition, there is currently no available information on the effect of this type of training on vertical and horizontal jump performances, change of direction, and ball-throw velocity in handball.

Considering the specificity of handball, it is important to develop strength and explosiveness in both the lower and upper limbs in a coordinated manner, rather than dissociating them. This is particularly crucial given that the activity of the upper limbs, particularly during shooting, is always initiated by a motor action of the lower limbs. Thus, arm-leg coordination should be a primary focus in the physical preparation of handball players. Under the principle of training specificity, as stated by Rumpf et al. [12], it was postulated that the utilization of a weighted belt-resisted sprint training program for the upper and lower limbs would result in a more significant improvement in sprinting, and jumping abilities, change of direction, and ball-throw velocity in pubertal handball players.

To the best of our knowledge, no previous studies have explored the impact of distributed loaded limbs' resisted sprint training on ball-throw velocity in handball. This particular handball skill is considered a crucial factor in handball performance [1]. It is widely acknowledged that the primary determinants of throwing ball velocity are the timing of movement in consecutive body segments, technique, and the strength and power of both upper and lower limbs [4]. This study aimed to investigate the effect of a resisted sprint-training program using either distributed external load on upper and lower limbs (weighted belt) or vertical (weighted vest) on sprinting and jumping abilities, change of direction, and handball-throw velocity in young handball players over a six-week in-season period, in comparison to un-resisted normal sprint training program. Therefore, we hypothesized that a belt-resisted sprint-training program in young male handball players would result in more significant training-induced adaptation than a vest-resisted sprint or an un-resisted normal sprint-training program.

MATERIALS AND METHODS

Experimental Approach to the Problem

To explore the substantive research question, we matched adolescent handball players for age, maturation status, field position, height, and training experience. These players were randomly assigned to three training groups: normal sprint training (NST), weighted-vest resisted sprint training (VRST), and upper and lower limbs' weighted-belt resisted sprint training (BRST). This design has been intended to investigate whether additional vertical or upper and lower extremity loading during sprint training improves skill-related physical performance in young handball players over un-resisted normal sprint training alone. The outcome measures included horizontal and vertical jump (squat jump [SJ], countermovement jump [CMJ], free-arm countermovement jump [CMJFA], standing long jump [SLJ], Five-jump test [FJT]), sprint (10-m and 30-m), change of direction (T-*half* test) and ball-throw velocity performances. The training program lasted 6 weeks and was conducted during the in-season competitive period. During this period, participants train at their club five times per week for 90 minutes. The majority of training sessions focus on technical and tactical skills, accounting for 60–65% of overall training time. Conditioning sessions are conducted twice a week and account for around 35–40% of total training time (Table 1). This program was preceded by 1 week of familiarization and 1 week for the pretest followed by 1 week for the final test (Figure 1). In addition to their standard handball training pattern, all groups performed two sprint

TABLE 1. Participant's characteristics (mean ± SD).

	Age (y)	Body mass (kg)	Height (cm)	% Body fat	Lower limb length (cm)	Upper limb length (cm)	Tanner stage
NST (n = 8)	14.4 ± 0.3	68.1 ± 4.7	173.6 ± 3.0	21.8 ± 0.5	89.3 ± 2.3	70.4 ± 1.5	3.63 ± 0.52
VRST (n = 8)	14.4 ± 0.2	68.6 ± 3.9	177.1 ± 4.1	21.6 ± 0.3	90.6 ± 2.7	70.9 ± 1.9	3.78 ± 0.44
BRST (n = 9)	14.3 ± 0.2	67.7 ± 4.5	176.2 ± 3.0	21.7 ± 0.3	90.3 ± 2.4	70.6 ± 1.3	3.67 ± 0.50
P value (ES)	0.57 (0.34)	0.90 (0.14)	0.12 (0.68)	0.52 (0.37)	0.54 (0.36)	0.82 (0.19)	0.88 (0.16)

NST: normal sprint training; VRST: vest resisted sprint training; BRST: belt resisted sprint training; ES: effect size.

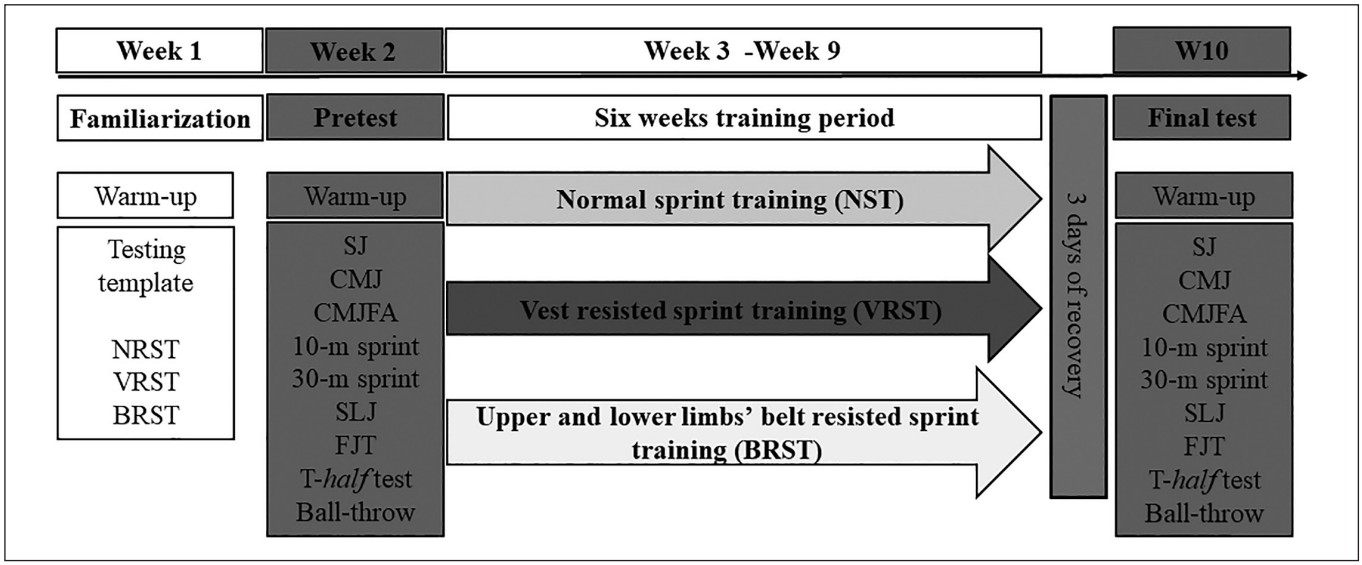


FIG. 1. Schematic overview of the study design. SJ: squat jump; CMJ: countermovement jump; CMJFA: free-arm countermovement jump; SLJ: standing long jump; FJT: five jump test.

sessions with or without additional load. Testing was carried out at the same time of the day, and under the same experimental conditions, at least three days after the last game. Standard verbal encouragement ensured maximal effort throughout was provided for all subjects.

Participants

Twenty-five young handball players volunteered to participate in this study. All players regularly participated in high-level national competitions. The sample size was calculated a priori according to Beck's procedures [17] and using the software G*Power [18]. Values for α were set at 0.05 and for power at 96%. Based on the results of Hammami et al. [6] and Aloui et al. [19], effect sizes were estimated to be > 0.8 (Large effect). Eight participants per group would provide maximal chances to minimize the risk of incurring a type II statistical error. The study participants were randomly assigned to either NST (n = 8), VRST (n = 8) or BRST (n = 9) groups. Written consent was obtained from the participant's parents/legal guardians after being fully informed about the purpose of the study, testing procedures, and potential risks. The study protocol was conducted with the agreement of the Ministries of both Education and Sports (MES-00002022-014) and was performed according to the Declaration of Helsinki (2013), and was approved by the local Institutional Ethical Committee of the University of Sousse.

Anthropometrics

The anthropometric data of participants are summarized in Table 2. Body mass and height were measured with calibrated devices (Tanita Corporation of America, Arlington Heights, IL, United States, accuracy 100 g, and Harpenden Portable Stadiometer, Pembs, United Kingdom, accuracy 0.1 cm, respectively). Body fat mass (%) was estimated by the four skinfolds method with a clamp mark Harpenden caliper (Harpenden 1124, Groningen, Netherlands) using the revised formula of Durnin and Womersley [20]. In addition, the measurements of each length extremity were performed; participants' were in a supine position, using a standard tape measure with an accuracy of 0.1 cm. The upper limb length was taken on the dominant arm and was the distance from the tip of the acromion to the wrist flexion crease. The lower limb length was the distance from the anterior superior iliac spine to the medial malleolus. All of the measurements were performed twice by the same evaluator to ensure consistency and the average was retained for analysis. All participants were in puberty and this was determined by pubic hair development according to the Tanner classification [21] at the beginning and the end of the 6-week training period by a trained paediatrician.

10 and 30-meter sprint test

Sprint performance was assessed at 10-m and 30-m test runs using photocells (HL3-1x Wireless Photocell-TAG-Heuer Professional Timing). The photocells were placed at waist height and the time was measured to one-hundredth of a second. From a standing position 0.3 m behind the starting line, the players initiated the sprint when they were ready and were encouraged to perform each sprint as fast as possible. After one practice trial, each participant had two attempts separated by a 5-minute rest and the best performance was taken for analysis.

TABLE 2. Details of weekly training design followed by NST, VRST and BRST groups over the six-week training program.

Day	Objectives
Monday	Recovery session
Tuesday	Conditioning +Technical training + Game Sprint training with and without additional load (NST, VRST, and BRST)
Wednesday	Technical and tactical training + Game
Thursday	Conditioning +Technical training + Game Sprint training with and without additional load (NST, VRST, and BRST)
Friday	Day off
Saturday	Technical and tactical training + Game
Sunday	Match

NST: normal sprint training; VRST: vest resisted sprint training; BRST: belt resisted sprint training.

TABLE 3. Summary of the sprint-training program for NST, VRST and BRST groups. Number of Sets × Number of Sprints in 1 Set × Distance of Each Sprint.

Weeks	Training	Total distance per session	Total distance per week
1–2	3 × 3 × 20-m 2 × 5 × 10-m	280-m	560-m
3–4	3 × 3 × 30-m 2 × 5 × 10-m	370-m	740-m
5–6	3 × 3 × 20-m 2 × 5 × 10-m	280-m	560-m

Rest interval between repetitions and sets is 2 and 5 minutes, respectively.

Vertical jump tests

Players had to perform both the squat jump (SJ), the counter-movement jump (CMJ), and the free-arm countermovement jump (CMJFA) according to the standardized protocols described previously [22]. Jump performances were measured using an infrared timing system (Optojump; Microgate SARL, Italy). After one practice trial, each jump was performed twice separated by a 2-minute rest and the best performance was recorded. In the SJ, subjects started with their hands on the hip with a 90° leg-thigh angle. For the CMJ, subjects dropped their body from a standing position by bending their hips and knees during a short pre-stretch counter-movement action, and then immediately extended their hips and knees and jumped as high as possible. For the CMJFA, participants followed the same pattern as the CMJ using their arms in the final phase of the jump. After one practice trial for each test, SJ, CMJ and CMJFA were repeated twice, and the best height in cm was recorded.

Horizontal jump tests

Each player performed two horizontal jump tests including the 2-footed standing long (SLJ) and the five-jump test (5JT) according to the standardized protocols described previously [22, 23]. For the SLJ test, participants stand behind the starting line with feet together and vigorously push and jump forward as far as possible. The distance is measured from the take-off line to the point where the back of the heel closest to the take-off line lands on the mat or non-slippery ground. For the FJT, each participant began the test with their feet together and had to choose which foot to land first at the beginning of the exercise. Throughout the final stride, the player was asked to finish with their feet together. After one practice trial for each test, SLJ and FJT were repeated twice, and the best result in meters was recorded.

Change of direction test

Each player performed the T-*half* test according to the standardized protocols described previously [24]. The players initiated to start when they were ready and were encouraged to perform the test as fast as possible. The participant first ran or moved as fast as possible forward to the centre cone, second side-stepped right 2.5 m to the right cone, third side-stepped left 5 m to the far-left cone, and then side-stepped back right to the centre cone. The participant then ran or backed up as fast as possible to cross the finish line. After one practice trial, the T-*half* test was repeated twice, and the best result in seconds was recorded.

TABLE 4. Pre- and post-training program testing performances (mean ± SD).

Variable	Condition	NST (n = 8)	VRST (n = 8)	BRST (n = 9)	η_p^2 (group)/ p value	η_p^2 (Time)/ p value	η_p^2 (time × group)/ p value
SJ height (cm)	Pre	29.7 ± 4.3	26.9 ± 4.1	29.5 ± 4.1	0.10	0.53	0.46
	Post	29.3 ± 4.1	30.0 ± 5.2	34.2 ± 4.8	/	/	/
	Δ (CI 95%)	-0.6 (11.6)$^{\$‡‡}$	11.4 (4.5)**	16.3 (4.0)***	0.31	0.000	0.001
	ES (Cohen's *d*)	0.09	0.62	1.0			
	Chances (%)	11/85/4	84/16/0	99/1/0			
	Quantitative assessment	Unclear	Likely	Very likely			
CMJ height (cm)	Pre	29.5 ± 3.5	28.1 ± 3.8	31.2 ± 3.7	0.23	0.32	0.27
	Post	30.0 ± 3.9	28.9 ± 4.2	34.9 ± 3.7	/	/	/
	Δ (CI 95%)	1.8 (5.6)‡‡	3.4 (11.9)†	12.0 (3.8)**	0.06	0.004	0.03
	ES (Cohen's *d*)	0.13	0.18	0.93			
	Chances (%)	5/94/1	16/81/3	99/1/0			
	Quantitative assessment	Unclear	Unclear	Very likely			
CMJFA height (cm)	Pre	34.7 ± 4.2	33.6 ± 3.4	38.3 ± 5.0	0.36	0.37	0.35
	Post	35.2 ± 3.6	34.6 ± 3.9	43.0 ± 4.6	/	/	/
	Δ (CI 95%)	1.7 (6.5)‡	3.2 (7.8)†	12.9 (7.1)**	0.007	0.001	0.009
	ES (Cohen's *d*)	0.10	0.26	0.93			
	Chances (%)	6/92/2	21/77/2	99/1/0			
	Quantitative assessment	Unclear	Unclear	Very likely			
SLJ (m)	Pre	2.0 ± 0.2	2.0 ± 0.1	2.1 ± 0.1	0.22	0.67	0.23
	Post	2.1 ± 0.2	2.1 ± 0.1	2.3 ± 0.1	/	/	/
	Δ (CI 95%)	2.7 (4.6)	5.3 (1.7)***	6.5 (1.5)***	0.06	0.000	0.06
	ES (Cohen's *d*)	0.29	1.10	0.97			
	Chances (%)	20/79/1	100/0/0	99/1/0			
	Quantitative assessment	Unclear	Almost certainly	Very likely			
FJT (m)	Pre	10.1 ± 0.8	10.1 ± 0.4	10.6 ± 0.8	0.24	0.57	0.29
	Post	10.3 ± 0.9	10.6 ± 0.4	11.6 ± 0.9	/	/	
	Δ (CI 95%)	2.7 (5.5)‡	4.3 (2.3)**	8.9 (3.6)***	0.05	0.000	0.02
	ES (Cohen's *d*)	0.28	0.91	1.04			
	Chances (%)	21/78/1	96/4/0	100/0/0			
	Quantitative assessment	Unclear	Very likely	Almost certainly			
10-m time (s)	Pre	2.06 ± 0.04	2.07 ± 0.08	2.04 ± 0.07	0.13	0.69	0.31
	Post	2.02 ± 0.09	1.98 ± 0.07	1.92 ± 0.08	/	/	/
	Δ (CI 95%)	-1.7 (2.4)‡	-4.1 (2.4)**	-6.0 (2.1)$^{**\$}$	0.22	0.000	0.02
	ES (Cohen's *d*)	0.44	1.12	1.5			
	Chances (%)	41/59/0	97/3/0	100/0/0			
	Quantitative assessment	Unclear	Very likely	Almost certainly			
30-m time (s)	Pre	4.83 ± 0.13	4.81 ± 0.12	4.77 ± 0.20	0.14	0.47	0.51
	Post	4.86 ± 0.21	4.73 ± 0.14	4.61 ± 0.18	/	/	/
	Δ (CI 95%)	0.5 (1.0)‡‡	-1.7 (1.1)*	-3.5 (0.9)**	0.20	0.000	0.000
	ES (Cohen's *d*)	0.16	0.57	0.80			
	Chances (%)	11/87/2	66/34/0	98/2/0			
	Quantitative assessment	Unclear	Possibly	Very likely			

TABLE 4. Continue.

Variable	Condition	NST (n = 8)	VRST (n = 8)	BRST (n = 9)	η_p^2 (group)/ p value	η_p^2 (Time)/ p value	η_p^2 (time × group)/ p value
T-*half* test (s)	Pre	6.33 ± 0.26	6.30 ± 0.36	6.20 ± 0.31	0.05	0.70	0.02
	Post	6.01 ± 0.41	5.94 ± 0.32	5.80 ± 0.26	/	/	/
	Δ (CI 95%)	-5.0 (4.1)*	-5.6 (2.7)**	-6.3 (2.3)***	0.54	0.000	0.81
	ES (Cohen's *d*)	0.87	0.99	1.33			
	Chances (%)	87/13/0	97/3/0	100/0/0			
	Quantitative assessment	Likely	Very likely	Almost certainly			
Ball-throw velocity (km · $^{-1}$)	Pre	78.6 ± 2.6	78.5 ± 2.2	78.7 ± 2.6	0.13	0.99	0.96
	Post	80.7 ± 2.7	83.6 ± 2.6	88.6 ± 3.0	/	/	/
	Δ (SD)	2.8 (1.0)$^{\$\$‡‡}$	6.5 (0.5)***††	12.5 (3.7)***	0.21	0.000	0.000
	ES (Cohen's *d*)	0.44	1.12	2.27			
	Chances (%)	36/64/0	100/0/0	100/0/0			
	Quantitative assessment	Unclear	Almost certainly	Almost certainly			

NST: normal sprint training; VRST: vest resisted sprint training; BRST: belt resisted sprint training; Δ: changes (%); ES: effect size; significant difference within group: *p < 0.5, **p < 0.01, ***p < 0.001; significant difference between BRST and VRST: †p < 0.05, ††p < 0.01; significant difference between BRST and NST: ‡P < 0.05, ‡‡p < 0.01; significant difference between VRST and NS: $p < 0.05, $$p < 0.01.

Ball-throw velocity

The ball-throwing velocity was recorded using a radar gun (Sports Radar Gun SRA 3000; Precision Training Instrument, IL) with an accuracy of about 1.24 km/h. According to the protocol previously reported by Laffaye et al. [25], the radar gun was positioned three meters behind the player, in the thrower-target axis at a height corresponding to the player's height. After a standardized warm-up, participants were given 5 attempts to execute a jump throw using ball standards (circumference 54 cm, mass 325 grams) and a rest of 45-s between throws. Participants performed a jump throw according to the protocol previously described by Aloui et al. [19], starting with a preliminary three-step run before jumping vertically and releasing the ball into the air behind a line 9-m from the goal. Players are instructed to cock their shooting arms and aim for the goal's centre, with only throws entering the goal without touching the ground are considered valid. The greatest ball-throw velocity was selected for further analysis.

Training

During the six-week training program, NST, VRST, and BRST performed, in addition to their standard handball training, twice a week additional un-resisted sprint and resisted sprint training using a weighted vest or distributed weighted belt on upper and lower limbs, respectively as recommended by Alcaraz et al. [26] (Table 3). During loading, VRST players wore vests with 12.6% body mass, while RBST players carried 0.22 kg wrist and 1.22 kg ankle belts. Participants were introduced to load-bearing devices the week before training.

Statistical analysis

Data were presented as mean ± SD. Statistical analyses were performed using the SPSS package (SPSS Inc. Chicago. IL. version 20.0). After checking the normality and homogeneity distribution of data using the Shapiro-Wilk and Levene tests, an independent *t*-test was calculated to determine significant differences between groups in baseline values. The variations in the dependent parameters were analyzed by separate mixed-factors ANOVA (time × group) for repeated measurements. Post-hoc analysis using Bonferroni's correction was then performed to calculate the main effect for group (two levels: Experimental group and Control group) and time (two levels: pre- and post-training). Considering that, in the sample small findings with no statistical significance may present considerable practical relevance; partial eta-squared (η_p^2) was quantified as this is appropriate in the analysis of variance of repeated measures [27]. Effect sizes were classified as small (η_p^2 up to 0.059), medium (between 0.059 and 0.138) and large (greater than 0.138). Additionally, between-groups standardized mean differences or effect sizes (ES) in pre- and in pre-to-post performance change were calculated using Cohen's *d* and corrected by Hedge's g to avoid a biased estimation of the population effect size provided by Cohen's *d*. According to Cohen,

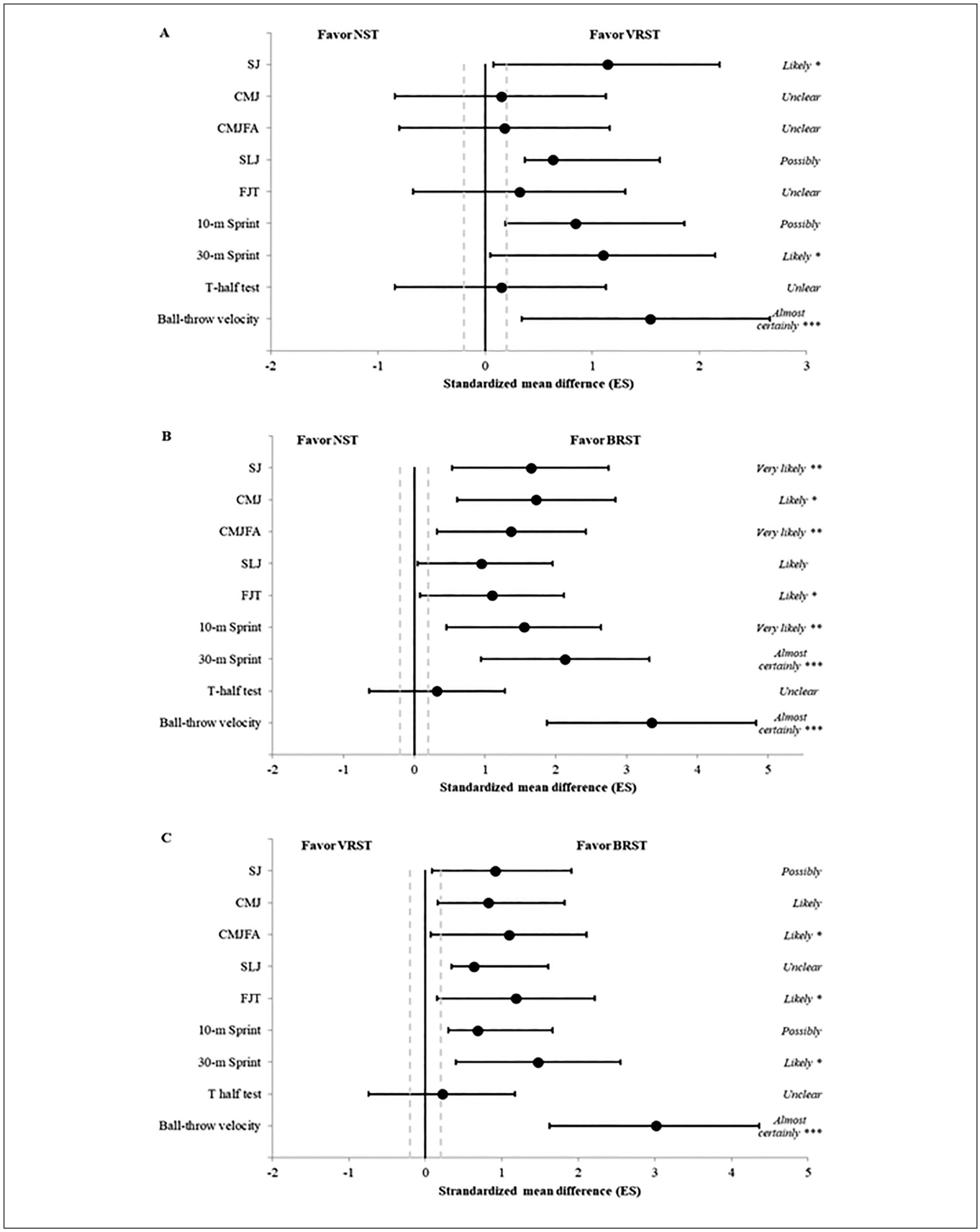


FIG. 2. Between-group comparison of sprint, jump, change of direction and ball-throw velocity performance. Bars indicate uncertainly in the true mean changes with 95% confidence intervals. BRST: bled resisted sprint training group; VRST: vest resisted sprint training group; NST: normal sprint training group. SJ: squat jump; CMJ: countermovement jump; CMJFA: free-arm countermovement jump; SLJ: standing long jump; FJT: five jump test; ES: effect size. Inferences are small ($0 \leq d \leq 0.49$), medium ($0.50 \leq d \leq 0.79$) and large ($d \geq 0.80$). Qualitative assessment: possibly (25%–75%), *likely (75%–95%), **very likely (95%–99%), and ***almost certainly (> 99%).

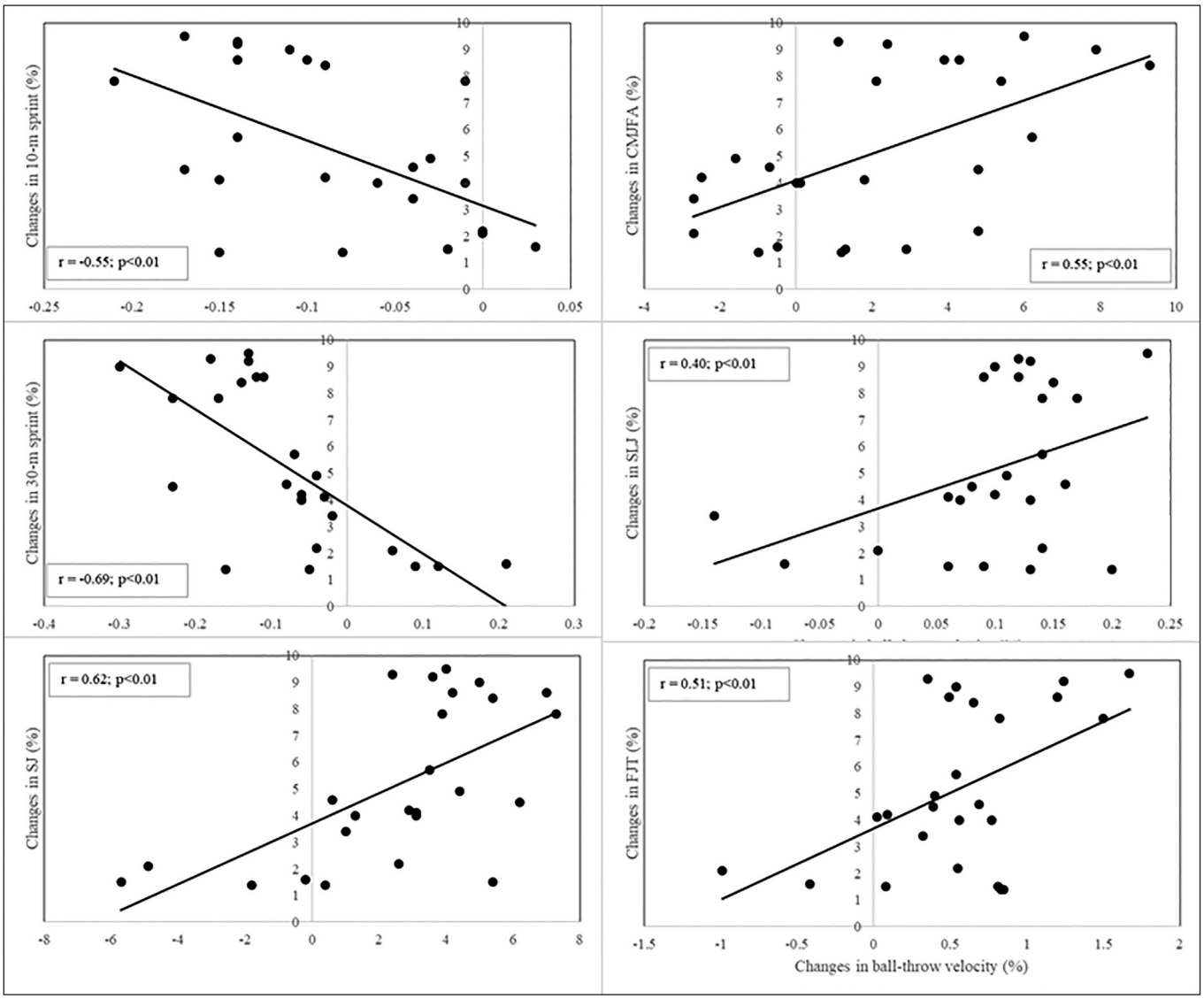


FIG. 3. Correlation between changes in SJ, CMJFA, SLJ, FJT and 10-m and 30-m sprint performances and changes in ball-throw velocity. SJ: squat jump; CMJFA: free-arms countermovement jump; SLJ: standing long jump; FJT: five jump test.

ES can be classified as small ($0 \leq d \leq 0.49$), medium ($0.50 \leq d \leq 0.79$) and large ($d \geq 0.80$) [28]. Sprinting, jumping, and ball-throw velocity performances showed an ICC > 0.8 and a CV < 5%. The level of significance was set at $p < 0.05$.

RESULTS

All participants in the BRST, VRST, and NST groups underwent the intended training procedure, and none of them reported any injuries related to the training or testing. Before the training, the Shapiro-Wilk and Levene statistics showed anthropometric and physical testing values ranging from 0.93 to 0.98, with p-values ranging from 0.11 to 0.87 for normality and 0.10 to 2.43, with p-values ranging from 0.90 to 0.11 for homogeneity. In addition, there were no statistically significant differences in anthropometric measurements (Table 2) or performance in testing between the three groups (Table 4).

The mean values of all tests in pre- and post-training program are illustrated in Table 4. Significant interactions were found (training × group) for SJ, CMJ, CMJFA, SLJ and 5JT performances ($F_{(2.22)} = 9.32$, $\eta_p^2 = 0.46$; $F_{(2.22)} = 4.04$, $\eta_p^2 = 0.27$; $F_{(2.22)} = 5.90$, $\eta_p^2 = 0.35$; $F_{(2.22)} = 5.90$, $\eta_p^2 = 0.35$, respectively). Post-hoc analysis revealed that the performances of SJ, SLJ and FJT increased only in BRST group ($p < 0.001$) and VRST group ($p < 0.01$). Moreover, post-hoc analysis revealed that the performances of CMJ and CMJFA increased only in BRST group ($p < 0.01$). Significant interactions were also found for 10-m and 30-m sprint performances ($F_{(2.22)} = 10.88$, $\eta_p^2 = 0.25$ and $F_{(2.22)} = 8.86$, $\eta_p^2 = 0.22$, respectively). Post-hoc analysis revealed that the performances of the

10-m and 30-m sprints increased only BRST group ($p < 0.01$) and VRST group ($p < 0.01$ and < 0.05, for 10-m and 30-m sprints respectively). In addition, a significant interaction was found for handball-throw performance ($F_{(2.22)} = 0.96$). Post-hoc analysis also revealed that handball-throw performance increased only BRST group ($p < 0.001$) and VRST group ($p < 0.001$). No significant interactions were found (training × group) for the T-*half* Test. Post-hoc analysis also revealed that all groups improved change of direction performance with the largest effect (large) observed for the BRST group.

Figures 2A, 2B, and 2C showed the between-group comparison on sprinting, jumping ability, change of direction and handball-throw velocity performances. The improvement in 30-m sprint (ES: 1.10 [95% CI: 0.05–2.15]), SJ and ball-throw velocity performances (ES: 1.14 [95% CI: 0.08–2.19] and ES: 1.54 [95% CI: 0.34–2.66]. respectively) were largely greater in VRST group than NST group (Figure 2A). In addition, the improvements in all test performances (ES from 1.10 [95% CI: 0.05–2.12] for FJT to ES: 3.35 [95% CI: 1.88–4.83] for ball-throw velocity) except SLJ, were largely grater in BRST group compared with NST group (Figure 2B). Similarly, between-group comparisons showed that BRST group had the greatest improvement for the 30-m sprint (ES: 1.47 [95% CI: 0.40–2.55]), CMJFA (ES: 1.09 [95% CI: 0.07–2.11]), and ball-throw velocity (ES: 3.01 [95% CI: 1.62–4.40]) performances than VRST group (Figure 2C).

When data from all groups were pooled, there were positive relationships between individual percentage changes in ball-throw velocity and individual percentage changes in SJ, CMJFA, SLJ, and FJT performances ($r = 0.62$, $r = 0.56$, $r = 0.40$, and $r = 0.51$, respectively; $p < 0.01$). Individual percentage changes in ball throw also showed negative relationships with individual percentage changes in 10-m and 30-m sprint performances ($r = -0.55$ and $r = -0.69$, respectively; $p < 0.01$) (Figure 3).

DISCUSSION

This study aimed to investigate the effects of a resisted sprint-training program using upper and lower limb distributed loads and weighted vest compared to un-resisted normal sprint training on sprinting, jumping, change of direction abilities and ball-throw velocity in young handball players. The main findings of the present study were the greater effectiveness of upper and lower limbs weighted-belt resisted sprint training compared with weighted vest resisted sprint training or un-resisted normal sprint training for improving sprint and vertical and horizontal jump abilities as well as ball-throw velocity in pubertal handball players.

The results of the sprinting performances showed a significant (group × time) interaction effect for both 10-m and 30-m tests with a substantial effect size observed in the BRST group (ES: 1.55 for 10-m sprint and ES: 2.13 for 30-m sprint). These findings are consistent with previous studies using weighted sledges or weighted vests resisted sprint training in several team sports such as rugby and soccer [10, 11, 29]. Ben Brahim et al. [10] found that six weeks of resisted sprint training with a load of 13% body mass resulted in a 5% increase in 5-m sprint speed in U-19 soccer players after training. In addition, Bachero-Mena and Gonzalez-Badillo [30] assessed the impact of seven weeks of resisted sprint training with weights of 5, 12.5, and 20% body mass, concluding that a load of 20% body mass should be used to enhance the first phase of acceleration up to 30 m. Similarly, Carlos-Vivas et al. [9] found that all resisted sprint training groups, except un-resisted sprint, slightly improved (1.4%–1.9%; ES form -0.43 to -1.0) and 30-m (1.3%–1.5%; ES from -0.37 to -0.76) sprint performances after 8 weeks of training.

The precise mechanisms behind the significant training impact in the BRST group remain unclear. The fundamental principle underlying this training strategy is to develop muscle strength and neural activity through extra load stimulation while maintaining certain movement patterns [31]. In general, it has been suggested that the central nervous system achieves the desirable goal of correcting for increased inertia by modifying muscle activation properties [32]. The BRST group used a load-weighted belt during their resisted training program, possibly increasing the moment of inertia by 50% of their legs [33], resulting in higher contraction velocities in both concentric and eccentric phases of the sprint. This preload stimulus led to post-activation potentiation during sprints with prolonged exposure, leading to greater training responses [15, 29]. Indeed, post-activation potentiation refers to a muscle's ability to generate force based on previous internal events and the improvement in performance following a submaximal or maximal contraction [34]. Specifically, the induction of these adaptations, along with the potential preservation of the sprinting technique through traditional sprint performance, may have contributed to the speed improvements registered at the BRST group.

Vertical and horizontal jumping are crucial skills in handball, particularly for defensive and offensive tactics like blocking, rebounding, stealing, passing, and shooting [1]. The present vertical and horizontal jump data indicated significant intervention in all groups with a significant (group × time) interaction effect with a significant effect size in players involved in weighted-belt resisted training (ES from 0.96 to 1.72). These results corroborate those of several previous findings [9–11]. Carlos-Vivas et al. [9] compared the effectiveness of horizontal resisted sprint, vertical resisted sprint, combined resisted sprint, and un-resisted sprint training on performance in horizontal and vertical jumps in youth soccer players. They found small to moderate improvement in SLJ performance in players undergoing the different resisted sprint training regimens (1.4% to 4.7%, ES from 0.14 to 0.63). In addition, Chaalali et al. [11] observed significant improvement in SJ, CMJ t (4.23% and 3.59%; ES 0.35 and 0.37, for SJ and CMJ, respectively); and FJT (3.10%; ES = 0.44) performances in young soccer players after six weeks of biweekly partner-towing resisted sprint training. In contrast, the study by Aloui et al. [5] found that junior handball players who underwent 8 weeks of bi-weekly lower limb elastic band-based loaded plyometric training showed significant comparable improvements in SJ (9.4%; ES = 0.83); and CMJ (9.1%; ES = 0.99) performances in experimental and control groups.

The use of upper and lower weighted belts during sprinting in the current study can result in muscular overload, increasing the moment of inertia [33], which in turn probably increases neural recruitment and activation rates during jumps [32]. This leads the nervous system to signal the muscles to contract more efficiently, resulting in greater force during the jump, which is effective in eliciting the meaningful post-activation potentiation effect. The additional resistance of the belt also increases strength in the lower body; specifically the hip extensors, quadriceps, and calf muscles, allowing for greater power generation during the takeoff phase of the jump. These neurophysiological changes, including the increased neural drive to agonist muscles and changes in muscle activation strategies, may enhance the ability to store and release elastic energy during the stretch-shortening cycle [35]. Furthermore, training with additional loads (e.g., a triple extension of the ankle, knee, and hip) during sprint movements with similar biomechanical patterns to jump can improve movement efficiency and movement control for jumping motion [36].

The ability to change direction is a key determinant of handball performance [2]. However, the study found no significant intervention effect (group × time interaction) on change of direction performance, but all groups showed significant time interaction effects, with the weighted vest and belt-resisted sprint training resulting in better improvement. These findings are somewhat expected as all players were involved, in addition to their resisted and un-resisted sprint, into technical and tactical session drills as a part of their normal training program over the present study. Previous studies have shown an improved change of direction ability in response to elastic band training [5, 37] or combined plyometric and short sprint training [6, 19] in young handball players. The lack of response in change-of-direction performance in the present study could be attributed to the limited selection of sprint exercise types or the participants' similar abilities before the training program. As suggested by Rodríguez-Osorio et al. [38], additional resisted sprint exercises with a change of direction should be included in the training process if the goal is to improve this ability.

The most salient result of the current study is the significant improvement in ball-throwing velocity in all groups after training, with a significant interaction effect (group × time) with a substantial effect size in the weighted-belt resisted sprint training group (ES: 9.55; $p < 0.0001$). Handball-throwing is a fundamental motor skill involving quick, complex movements and a whole-body kinetic chain from proximal to distal motion [39]. Its accuracy and velocity are crucial for effective scoring [40]. It should be noted that this study is the first to explore the effectiveness of upper and lower limbs weighted belt resisted sprint training in enhancing the throwing performance of pubertal handball players. Several studies applying alternative training strategies for throwing velocity have demonstrated enhanced performance [19, 41, 42]. Mascarin et al. [41] and Bouagina et al. [42] found that strength training with an elastic band and a ballistic training program improved ball throw in young handball players after six and ten weeks of training, respectively. The current study found that resisted sprint training with weight belts significantly improved ball-throw velocity compared to VRST and NST groups. This improvement was significantly associated with enhanced sprinting and jumping abilities after six weeks of bi-weekly resisted sprint training. Indeed, the percentage changes in ball-throw velocity were associated with the changes in the 10-m ($r = -55$; $p < 0.01$) and 30-m ($r = -0.69$; $p < 0.01$) sprints as well as the horizontal and vertical jumping performance ($r = 0.62$; $r = 0.56$; $r = 0.40$ and $r = 0.51$, respectively). Our findings support Serrien and Baeyens' [38] conclusion that handball throwing is a complex movement involving the whole-body kinetic chain from proximal to distal motion. Consequently, the present study's weighted belt-resisted sprint training program increased the ball-throwing speed of handball players by improving muscular strength and power, motor control, neuromuscular coordination, and structural adaptations in muscles and connective tissues, thus improving their ability to withstand greater forces. Considering the special characteristics of handball, players require agility, quick reactions, and multidirectional movement skills for dynamic, fast-paced games [1–3]. They should also improve shooting accuracy, power under pressure, jumping ability, hand-eye coordination, and spatial awareness to deliver strong shots [1–3]. Training in real handball gameplay situations is a sensible approach to achieve physical fitness improvements suitable for the sport's demands, as it helps players deliver strong shots over defenders. Nevertheless, the performance gains observed in the current study may be transferred to skill gains even without specific training regimens.

In addition to the explanations provided further up, the study improved sprinting, jumping, and ball-throw performances in both vest and belts-resisted training groups could be explained by the implementation of Alcaraz et al. [26] criteria for resisted sprint training efficiency. Our training program used over 160 m per session and 3700 m for six weeks, with the BRST group showing a greater effect.

The study has some limitations, including not calculating kinetic variables of force and power developed during resisted sprint training, which is crucial for understanding neuromuscular and biomechanical adaptations [14]. Additionally, factors such as knee extensor and shoulder rotator mechanical parameters were not assessed in the study, which could explain muscle adaptation processes elbow extension and shoulder internal rotation torques are primary mechanical contributors to total ball release velocity during standing throws [43]. Future studies ought to investigate how resistance training with weighted belts affects knee extensor isometric parameters and shoulder-related strength of both external and internal rotator torques in young athletes. Furthermore, the inclusion of electromyography activity could provide insights into neuromuscular adaptation.

CONCLUSIONS

The current study showed that bi-weekly weighted belt-resisted sprint training was more effective than weighted vest-resisted sprint training or un-resisted sprint training for improving sprinting, horizontal

and vertical jumping, and ball-throw velocity performances in pubertal male handball players. Handball coaches might incorporate this training form into their gameplay training processes to maximize its benefits and transfer it into specific handball abilities without interfering with their players' skills.

Author Contributions

Conceptualization, E.M and M.E; methodology, F.Z, R.H, M.A, and R.T; data collection and statistical analysis, M.A; writing-original draft preparation, E.M., and M.E; writing-review and editing, E.M, F.Z, R.T, and M.E. All authors have read and agreed to the published version of the manuscript.

Acknowledgements

The authors would like to express their gratitude to the players, parents, and coaches for their cooperation. We also would like to thank the Tunisia Handball Federation for their consent to the study. Mohamed Abdelkader extends appreciation to King Saud University in Riyadh, Saudi Arabia for funding this research work through Researchers Supporting Project number (RSPD2024R1068)

Conflicts of Interest

The authors declare no conflicts of interest related to the paper.

REFERENCES

1. Bragazzi NL, Rouissi M, Hermassi S, Chamari K. Resistance training and handball Players' isokinetic, isometric and maximal strength, muscle power and throwing Ball Velocity: A Systematic Review and Meta-Analysis. Int J Environ Res Public Health. 2020; 17(8):2663.
2. Wagner H, Finkenzeller T, Wurth S, Von Duvillard SP. Individual and team performance in team-handball: a review. J Sports Sci. Med. 2013; 13:808–816.
3. Ortega-Becerra M, Belloso-Vergara A, Pareja-Blanco F. Physical and physiological demands during Handball matches in male adolescent players. J Hum Kinet. 2020; 72:253–263.
4. Black GM, Gabbett TJ, Cole MH, Naughton G. Monitoring workload in throwing-dominant Sports: A Systematic Review. Sports Med. 2016; 46(10):1503–1516.
5. Aloui G, Hermassi S, Hammami M, Cherni Y, Gaamouri N, Shephard RJ, van den Tillaar R, Chelly MS. Effects of Elastic Band Based Plyometric Exercise on Explosive Muscular Performance and Change of Direction Abilities of Male Team Handball Players. Front Physiol. 2020; 11:604983.
6. Hammami, M, Gaamouri, N, Aloui, G, Shephard, RJ, and Chelly, MS. Effects of combined plyometric and short sprint with change-of-direction training on athletic performance of male U15 handball players. J Strength Cond Res. 2019; 33(3):662–675.
7. Rey E, Padron-Cabo A, Fernandez--Penedo D. Effects of sprint training with and without weighted vest on speed and repeated sprint ability in male soccer players. J Strength Cond Res. 2017; 31:2659–2666.
8. Gil S, Barroso R, Crivoi do Carmo E, Loturco I, Kobal R, Tricoli V, Ugrinowitsch C, Roschel H. Effects of resisted sprint training on sprinting ability and change of direction speed in professional soccer players. J Sports Sci. 2018; 36(17):1923–1929.
9. Carlos-Vivas J, Perez-Gomez J, Eriksrud O, Freitas TT, Marín-Cascales E, Alcaraz PE. Vertical versus horizontal resisted sprint training applied to young soccer players: Effects on physical performance. Int J Sports Physiol Perform. 2020; 15(5):748–758.
10. Ben Brahim M, Bougatfa R, Makni E, Gonzalez PP, Yasin H, Tarwneh R, Moalla W, Elloumi M. Effects of Combined Strength and Resisted Sprint Training on Physical Performance in U-19 Elite Soccer Players. J Strength Cond Res. 2021; 35(12):3432–3439.
11. Chaalali A, Bouriel K, Rouissi M, Chtara M, Mkaouer B, Cronin J, Chaouachi A, Chamari K. Resisted sprint training with partner towing improves explosive force and sprint performance in young soccer players – a pilot study. Biol Sport. 2022; 39(2):379–387.
12. Rumpf MC, Lockie RG, Cronin JB, Jalilvand F. Effect of different sprint training methods on sprint performance over various distances: A brief review. J Strength Cond Res. 2016; 30(6):1767–85.
13. Loturco I, Tricoli V, Roschel H, Nakamura FY, Cal Abad CC, Kobal R, Gil S, González-Badillo JJ. Transference of traditional versus complex strength and power training to sprint performance. J Hum Kinet. 2014; 41:265–73.
14. Loturco I, Contreras B, Kobal R, Fernandes V, Moura N, Siqueira F, Winckler C, Suchomel T, Pereira LA. Vertically and horizontally directed muscle power exercises: Relationships with top-level sprint performance. PLoS One. 2018; 13(7): e0201475.
15. Matusiński A, Pietraszewski P, Krzysztofik M, Gołaś A. The Effects of Resisted Post-Activation Sprint Performance Enhancement in Elite Female Sprinters. Front Physiol. 2021; 12:651659.
16. Luteberget LS, Raastad T, Seynnes O, Spencer M. Effect of traditional and resisted sprint training in highly trained female team handball players. Int J Sports Physiol Perform. 2015; 10(5):642–647.
17. Beck, TW. The importance of a priori sample size estimation in strength and conditioning research. J Strength Cond Res. 2013; 27:2323–2337.
18. Faul F, Erdfelder E, Lang AG Buchner AG. Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2017; 39:175–191.
19. Aloui G, Hermassi S, Hammami M, Gaamouri N, Bouhafs EG, Comfort P, Shephard RJ, Schwesig R, Chelly MS. Effects of an 8-Week In-Season Upper Limb Elastic Band Training Programme on the Peak Power, Strength, and Throwing Velocity of Junior Handball Players. Sportverletz Sportschaden. 2019; 33(3):133–141.
20. Davidson LE, Wang J, Thornton JC, Kaleem Z, Silva-Palacios F, Pierson RN, Heymsfield SB, Gallagher D. Predicting fat percent by skinfolds in racial groups: Durnin and Womersley revisited. Med Sci Sports Exerc. 2011; 43:542–549.
21. Tanner JM, Whitehouse RH, Takaishi M. Standards from birth to maturity for height, weight, height velocity, and weight velocity: British children 1965 II. Arch Dis Child 1966; 41:613–635.
22. Castro-Piñero J, Ortega FB, Artero EG, Girela-Rejón MJ, Mora J, Sjöström M, Ruiz JR. Assessing muscular strength in youth: usefulness of standing long jump as a general index of muscular fitness. J Strength Cond Res. 2010; 24(7):1810–1817.
23. Chamari K, Chaouachi A, Hambli M, Kaouech F, Wisløff U, Castagna C. The five-jump test for distance as a field test to assess lower limb explosive power in soccer players. J Strength Cond Res. 2008; 22(3):944–50.
24. Sassi RH, Dardouri W, Yahmed MH, Gmada N, Mahfoudhi ME, Gharbi Z. Relative and absolute reliability of a modified agility T-test and its relationship with vertical jump and straight sprint. J Strength Cond Res. 2009; 23(6):1644–1651.

25. Laffaye G, Debanne T, Choukou AM. Is the ball velocity dependent on expertise? A multidimensional study in handball. Int J Perfor Anal Sport. 2012; 12(3):629–642.
26. Alcaraz PE, Carlos-Vivas J, Oponjuru BO, Martínez-Rodríguez A. The Effectiveness of Resisted Sled Training (RST) for Sprint Performance: A Systematic Review and Meta-analysis. Sports Med. 2018; 48(9):2143–2165.
27. Levine, TR and Hullett, CR. Eta Squared, Partial Eta Squared, and Misreporting of Effect Size in Communication Research. Human Communication Research. 2006; 28:612–625.
28. Batterham, AM, and Hopkins, WG. Making meaningful inferences about magnitudes. Int J Sports Physiol Perform. 2006; 1:50–57.
29. West DJ, Cunningham DJ, Bracken RM, Bevan HR, Crewther BT, Cook CJ, Kilduff LP. Effects of resisted sprint training on acceleration in professional rugby union players. J Strength Cond Res. 2013; 27(4):1014–1018.
30. Bachero-Mena B, Gonzalez-Badillo JJ. Effects of resisted sprint training on acceleration with three different loads accounting for 5, 12.5, and 20% of body mass. J Strength Cond Res. 2014; 28:2954–2960.
31. Hrysomallis C. The effectiveness of resisted movement training on sprinting and jumping performance. J Strength Cond Res. 2012; 26(1):299–306.
32. Hatzitaki V, McKinley P. Effect of single-limb inertial loading on bilateral reaching: interlimb interactions. Exp Brain Res. 2001; 140(1):34–45.
33. Ropret R, Kukolj M, Ugarkovic D, Matavulj D, Jaric S. Effects of arm and leg loading on sprint performance. Eur J Appl Physiol Occup Physiol. 1998; 77(6):547–550.
34. Baudry S, Duchateau J. Postactivation potentiation in a human muscle: effect on the load-velocity relation of tetanic and voluntary shortening contractions. J Appl Physiol. 2007; 103(4):1318–1325.
35. Negra Y, Chaabene H, Sammoud S, Prieske O, Moran J, Ramirez-Campillo R, Nejmaoui A, Granacher U. The Increased Effectiveness of Loaded Versus Unloaded Plyometric Jump Training in Improving Muscle Power, Speed, Change of Direction, and Kicking-Distance Performance in Prepubertal Male Soccer Players. Int J Sports Physiol Perform. 2020; 15(2):189–195.
36. Chang E, Norcross MF, Johnson ST, Kitagawa T, Hoffman M. Relationships between explosive and maximal triple extensor muscle performance and vertical jump height. J Strength Cond Res. 2015; 29(2):545–51.
37. Aloui G, Hammami M, Fathloun M, Hermassi S, Gaamouri N, Shephard RJ, Chelly MS. Effects of an 8-Week in-Season elastic band training program on explosive muscle performance, change of direction, and repeated changes of direction in the lower limbs of Junior male handball players. J Strength Cond Res. 2019; 33(7):1804–1815.
38. Rodríguez-Osorio D, Gonzalo-Skok O, Pareja-Blanco F. Effects of resisted sprint with changes of direction training through several relative loads on physical performance in soccer players. Int J Sports Physiol Perform. 2019; 14(8):1022–1028.
39. Serrien B, Baeyens JP. Systematic Review and Meta-Analysis on Proximal-to-Distal Sequencing in Team Handball: Prospects for Talent Detection? J Hum Kinet. 2018; 63:9–21.
40. Rios LJC, Cuevas-Aburto J, Martínez-García D, Ulloa-Diaz D, Ramírez OAA, Martin IM, Ramos AG. Reliability of Throwing Velocity during Non-specific and Specific Handball Throwing Tests. Int J Sports Med. 2021; 42(9):825–832.
41. Mascarin NC, de Lira CAB, Vancini RL, de Castro Pochini A, da Silva AC, Dos Santos Andrade M. Strength Training Using Elastic Bands: Improvement of Muscle Power and Throwing Performance in Young Female Handball Players. J Sport Rehabil. 2017; 26(3):245–252.
42. Bouagina R, Padulo J, Fray A, Larion A, Abidi H, Chtara M, Chelly MS, Khalifa R. Short-term in-season ballistic training improves power, muscle volume and throwing velocity in junior handball players. A randomized control trial. Biol Sport. 2022; 39(2):415–426.
43. Van den Tillaar, R and Ettema, G. A three-dimensional analysis of overarm throwing in experienced handball players. J Appl Biomech. 2007; 23(1):12-9.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.141063
© Institute of Sport – National Research Institute

Optimizing athletic performance through advanced nutrition strategies: can AI and digital platforms have a role in ultra-endurance sports?

AUTHORS: Luca Puce[1], Halil İbrahim Ceylan[2], Carlo Trompetto[1,3], Filippo Cotellessa[1], Cristina Schenone[1], Lucio Marinelli[1,3], Piotr Zmijewski[4], Nicola Luigi Bragazzi[1], Laura Mori[1,3]

[1] Department of Neuroscience, Rehabilitation, Ophthalmology, Genetics, Maternal and Child Health, University of Genoa, Italy
[2] Physical Education and Sports Teaching Department, Faculty of Kazim Karabekir Education, Atatürk University, Erzurum, Turkey
[3] Istituto di Ricovero e Cura a Carattere Scientifico (IRCCS) Ospedale Policlinico San Martino, Genova, Italy
[4] Jozef Pilsudski University of Physical Education in Warsaw Poland

Corresponding author:
Nicola Luigi Bragazzi
University of Genoa, Via Antonio Pastore 1, 16132, Genoa, Italy

ORCID:
Luca Puce
0000-0003-0825-2707

Halil İbrahim Ceylan
0000-0003-1133-5511

Carlo Trompetto
0000-0003-3419-0669

Filippo Cotellessa
0009-0007-8518-365X

Cristina Schenone
0009-0009-0442-3549

Lucio Marinelli
0000-0003-0620-7654

Piotr Zmijewski
0000-0002-5570-9573

Nicola Luigi Bragazzi
0000-0001-8409-868X

Laura Mori
0000-0003-2762-8327

ABSTRACT: Nutrition is vital for athletic performance, especially in ultra-endurance sports, which pose unique nutritional challenges. Despite its importance, there exist gaps in the nutrition knowledge among athletes, and emerging digital tools could potentially bridge this gap. The ULTRA-Q, a sports nutrition questionnaire adapted for ultra-endurance athletes, was used to assess the nutritional knowledge of ChatGPT-3.5, ChatGPT-4, Google Bard, and Microsoft Copilot. Their performance was compared with experienced ultra-endurance athletes, registered sports nutritionists and dietitians, and the general population. ChatGPT-4 demonstrated the highest accuracy (93%), followed by Microsoft Copilot (92%), Bard (84%), and ChatGPT-3.5 (83%). The averaged AI model achieved an overall score of 88%, with the highest score in Body Composition (94%) and the lowest in Nutrients (84%). The averaged AI model outperformed the general population by 31% points and ultra-endurance athletes by 20% points in overall knowledge. The AI model exhibited superior knowledge in Fluids, outperforming registered dietitians by 49% points, the general population by 42% points, and ultra-endurance athletes by 32% points. In Body Composition, the AI model surpassed the general population by 31% points and ultra-endurance athletes by 24% points. In Supplements, it outperformed registered dietitians by 58% points and the general population by 55% points. Finally, in Nutrients and in Recovery, it outperformed the general population only, by 24% and 29% points, respectively. AI models show high proficiency in sports nutrition knowledge, potentially serving as valuable tools for nutritional education and advice. AI-generated insights could be integrated with expert human judgment for effective athlete performance optimization.

CITATION: Puce L, Ceylan HI, Trompetto C et al. Optimizing athletic performance through advanced nutrition strategies: can AI and digital platforms have a role in ultra-endurance sports? Biol Sport. 2024;41(4):305–313.

Received: 2024-05-08; Reviewed: 2024-05-18; Re-submitted: 2024-06-19; Accepted: 2024-06-21; Published: 2024-07-23.

Key words:
Nutrition
Athletes
Artificial Intelligence
Nutritional knowledge
Ultra-endurance sports

INTRODUCTION

Nutrition plays a crucial role in the performance and overall health of sports athletes [1]. Proper nutrition is, indeed, essential for optimal athletic prowess, as it provides the energy and nutrients athletes need to train, compete, and recover effectively [2]. Key components include i) adequate energy requirements, with athletes needing sufficient calories to fuel their activities, maintain body weight, and preserve their health and well-being, with the precise caloric intake recommended varying depending on the sports discipline, training intensity, and individual metabolism [3]; ii) macronutrient balance, since a balanced intake of carbohydrates, proteins, and fats is vital for athletes, with carbohydrates being the primary energy source during high-intensity activities, proteins being essential for muscle repair and growth, and fats being important for overall health [4, 5]; iii) hydration as staying hydrated is critical for athletes' performance and health, with sportsmen needing to replace the fluids lost through sweat during exercise [6]; iv) micronutrients, since vitamins and minerals support various bodily functions, including muscle contraction, bone health, and oxygen transport [7]; and v) timing of nutrient intake as the timing of meals and snacks can impact performance and recovery (for instance, eating carbohydrates before exercise can improve performance, while protein and carbohydrate intake after exercise can aid in recovery) [8].

Nutrition is paramount for athletes participating in ultra-endurance sports, which involve events lasting at least 6 hours, who need to carefully manage their nutrition, focusing particularly on maintaining energy and fluid balance [9]. During such extensive activities,

athletes might face substantial nutritional challenges, including an energy deficit of about 7,000 kcal *per* day: this significant energy imbalance can seriously impact health and performance, leading to the loss of fat and skeletal muscle mass, as seen in events like 24-hour swimming, 6-day cycling, or 17-day running [10]. Athletes also experience substantial fluid loss through sweat, potentially up to 2 liters *per* hour, especially during prolonged exercise or in hot conditions, which can lead to hypohydration [11]. Excessive fluid intake compared to the amount lost can increase the risk of exercise-associated hyponatremia (EAH) and limb swelling [12]. Effective pre-race nutritional strategies should focus on enhancing fat utilization, by consuming fat-rich foods during the race, along with carbohydrates, electrolytes, and fluids [13]. To minimize EAH risks, athletes are advised to include 10–25 mmol of sodium in their fluid intake and limit it to 300–600 mL *per* hour during the race [14].

Despite the importance of nutrition in sports, athletic dietary practices often fall short of sports nutrition guidelines [15]. One contributing factor to this could be the level of nutrition knowledge among athletes [16]. Unfortunately, the tools used to measure this knowledge are frequently outdated or lack proper validation, resulting in inconsistent findings regarding athletes' nutrition knowledge [17, 18]. Partly accounting for this, according to a recently published systematic review, the general level of knowledge about sports nutrition varies widely among athletes, with average general and sports nutrition knowledge scores ranging from 40 ± 12% to 70 ± 9%, and with weak-to-moderate positive correlations between nutrition knowledge and healthy dietary behaviors [18].

The overall athletes' understanding of nutrition is relatively low, with significant gaps and room for improvement. Some sportsmen may have a deep understanding of nutritional principles, while others may have minimal knowledge. This discrepancy, besides the tool used for the assessment, as previously mentioned, often depends on the resources available, such as access to dietitians or nutritionists [19].

Digital platforms have revolutionized the accessibility of nutritional information and personalized dietary advice, with numerous apps and websites dedicated to sports nutrition, offering meal planning, tracking tools, and educational content [20]. These platforms can be highly beneficial for athletes looking to improve their diet and performance. Ultra-endurance athletes prefer, indeed, to seek nutritional advice from fellow athletes and magazines or websites (73%) rather than from nutrition experts (8%) [21].

The advent of generative AI has further expanded the possibilities in sports nutrition, as AI can analyze vast amounts of data to provide personalized nutrition plans based on an athlete's specific needs, lifestyle, and goals. In the area of sports training process, the emergence of AI-based fitness applications raises pertinent questions regarding their potential to revolutionize personalized health management [20].

However, the scholarly literature on this topic is scarce, making it challenging to draw definitive conclusions. In one of the few studies relevant to the subject, ChatGPT-3.5 and ChatGPT-4 versions, two OpenAI's advanced large language models, with enhanced capabilities to understand and generate human-like text, were tasked with designing 12-week resistance training programs for both male and female hypothetical subjects [22]. The two AI models generated satisfactory training prescriptions. On the other hand, these contained a few questionable assertions, requiring further fine-tuning before their application. Also, they were not differentiated based on sex/gender, and exhibited some limitations. For instance, the AI models were not able to make real-time revisions or adjustments to training protocols, according to individual progression and user's feedback. While generally incorporating the well-established, foundational principles of training (variation, specificity, and progressive overload), there were slight differences between the two AI prototypes in terms of selection, frequency, repetition, and intensity of exercise-related variables, with ChatGPT-4 being able to provide more detailed information than ChatGPT3.5, and tailoring the programs based on training experience levels. Specifically concerning nutrition and hydration, AI-generated advice was deemed "noteworthy" [22].

Another simulation study assessed the efficacy of ChatGPT-4 to generate 30-day exercise prescriptions for five example patient profiles. They were characterized by different fitness objectives and health conditions encompassing scenarios of diverse underlying co-morbidities of varying severity. Co-morbidities included cardiovascular diseases, musculoskeletal disorders, dysmetabolic conditions, respiratory, and mental issues [23]. The AI-generated programs prioritized safety over effectiveness, generally lacking precision in achieving predetermined goals. Moreover, they failed to account for individual biopsychosocial factors and cope with the complexity of specific health conditions and the influence of medications. Besides this overly conservative approach, the model was unable to monitor an individual's physiological responses to exercise and adjust the protocol accordingly in real-time. The lack of protocol personalization and lack of preliminary patient assessment represented further shortcomings of the AI prototype.

Taken altogether, these recent findings show the potential of AI models and underscore the need to explore whether these AI-based applications can, indeed, offer novel avenues for tailored health enhancement.

However, the effectiveness and accuracy of AI-generated advice must be rigorously tested and validated. A limitation of the previously mentioned studies is that they focused on only one or two AI models. Currently, there exist different AI prototypes, besides those developed by OpenAI (ChatGPT-3.5 and ChatGPT-4), such as Microsoft Copilot and Google Bard (currently known as Google Gemini). All these models share many foundational elements, being built on the Transformer architecture and trained on diverse datasets, which include a broad range of texts from books and websites. These features allow them to generate and understand human-like text, and excel in natural language processing and conversational AI. However, the prototypes vary in terms of model size and outcomes,

including performance, accuracy, and coherence. As such, they can differ in handling and reacting to complex or ambiguous queries and generating contextually relevant responses.

Comparing these models, instead of focusing on a single AI prototype, is essential for several reasons: understanding their strengths and weaknesses helps users select the most suitable tool for their specific needs and can contribute to the advancement of AI technology. By analyzing what each AI model excels at and where it falls short, researchers can identify areas for optimization, improvement, and innovation in future models.

More specifically, it is important to ensure that, in the field of sports nutrition, AI recommendations are based on sound nutritional science and are tailored to individual athletes' needs. This can be done by testing different AI prototypes using reliable tools. To the best of our knowledge, no one has ever appraised AI's proficiency in nutritional knowledge in ultra-endurance sports. Therefore, the present study was undertaken to fill in this gap of knowledge utilizing a validated sports nutrition questionnaire and comparing the responses of various AI models with those of different human populations and groups, including qualified sports nutritionists, dietitians, athletes, and the general population. The main aim was to identify the strengths and weaknesses of AI-generated advice relative to human expertise in terms of consistency and accuracy, also seeking to pinpoint specific areas where AI models can excel or fall short in providing nutritional advice, paving the way for potential future applications of AI in sports nutrition.

We hypothesized that the AI models, particularly the more advanced versions like ChatGPT-4, would provide nutrition advice comparable to or even superior to that provided by sports nutritionists and dietitians, especially in terms of accuracy and consistency. Also, we expected significant differences in performance among the AI models, with ChatGPT-4 predicted to outperform ChatGPT-3.5, Google Bard, and Microsoft Copilot due to its more sophisticated algorithms and larger training dataset.

MATERIALS AND METHODS

Procedure

A literature search was conducted to retrieve a recently published, comprehensive and reliable tool for assessing nutrition knowledge among ultra-endurance athletes. The ULTRA-Q [21], a sports nutrition questionnaire, specifically adapted for testing nutritional knowledge in the specific ultra-endurance athlete population, was found and deemed suitable for the purposes of the present research. The ULTRA-Q has been, indeed, validated both in terms of construct and content validity, showing satisfactory test-retest reliability (with intraclass correlation coefficients ranging between 0.75 and 0.95).

The questionnaire consists of five sections, each targeting a critical aspect of nutrition essential for athletes involved in ultra-endurance sports: namely, "Nutrients" consisting of 37 items, "Fluid" with 8 items, "Recovery" with 11 items, "Body Composition" with 12 items, and "Supplement" with 8 items.

All items from this questionnaire were extracted and submitted to ChatGPT-3.5, ChatGPT-4, Google Bard, and Microsoft Copilot. The four AI models were queried using zero-shot prompts, which means that the machine learning models were queried without any prior specific training or examples given for the task at hand. In other words, the AI-based tools were asked to perform a task they had not explicitly been trained to do, using only their pre-existing knowledge and capabilities. The prompts used were exactly the items from the ULTRA-Q questionnaire [21].

Responses provided by the AI models were, then, collected and scored according to the scoring instructions of the ULTRA-Q questionnaire [21].

Statistical analysis

Descriptive statistics of the overall assessments and the scores broken down according to each section for each AI model were carried out. Then, the performances of the four AI models were averaged for statistical comparison with the performances of ultra-endurance athletes (extracted from [21]). More in detail, the scores obtained by the four AI models were compared against those achieved by a sample of experienced ultra-endurance athletes (74 males and 27 females) who had filled out the ULTRA-Q in the validation study of the questionnaire. Their overall nutrition knowledge score was computed at 68 ± 10%, without any notable differences between male and female athletes (67 ± 10% and 71 ± 9%, respectively) or between runners and triathletes (69 ± 10% and 65 ± 9%). The scores were also compared with those achieved by ten registered sports nutritionists, further ten registered dietitians, and thirteen members of the general population. All these scores were extracted from [21] and were compared by conducting an analysis of variance (ANOVA) from summary statistics and using the Tukey Honest Significant Difference (HSD) test for the post-hoc analysis.

All statistical analyses were done using the commercial software "Statistical Package for Social Sciences" (SPSS version 28 for Windows, IBM, Armonk, NY, USA).

RESULTS

Comparative Analysis of Performance on the ULTRA-Q Questionnaire among the four Artificial Intelligence Models

Overall, Chat-GPT4 demonstrated the highest accuracy, making only 5 mistakes, resulting in an accuracy rate of 93%, followed by Microsoft Copilot, which made 6 mistakes, with an accuracy rate of 92%. Chat-GPT3.5, on the other hand, made 13 mistakes, which translates to an accuracy rate of 83%. Bard, closely following, made 12 mistakes, achieving an accuracy rate of 84%. This data highlights the progressive improvement in accuracy from Chat-GPT3.5 to Chat-GPT4, with Bard positioned in between these two in terms of performance (Table 1).

Concerning the different sections of the ULTRA-Q questionnaire, ChatGPT-3.5 showed strong performance across most categories, particularly excelling in "Fluids" and "Recovery" with scores above

TABLE 1. Comparative analysis of AI models: a detailed breakdown of accuracy rates in various categories of nutritional knowledge in ultra-endurance sports, highlighting mean performances and variability.

AI Model	Nutrients	Fluid	Recovery	Body Composition	Supplements	Overall
ChatGPT-3.5	28/37 (75.7%)	7/8 (87.5%)	11/11 (100.0%)	10/12 (83.3%)	7/8 (87.5%)	63/76 (82.9%)
ChatGPT-4	34/37 (91.9%)	7/8 (87.5%)	10/11 (90.9%)	12/12 (100.0%)	8/8 (100.0%)	71/76 (93.4%)
Google Bard	31/37 (83.8%)	8/8 (100.0%)	8/11 (72.7%)	11/12 (91.7%)	6/8 (75.0%)	64/76 (84.2%)
Microsoft Copilot	32/37 (86.5%)	7/8 (87.5%)	11/11 (100.0%)	12/12 (100.0%)	8/8 (100.0%)	70/76 (92.1%)
Averaged AI model	31.3 ± 2.2 (84.5 ± 5.9%)	7.3 ± 0.4 (90.6 ± 5.4%)	10.0 ± 1.2 (90.9 ± 11.1%)	11.3 ± 0.8 (93.8 ± 6.9%)	7.3 ± 0.8 (90.6 ± 10.4%)	67.0 ± 3.5 (88.2 ± 4.7%)

TABLE 2. Comparative analysis of knowledge in ultra-endurance sports nutrition: statistical insights from ULTRA-Q questionnaire responses across averaged AI model (AvAI), registered sports nutritionists (SENr), registered dietitians (RD), ultra-endurance athletes (Ultra-End), and general population.

ULTRA-Q sections	ANOVA	Tukey HSD Post-hoc Test			
		AvAI vs SENr	AvAI vs RD	AvAI vs Ultra-End	AI vs GenP
Overall	F = 19.14 (p = 0.0000)	4.1 ([95%CI -10.5 to 18.6], p = 0.9379)	11.9 ([95%CI -2.7 to 26.4], p = 0.1653	19.9 ([95%CI 7.3 to 32.4], p = 0.0002)	30.8 ([95%CI 16.7 to 44.8], p = 0.0000)
Nutrients	F = 16.80 (p = 0.0000)	-4.4 ([95%CI -21.9 to 13.0], p = 0.9552)	-3.3 ([95%CI -20.8 to 14.1], p = 0.9841)	13.7 ([95%CI -1.4 to 28.7], p = 0.0934)	23.6 ([95%CI 6.7 to 40.4], p = 0.0016)
Fluid	F = 9.61 (p = 0.0000)	14.3 ([95%CI -13.9 to 42.5], p = 0.6265)	49.3 [95%CI 21.1 to 77.5], p = 0.0000)	32.4 ([95%CI 8.1 to 56.7], p = 0.0030)	41.6 ([95%CI 14.4 to 68.9], p = 0.0004)
Recovery	F = 8.70 (p = 0.0000)	-1.8 ([95%CI -25.9 to 22.3], p = 0.9995)	1.8 ([95%CI -22.3 to 25.9], p = 0.9995)	13.1 ([95%CI -7.7 to 33.9], p = 0.4104)	29.4 ([95%CI 6.1 to 52.7], p = 0.0058)
Body Composition	F = 4.71 (p = 0.0014)	17.1 ([95%CI -8.2 to 42.3], p = 0.3379)	12.1 ([95%CI -13.2 to 37.3], p = 0.6777	23.7 ([95%CI 1.9 to 45.4], p = 0.0254)	31.0 ([95%CI 6.6 to 55.3], p = 0.0054)
Supplement	F = 4.36 (p = 0.0024)	21.8 ([95%CI -27.6 to 71.3], p = 0.7398)	58.1 ([95%CI 8.7 to 107.6], p = 0.0125)	39.5 ([95%CI -3.1 to 82.1], p = 0.0831)	55.0 ([95%CI 7.2 to 102.8], p = 0.0153)

88% and reaching 100% in "Recovery". Its weakest area appears to be "Nutrients", with a 76% score. ChatGPT-4 stood out with exceptionally high scores, surpassing 90% in nearly all categories and achieving perfect scores in "Body Composition" and "Supplements". Bard demonstrated solid knowledge, particularly in "Fluid" with a perfect score and in "Body Composition" with 92%. However, it showed relative weakness in "Recovery", scoring 73%. Finally, Copilot also exhibited robust performance, especially notable with perfect scores in "Recovery", "Body Composition", and "Supplements". Like Bard, its lowest score was in "Nutrients".

The Averaged AI Model, representing the mean performance of these four models, showed consistently high scores across all sections, with the highest in "Body Composition" (94%) and the lowest in "Nutrients" (84%). This model achieved an overall score of 88%, reflecting a strong aggregate capability across various aspects of sports nutrition in ultra-endurance disciplines. This analysis revealed the strengths and weaknesses of each AI model in different nutrition-related areas, with ChatGPT-4 and Copilot generally outperforming others. The Averaged AI Model's performance indicates that while individual models have their specific areas of expertise, collectively they provide a well-rounded and comprehensive understanding of sports nutrition as reflected by scores achieved on the ULTRA-Q questionnaire (Table 2, Figure 1).

Comparative Analysis of Artificial Intelligence Performance on the ULTRA-Q Questionnaire versus Professionals and the General Population

In the analysis of the performance of various population groups on the ULTRA-Q, distinct levels of knowledge and consistency could be observed. The averaged AI Model leads with an impressive overall score of 88% and the lowest standard deviation of 5, indicating both high accuracy and consistent responses. Following closely are registered sports nutritionists with a strong performance of 84%, although with a slightly higher standard deviation of 7, suggesting a bit more variability in their responses concerning the averaged AI model. Registered dietitians showed good knowledge with a score of 76% and a standard deviation of 6 (slightly higher than the standard deviation of the Averaged AI model), indicative of moderate consistency in their

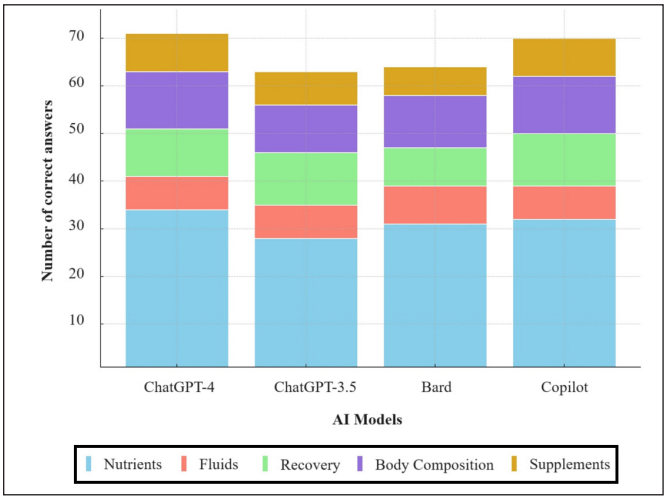


FIG. 1. Comparative analysis of AI models in ultra-endurance sports nutrition: a stacked bar chart illustrating the number of correct answers on the ULTRA-Q by ChatGPT-4, ChatGPT-3.5, Bard, and Copilot across key nutrition categories.

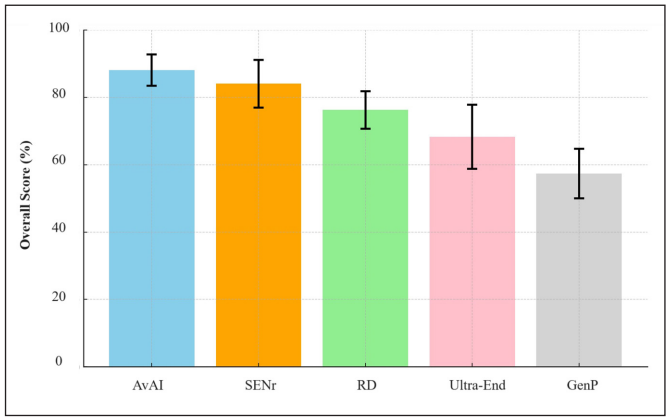


FIG. 2. Comprehensive comparison of nutrition knowledge across groups: this chart illustrates the average percentage of correct answers on the ULTRA-Q for AI models, sports and exercise nutrition register (SENr) members, registered dietitians (RD), ultra-endurance athletes, and the general population (GenP). It includes a detailed breakdown by ULTRA-Q categories (Nutrients, Fluids, Recovery, Body Composition, Supplements) and an overall score, providing a holistic view of nutrition knowledge expertise and variability within each group.

expertise. In contrast, ultra-endurance athletes and the general population exhibited lower scores and higher variability in their understanding of sports nutrition. More in detail, ultra-endurance athletes scored 68%, but with the highest standard deviation of 10, reflecting a diverse range of knowledge levels within the group. The general population, as could be expected, scored the lowest at 57% with a standard deviation of 7, highlighting their limited exposure to specialized knowledge in ultra-endurance sports nutrition. This analysis underscores the proficiency and reliability of AI models in providing accurate information, while also emphasizing the varying degrees of specialized knowledge among professionals and the general public (Figure 2).

From a quantitative standpoint, the ANOVA test showed a highly significant difference among groups for the overall scores ($F = 19.14$, $p < 0.0001$). The Tukey HSD revealed that the Averaged AI Model significantly outperforms the general population ($p < 0.0001$) and the ultra-endurance athletes ($p = 0.0002$), but is not significantly different from the registered sports nutritionists and the registered dietitians. This suggests that while AI models have a notable edge in general knowledge over athletes and the general public, they are on par with professional nutritionists and dietitians. Concerning the section "Nutrients", again, significant differences are observed among groups ($F = 16.80$, $p < 0.0001$), but the averaged AI model did not significantly outperform any group in this category, with the only exception of the general population ($p = 0.0016$). This indicates a relatively uniform understanding of nutrients across almost all groups, including the AI models and various human professionals. A significant difference in the scores achieved in "Fluids" could be noted ($F = 9.61$, $p < 0.0001$), with the averaged AI model notably outperforming not only the ultra-endurance athletes ($p = 0.0030$) and the general population ($p = 0.0004$), but also the registered dietitians ($p < 0.0001$). This highlights a particular strength of AI in fluid-related knowledge, a gap evident in ultra-endurance athletes and the general population, as well as in expert and qualified professionals. While there is a significant overall difference ($F = 8.70$, $p < 0.0001$), the post-hoc test indicates no significant difference between the averaged AI model and any other group in the "Recovery" section, with the only exception of the general population ($p = 0.0058$). This implies a more level playing field in terms of knowledge concerning this specific section. Finally, both "Body Composition" and "Supplement" sections showed statistically significant differences among groups ($F = 4.71$ and $F = 4.36$ respectively, with $p < 0.005$ in both cases). In "Body Composition", the averaged AI model significantly outperformed both the ultra-endurance athletes ($p = 0.0254$) and the general population ($p = 0.0054$), and in "Supplements", it significantly surpassed both the registered dietitians ($p = 0.0125$) and the general population ($p = 0.0153$). For further details, the reader is referred to Table 2.

All these results, taken together, point to specific areas where AI models excel and where human groups, including expert and qualified professionals, might benefit from additional education or resources.

DISCUSSION

Nutrition is a foundational element for athletic success, and while digital tools and AI offer promising avenues for personalized nutrition advice, it is crucial to ensure that such guidance is accurate, reliable, and based on scientific principles. In particular, nutrition in

ultra-endurance sports is a highly specialized topic that requires not only a broad understanding of general nutrition principles but also specific knowledge about the unique physiological demands of ultra-endurance activities. Given this complexity, the high accuracy rate of AI, and in particular of Chat-GPT4 (93%), is particularly impressive, suggesting that AI-based model have a strong capability in handling niche and specialized subjects, likely due to their advanced training and more extensive knowledge base.

Microsoft Copilot, with an accuracy rate of 92%, Chat-GPT3.5, with 83%, and Bard, with 84%, also performed reasonably well, indicating a good grasp of the subject. However, their slightly lower accuracy rates compared to Chat-GPT4 might reflect limitations in dealing with highly specialized topics, which could be due to less comprehensive training data or less cutting-edge algorithms.

The comparative analysis of the AI models – ChatGPT-3.5, ChatGPT-4, Google Bard, and Microsoft Copilot – revealed notable differences in their performance in replying to the ULTRA-Q questionnaire and, therefore, in their potential to provide nutrition advice for ultra-endurance athletes. These differences can be attributed to several factors, including the sophistication of the underlying codes and algorithms, the extent and quality of training data, and the specific design objectives of each model. ChatGPT-4 consistently demonstrated the highest accuracy and reliability among the AI models tested, likely due to its advanced algorithmic improvements in terms of state-of-the-art machine learning techniques and extensive training on a diverse and large dataset [24–26]. This superior performance proves ChatGPT-4's ability to handle complex and specialized queries effectively, which is crucial for ultra-endurance sports nutrition that requires a nuanced understanding of physiological demands, nutrient timing, and hydration strategies. ChatGPT-3.5, while competent, lagged behind its successor, being capable of providing accurate advice in certain areas, but lacking the comprehensive depth and consistency seen in ChatGPT-4. These findings are in line with the existing scholarly literature [22], which showed that, when comparing these two AI prototypes, ChatGPT-4 was able to provide more detailed and individualized information than ChatGPT3.5.

Google Bard's performance was mixed, with notable variations across the domains of the questionnaire, indicating that while this AI model can provide accurate advice in some areas, it may not be as reliable in others, possibly due to differences in training data and algorithmic design compared to ChatGPT models. Bard's integration with Google's extensive resources might offer advantages in information retrieval and real-time updates, but its performance variability suggests that it may not yet match the specialized focus of models like ChatGPT-4 in sports nutrition. This is in line with studies showing that Google Bard tends to perform worse than ChatGPT-4 [27].

Finally, Microsoft Copilot, primarily designed for coding assistance and strong in specific programming areas [28], surprisingly performed well in this nutrition context. Copilot's robust performance in these areas could be attributed to its design for precision and its algorithm's ability to adapt to different contexts. However, Copilot's low-performance scores in a few categories of the questionnaire indicated some limitations, probably stemming from its primary focus on coding and software development rather than on general knowledge and conversational AI, like the other AI prototypes tested. Despite this, its high scores in other categories highlight its potential versatility and adaptability.

Altogether, these findings suggest that while all AI models have their strengths, ChatGPT-4's comprehensive improvements make it the most reliable for providing nuanced and accurate nutrition advice for ultra-endurance athletes, highlighting the continual advancements in AI capabilities, especially in understanding and processing complex and specialized information like nutrition in ultra-endurance sports. These findings corroborate results from the literature [22, 23], which compare the performance of AI models, including ChatGPT-3.5 and ChatGPT-4, in designing training programs and providing nutrition advice. In these studies, it was found that while these AI models could generate satisfactory training prescriptions, they contained some questionable assertions and required further refinement. This aligns with the present study's findings, where AI models showed varying degrees of accuracy and consistency in different nutrition categories, with ChatGPT-4 generally outperforming the others. This suggests that while AI models are highly promising, there is still room for improvement, particularly in ensuring the advice is tailored and dynamically responsive to individual needs.

For future applications, integrating AI models like ChatGPT-4 into personalized nutrition strategies by combining AI-generated insights with expert human judgment could significantly enhance the precision and effectiveness of high-quality dietary recommendations.

Specifically, when assessing AI against human individuals, including qualified nutritionists, dietitians, ultra-endurance athletes, and the general population, the comparative analysis of the performance data from the ULTRA-Q nutrition questionnaire revealed insightful trends about knowledge levels across these different groups. Leading is the averaged AI Model: its top score of 88% coupled with the lowest standard deviation of 5 not only signifies its superior knowledge base but also showcases remarkable consistency in its responses. This high accuracy and reliability underscore the potential of AI as a valuable resource in specialized fields like sports nutrition. In comparison, human experts like registered sports nutritionists and registered dietitians also demonstrate strong knowledge, albeit with slightly more variability. The high score of the former group reflects their specialized expertise, though the variability indicated by their standard deviation suggests differences in individual experiences or focus areas within sports nutrition. The latter group, with a broader focus on diet and nutrition, shows commendable competence but less specialization in ultra-endurance sports nutrition, as reflected in their scores and standard deviation.

On the other hand, ultra-endurance athletes and the general population present a different picture. ultra-endurance athletes, while directly involved in the field, exhibit a considerable range in their

understanding of nutrition, as indicated by their higher standard deviation. This variation might stem from differing levels of interest or access to nutrition education among athletes [29]. According to a systematic review, athletes demonstrated a level of knowledge that was either comparable to or exceeded that of non-athletes. However, their knowledge did not reach the same level as certain comparison groups, such as students specializing in nutrition. The general population's lower score can be expected, considering their lack of necessity for specialized knowledge in this niche area. The variability here could be attributed to diverse backgrounds and varying degrees of general health awareness [30].

Overall, all these analyses highlight the intersection of specialized knowledge and its application, underscoring the AI-based model's prowess in providing accurate, reliable information and the importance of targeted education and knowledge dissemination among professionals and athletes in niche fields like ultra-endurance sports nutrition. The differences in scores and standard deviations across these groups also point towards the potential gaps in knowledge that could be addressed through tailored educational programs, especially for athletes and the general public.

Strengths and limitations

The present study has several notable strengths. Firstly, it demonstrates a high degree of originality and innovation by investigating the use of AI models to assess nutritional knowledge among ultra-endurance athletes, a unique and relatively unexplored topic. The research employs a methodologically rigorous approach by utilizing the ULTRA-Q survey, which is specifically designed for this athletic population and has been validated for reliability and accuracy. This survey helps in providing a detailed evaluation of the performance of various AI models across different groups, including athletes, experts, and the general public. Moreover, the study's comparative analysis is another major strength. By comparing the AI models' performance against both the general population and certified sports nutritionists and dietitians, the research offers a comprehensive evaluation of AI capabilities in the field of sports nutrition. This analysis not only highlights the potential of AI models to support nutrition education but also emphasizes the importance of integrating AI insights with expert human judgment to enhance nutritional advice and dietetics. However, the study also has certain limitations that need to be acknowledged. One significant limitation is the limited sample size of ultra-endurance athletes, professionals, and individuals from the general population in the comparative groups. Increasing the sample size would enhance the generalizability of the findings. Additionally, the study briefly mentions the AI models' inability to make real-time adjustments but overlooks other potential challenges in using AI for sports nutrition. These challenges include the models' handling of individual variability and specific dietary needs in dynamic conditions, which could impact the practical use of AI in real-world sports environments. Furthermore, the AI models' outputs were not validated by an unbiased external source. Incorporating external verification would further enhance the credibility of the AI-generated nutritional advice.

Future Directions

The present analysis, including the part of the comparison of AI versus human individuals, highlights the continuous advancements in AI technology, with each new version showing improved accuracy and performance. In a study assessing the potential of ChatGPT as a reliable source of nutritional advice, it was found that ChatGPT-3.5, when tasked with three hypothetical scenarios encompassing diverse health conditions, could generate various options of meal plans incorporating basic nutrition principles. However, it failed to properly recommend individual macronutrient distribution, and could not effectively deal with underlying health issues and drug interactions. Similarly, ChatGPT-3.5 was unable to set realistic weight loss goals [31].

In our study, Chat-GPT4's significantly higher accuracy rate compared to its predecessor (ChatGPT-3.5) and other AI prototypes (Microsoft Copilot and Google Bard) indicates substantial improvements in its underlying algorithms and knowledge base. In the future, dietary counseling of athletes could leverage advanced platforms like machine learning and AI to provide reliable, updated resources, as well as more accurate, personalized dietary recommendations. Overall, the integration of AI and advanced digital platforms in sports nutrition promises to enhance the precision and personalization of dietary strategies, counseling, education, and body composition analysis, potentially revolutionizing the field of sports nutrition and athlete performance optimization.

The juxtaposition of AI performance with that of registered nutritionists, dietitians, and ultra-endurance athletes is intriguing, as it contrasts humans with AI's intellectual or problem-solving capabilities. However, it is important to note that the unique value of specialized human education and expertise is irreplaceable and cannot be understated, highlighting the importance of integrating AI insights with the discerning judgment of experts in the fields of nutrition and dietetics for the most effective outcomes.

Potential risks and ethical considerations also need to be addressed. These include the possibility of over-reliance on AI for nutritional advice without human oversight, the risk of biased or inaccurate information due to limitations in AI training data, and concerns regarding data privacy and security. It is crucial to ensure that AI recommendations are based on sound nutritional science and are tailored to individual athletes' needs. This can be done by testing different AI prototypes using reliable tools and continuously updating AI algorithms to reflect the latest scientific findings.

CONCLUSIONS

This study highlighted the significant advancements in AI technology, particularly in the context of sports nutrition for ultra-endurance athletes. By evaluating the performance of four major AI models – ChatGPT-3.5, ChatGPT-4, Google Bard, and Microsoft Copilot

– using the ULTRA-Q nutrition questionnaire, the research demonstrated that AI models, especially the advanced ChatGPT-4, can generate accurate and reliable nutritional advice. The comparison between AI models and human groups, including registered sports nutritionists, registered dietitians, ultra-endurance athletes, and the general population, revealed that AI models can match or even surpass human experts in certain areas of nutrition knowledge. ChatGPT-4, in particular, exhibited the highest accuracy and consistency, outperforming other AI models and showing strong potential in specialized subjects like nutrition for ultra-endurance sports. The study also identified specific strengths and weaknesses of the AI models in various nutrition-related areas. While AI models excelled in categories such as fluid management and recovery, they showed limitations in more nuanced areas like nutrient timing and specific dietary needs for ultra-endurance activities. Overall, the findings suggest that AI models have the potential to enhance personalized nutrition strategies for athletes, leading to improved performance and health outcomes.

On the other hand, while highlighting the significant advancements in AI and its applicability in sports nutrition, the present study reaffirms the indispensable value of specialized human education and expertise. The integration of AI insights with expert human judgment in nutrition and dietetics could provide more effective and personalized dietary recommendations. This study paves the way for future research and developments in the integration of AI into sports nutrition, aiming to optimize athlete performance and overall well-being.

REFERENCES

1. Rodriguez NR, DiMarco NM, Langley S; American Dietetic Association; Dietitians of Canada; American College of Sports Medicine: Nutrition and Athletic Performance. Position of the American Dietetic Association, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and athletic performance. J Am Diet Assoc. 2009 Mar; 109(3):509–27. doi: 10.1016 /j.jada.2009.01.005. Erratum in: J Am Diet Assoc. 2013 Dec; 113(12):1759. PMID: 19278045.
2. Beck KL, Thomson JS, Swift RJ, von Hurst PR. Role of nutrition in performance enhancement and postexercise recovery. Open Access J Sports Med. 2015 Aug 11; 6:259–67. doi: 10.2147/OAJSM.S33605. PMID: 26316828; PMCID: PMC4540168.
3. Roberts BM, Helms ER, Trexler ET, Fitschen PJ. Nutritional Recommendations for Physique Athletes. J Hum Kinet. 2020 Jan 31; 71:79–108. doi: 10.2478/hukin-2019-0096. PMID: 32148575; PMCID: PMC7052702.
4. Bytomski JR. Fueling for Performance. Sports Health. 2018 Jan/Feb; 10(1):47–53. doi: 10.1177/1941738 117743913. Epub 2017 Nov 27. PMID: 29173121; PMCID: PMC5753973.
5. Purcell LK; Canadian Paediatric Society, Paediatric Sports and Exercise Medicine Section. Sport nutrition for young athletes. Paediatr Child Health. 2013 Apr; 18(4):200–5. doi: 10.1093/pch /18.4.200. PMID: 24421690; PMCID: PMC3805623.
6. Judge LW, Bellar DM, Popp JK, Craig BW, Schoeff MA, Hoover DL, Fox B, Kistler BM, Al-Nawaiseh AM. Hydration to Maximize Performance and Recovery: Knowledge, Attitudes, and Behaviors Among Collegiate Track and Field Throwers. J Hum Kinet. 2021 Jul 28; 79:111–122. doi: 10.2478/ hukin-2021-0065. PMID: 34400991; PMCID: PMC8336541.
7. Ghazzawi HA, Hussain MA, Raziq KM, Alsendi KK, Alaamer RO, Jaradat M, Alobaidi S, Al Aqili R, Trabelsi K, Jahrami H. Exploring the Relationship between Micronutrients and Athletic Performance: A Comprehensive Scientific Systematic Review of the Literature in Sports Medicine. Sports (Basel). 2023 May 24; 11(6):109. doi: 10.3390 /sports11060109. PMID: 37368559; PMCID: PMC10302780.
8. Kerksick CM, Arent S, Schoenfeld BJ, Stout JR, Campbell B, Wilborn CD, Taylor L, Kalman D, Smith-Ryan AE, Kreider RB, Willoughby D, Arciero PJ, VanDusseldorp TA, Ormsbee MJ, Wildman R, Greenwood M, Ziegenfuss TN, Aragon AA, Antonio J. International society of sports nutrition position stand: nutrient timing. J Int Soc Sports Nutr. 2017 Aug 29; 14:33. doi: 10.1186/s12970-017 -0189-4. PMID: 28919842; PMCID: PMC5596471.
9. Nikolaidis PT, Veniamakis E, Rosemann T, Knechtle B. Nutrition in Ultra-Endurance: State of the Art. Nutrients. 2018 Dec 16; 10(12):1995. doi: 10.3390/nu1012 1995. PMID: 30558350; PMCID: PMC6315825.
10. Kerksick CM, Wilborn CD, Roberts MD, Smith-Ryan A, Kleiner SM, Jäger R, Collins R, Cooke M, Davis JN, Galvan E, Greenwood M, Lowery LM, Wildman R, Antonio J, Kreider RB. ISSN exercise & sports nutrition review update: research & recommendations. J Int Soc Sports Nutr. 2018 Aug 1; 15(1):38. doi: 10.1186/s12970-018-0242-y. PMID: 30068354; PMCID: PMC6090881.
11. James LJ, Funnell MP, James RM, Mears SA. Does Hypohydration Really Impair Endurance Performance? Methodological Considerations for Interpreting Hydration Research. Sports Med. 2019 Dec; 49(Suppl 2):103–114. doi: 10.1007/s40279-019-01188-5. PMID: 31696453; PMCID: PMC6901416.
12. Buck E, McAllister R, Schroeder JD. Exercise-Associated Hyponatremia. [Updated 2023 Jun 12]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2023 Jan-. Available from: https://www.ncbi.nlm.nih .gov/books/NBK572128/
13. Tiller NB, Roberts JD, Beasley L, Chapman S, Pinto JM, Smith L, Wiffin M, Russell M, Sparks SA, Duckworth L, O'Hara J, Sutton L, Antonio J, Willoughby DS, Tarpey MD, Smith--Ryan AE, Ormsbee MJ, Astorino TA, Kreider RB, McGinnis GR, Stout JR, Smith JW, Arent SM, Campbell BI, Bannock L. International Society of Sports Nutrition Position Stand: nutritional considerations for single-stage ultra-marathon training and racing. J Int Soc Sports Nutr. 2019 Nov 7; 16(1):50. doi: 10.1186/s12970-019-0312-9. PMID: 31699159; PMCID: PMC6839090.
14. Cejka C, Knechtle B, Knechtle P, Rüst CA, Rosemann T. An increased fluid intake leads to feet swelling in 100-km ultra-marathoners – an observational field study. J Int Soc Sports Nutr. 2012 Apr 3; 9(1):11. doi: 10.1186/1550-2783 -9-11. PMID: 22472466; PMCID: PMC3366912.
15. Vázquez-Espino K, Rodas-Font G, Farran-Codina A. Sport Nutrition Knowledge, Attitudes, Sources of Information, and Dietary Habits of Sport-Team Athletes. Nutrients. 2022 Mar 23; 14(7):1345. doi: 10.3390 /nu14071345. PMID: 35405958; PMCID: PMC9002668.
16. Janiczak A, Devlin BL, Forsyth A, Trakman GL. A systematic review update of athletes' nutrition knowledge and association with dietary intake. Br J Nutr. 2022 Sep 28; 128(6):1156–1169. doi: 10.1017/S0007114521004311. Epub 2021 Oct 28. PMID: 34706784.
17. Tam R, Gifford JA, Beck KL. Recent Developments in the Assessment of

Nutrition Knowledge in Athletes. Curr Nutr Rep. 2022 Jun; 11(2):241–252. doi: 10.1007/s13668-022-00397-1. Epub 2022 Feb 16. PMID: 35174474; PMCID: PMC9174104.
18. Jayawardena R, Weerasinghe K, Trakman G, Madhujith T, Hills AP, Kalupahana NS. Sports Nutrition Knowledge Questionnaires Developed for the Athletic Population: a Systematic Review. Curr Nutr Rep. 2023 Dec; 12(4):767–777. doi: 10.1007/s13668-023-00494-9. Epub 2023 Sep 16. PMID: 37715061.
19. Kinrade EJ, Galloway SDR. Dietary Observations of Ultra-Endurance Runners in Preparation for and During a Continuous 24-h Event. Front Physiol. 2021 Nov 24; 12:765888. doi: 10.3389/fphys.2021.765888. PMID: 34899391; PMCID: PMC8652078.
20. Peart DJ, Briggs MA, Shaw MP. Mobile applications for the sport and exercise nutritionist: a narrative review. BMC Sports Sci Med Rehabil. 2022 Feb 22; 14(1):30. doi: 10.1186/s13102-022-00419-z. PMID: 35193643; PMCID: PMC8862506.
21. Blennerhassett C, McNaughton LR, Cronin L, Sparks SA. Development and Implementation of a Nutrition Knowledge Questionnaire for Ultraendurance Athletes. Int J Sport Nutr Exerc Metab. 2019 Jan 1; 29(1):39–45. doi: 10.1123/ijsnem.2017-0322. PMID: 29757047.
22. Washif JA, Pagaduan J, James C, Dergaa I, Beaven CM. Artificial intelligence in sport: Exploring the potential of using ChatGPT in resistance training prescription. Biol Sport. 2024; 41(2):209–220. doi:10.5114/biolsport.2024.132987.
23. Dergaa I, Ben Saad H, El Omri A, et al. Using artificial intelligence for exercise prescription in personalised health promotion: A critical evaluation of OpenAI's GPT-4 model. Biol Sport. 2024; 41(2):221–241. doi:10.5114/biolsport.2024.133661.
24. Ray PP. ChatGPT: A comprehensive review on background, applications, key challenges, bias, ethics, limitations and future scope. Internet of Things and Cyber-Physical Systems. 2023; 3:121–154. doi:10.1016/j.iotcps.2023.04.003.
25. Alawida M, Mejri S, Mehmood A, Chikhaoui B, Isaac Abiodun O. A Comprehensive Study of ChatGPT: Advancements, Limitations, and Ethical Considerations in Natural Language Processing and Cybersecurity. Information. 2023; 14:462. doi:10.3390/info14080462.
26. Roumeliotis KI, Tselikas ND. ChatGPT and Open-AI Models: A Preliminary Review. Future Internet. 2023; 15(6):192. doi:10.3390/fi15060192.
27. Jedrzejczak WW, Kochanek K. Comparison of the audiological knowledge of three chatbots – ChatGPT, Bing Chat, and Bard. Audiol Neurootol. 2024 May 6. doi: 10.1159/000538983. Epub ahead of print. PMID: 38710158.
28. Alhur A. Redefining Healthcare With Artificial Intelligence (AI): The Contributions of ChatGPT, Gemini, and Co-pilot. Cureus. 2024 Apr 7; 16(4):e57795. doi: 10.7759/cureus.57795. PMID: 38721180; PMCID: PMC11077095.
29. Heaney S, O'Connor H, Michael S, Gifford J, Naughton G. Nutrition knowledge in athletes: a systematic review. Int J Sport Nutr Exerc Metab. 2011 Jun; 21(3):248–61. doi: 10.1123/ijsnem.21.3.248. PMID: 21719906.
30. Rosi A, Ferraris C, Guglielmetti M, Meroni E, Charron M, Menta R, Manini F, Di Gioia V, Martini D, Erba D. Validation of a General and Sports Nutrition Knowledge Questionnaire in Italian Early Adolescents. Nutrients. 2020 Oct 13; 12(10):3121. doi: 10.3390/nu12103121. PMID: 33066020; PMCID: PMC7600562.
31. Dergaa I, Ben Saad H, Ghouili H, Glenn JM, El Omri A, Slim I, et al. Evaluating the Applicability and Appropriateness of ChatGPT as a Source for Tailored Nutrition Advice: A Multi-Scenario Study. N Asian J Med. 2024; 2(1):1–16. doi:10.61838/kman.najm.2.1.1

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.

Original Paper DOI: https://doi.org/10.5114/biolsport.2024.142165
© Institute of Sport – National Research Institute

Erratum to: Effects of plyometric-based structured game active breaks on fundamental movement skills, muscular fitness, self-perception, and actual behaviour in primary school students

AUTHORS: Andrew Sortwell[1,2], Kate O'Brien[2], Aron Murphy[1], Rodrigo Ramirez-Campillo[3], Benjamin Piggott[4], Gregory Hine[5], Michael Newton[4]

[1] School of Health Sciences and Physiotherapy, University of Notre Dame Australia, Sydney, Australia
[2] Education and Research Directorate, Sydney Catholic Schools, Sydney, Australia
[3] Exercise and Rehabilitation Sciences Institute, School of Physical Therapy, Faculty of Rehabilitation Sciences, Universidad Andres Bello, Santiago, Chile
[4] School of Health Sciences and Physiotherapy, University of Notre Dame Australia, Perth, Australia
[5] School of Education, University of Notre Dame Australia, Perth, Australia

The authors would like to correct the error in the publication of the original article. The corrected detail is published with this erratum for your reading.

Erratum notice:
In the previously published version of the abstract, the following sentence was presented:
"A significant ($p < 0.01$) interaction group by time was observed, with greater improvements in the IG compared to the CG in FMS (%diff = 13.11, $\eta p^2 = 0.12$), SLJ (%diff = 6.67, $\eta p^2 = 0.02$), seated medicine ball chest throw (%diff = 4.69, $\eta p^2 = 0.08$), student social self-perception (%diff = 9.31, $\eta p^2 = 0.10$), student scholastic self-perception (%diff = 7.27, $\eta p^2 = 0.10$), and teacher perception of student social competence (%diff = 8.31, $\eta p^2 = 0.05$)."

This has been corrected to:
"A significant ($p < 0.01$) interaction group by time was observed, with greater improvements in the IG compared to the CG in FMS (%diff = 13.11, $\eta p^2 = 0.12$), SLJ (%diff = 6.67, $\eta p^2 = 0.16$), seated medicine ball chest throw (%diff = 4.69, $\eta p^2 = 0.08$), student social self-perception (%diff = 9.31, $\eta p^2 = 0.10$), student scholastic self-perception (%diff = 7.27, $\eta p^2 = 0.10$), and teacher perception of student social competence (%diff = 8.31, $\eta p^2 = 0.05$)."

CITATION: Erraton to: Sortwell A, O'Brien K, Murphy A et al. Effects of plyometric-based structured game active breaks on fundamental movement skills, muscular fitness, self-perception, and actual behaviour in primary school students. Biol Sport. 2024;41(4):315.

Published: 2024-08-27.

Corresponding author:
Andrew Sortwell
School of Health Sciences and Physiotherapy, University of Notre Dame Australia, Sydney, Australia
E-mail: sortwellandrew@gmail.com

ORCID:
Andrew Sortwell
0000-0001-9987-5939

Kate O'Brien
0009-0004-0985-3592

Aron Murphy
0000-0002-8964-072X

Rodrigo Ramirez-Campillo
0000-0003-2035-3279

Benjamin Piggott
0000-0003-0760-1944

Gregory Hine
0000-0003-4589-3159

Michael Newton
0009-0000-7892-2759

Key words:
Children
Motor skills
Resistance training
Self-concept
School-setting
Learning

Review Paper DOI: https://doi.org/10.5114/biolsport.2024.144014
© Institute of Sport – National Research Institute

Mpox in sports: A comprehensive framework for anticipatory planning and risk mitigation in football based on lessons from COVID-19

AUTHORS: Karim Chamari[1,#], Helmi Ben Saad[2,#], Wissem Dhahbi[3,4], Jad Adrian Washif[5], Abdelfatteh El Omri[6], Piotr Zmijewski[7], Ismail Dergaa[8]

[1] Research & Education, Naufar, Wellness and Recovery Center, Doha, Qatar
[2] Heart Failure Research Laboratory (LR12SP09), Farhat Hached Hospital, Faculty of Medicine of Sousse, University of Sousse, Tunisia
[3] High Institute of Sport and Physical Education of El Kef, University of Jendouba, El Kef, Tunisia
[4] Qatar Police Academy, Police College, Training Department, Doha, Qatar
[5] Sports Performance Division, Institut Sukan Negara Malaysia (National Sports Institute of Malaysia), Kuala Lumpur, Malaysia
[6] Surgical Research Section, Department of Surgery, Hamad Medical Corporation, Doha 3050, Qatar
[7] Institute of Sport - National Research Institute, Warsaw, Poland
[8] Higher Institute of Sports and Physical Education of Ksar Said, University of Manouba, Manouba, Tunisia
[#] Equal contribution as first author

Corresponding author:
Helmi BEN SAAD
University of Sousse
Farhat HACHED hospital
Research Laboratory LR12SP09
«Heart Failure», Sousse, Tunisia
E-mail: helmi.bensaad@rns.tn

ORCID:
Karim Chamari
0000-0001-9178-7678
Helmi Ben Saad
0000-0002-7477-2965
Wissem Dhahbi
0000-0001-6221-546X
Jad Adrian Washif
0000-0001-8543-4489
Abdelfatteh El Omri
0000-0003-4112-7924
Piotr Zmijewski
0000-0002-5570-9573
Ismail Dergaa
0000-0001-8091-1856

ABSTRACT: The World Health Organization's declaration of mpox (formerly known as monkeypox) as a public health emergency of international concern (PHEIC) in July 2022, followed by its resurgence in 2024, has sparked concerns about its potential impact on sports, especially contact sports such as football. Although mpox is not a pandemic (as of late September 2024), the coronavirus disease 2019 (COVID-19) experience offers valuable lessons for proactive planning in sports. Our conceptual framework has been designed to draw insightful lessons from the COVID-19 pandemic to assist sports organizations in planning for and preventing similar situations. We aimed to draw lessons from COVID-19 to help sports organizations enhance practical preparedness through effective planning and mitigation strategies. Accordingly, we sought to assess the potential impact of mpox on sports, with a focus on football (soccer), and to develop strategies for prevention, management, and preparedness based on epidemiological insights and lessons from COVID-19 pandemic experience. Here we review mpox's pathophysiology and possibility of transmission in sports settings and discuss tailored strategies, including risk assessments, testing protocols, hygiene measures, and return-to-play policies. This review highlights key differences between mpox and COVID-19 in transmission, incubation, and management, emphasizing the need for customized prevention and control measures in sports. We propose innovative risk assessment methods using global positioning system tracking and machine learning for contact analysis, alongside tailored testing and hygiene protocols. We emphasize the importance of proactive planning, noting improved preparedness in the sports community compared to the early days of COVID-19. In conclusion, our proposed framework provides sports organizations with practical tools to manage potential risks associated with mpox, ensuring the continuity of activities while prioritizing public health.

CITATION: Chamari K, Ben Saad H, Dhahbi W et al. Mpox in sports: A comprehensive framework for anticipatory planning and risk mitigation in football based on lessons from COVID-19. Biol Sport. 2024;41(4):317–335.

Received: 2024-09-05; Reviewed: 2024-09-22; Re-submitted: 2024-09-29; Accepted: 2024-09-30; Published: 2024-10-10.

Key words:
Athlete health
Contact
Epidemiology
Event management
Infection control
Infectious disease
Monkeypox
Mpox
MPXV
Orthopoxvirus
Pandemic preparedness
Risk assessment
Sports medicine

LIST OF ABBREVIATIONS

AI: artificial intelligence
CLIA: chemiluminescent immunoassay
COVID-19: coronavirus disease 2019
ELISA: enzyme-linked immunosorbent assay
EPA: environmental protection agency
FIFA: Fédération Internationale de Football Association
HIIT: high-intensity interval training
LFA: lateral flow assay
MPXV: monkeypox virus
PHEIC: public health emergency of international concern
PPE: personal protective equipment
RT-PCR: reverse transcription polymerase chain reaction
SEIRS-V: susceptible-exposed-infected-recovered-susceptible-vaccinated
UEFA: Union of European Football Associations
WHO: World Health Organization

INTRODUCTION

Mpox (previously known as monkeypox) is a disease that can be transmitted between animals and humans [1, 2]. It is caused by a specific virus called monkeypox virus (MPXV), which belongs to the Orthopoxvirus genus in the Poxviridae family [1]. In humans, the disease typically has an incubation period of 5–21 days and subsequently advances through two distinct phases (the prodromal phase and the rash phase, with the latter characterized by evolving skin lesions) [1, 3]. In May 2022, the World Health Organization (WHO) reported an occurrence of human mpox in multiple nations that had previously been free of the disease [4]. According to Centers for Disease Control and Prevention data (dated March 1, 2023), there have been 86,231 confirmed cases of mpox and 105 deaths reported from 110 countries and territories worldwide [5]. Importantly, over 90% of these nations were reporting mpox for the first time [6]. As of September 22, 2024, the total number of lab-confirmed cases of mpox has risen to 106,310 (234 total lab-confirmed deaths and 123 countries reporting cases) [7]. A phylogenetic study indicated that this outbreak was linked to the virus originating from the West African clade [8]. Phylogenetic studies have identified two distinct clades of MPXV: the Congo Basin clade and the West African clade, with the latter being responsible for the 2022 global outbreak [8]. Nevertheless, most of the individuals in this outbreak did not have any proof of having travelled to locations in Central or West Africa, where MPXV is commonly found [9]. The main factor contributing to this outbreak in humans was the spread of the virus through close physical contact among males who engage in sexual activity with other males [9]. The shifting epidemiology of mpox has prompted concerns regarding its increasing transmission in non-endemic nations and the pressing necessity to manage and avert its spread.

On August 14, 2024, the WHO declared that "the rise in mpox cases constitutes a public health emergency of international concern (PHEIC)" [6]. The transmission of mpox between humans primarily occurs through close physical contact, respiratory droplets, and contaminated objects [10–13]. The virus can spread through direct contact with skin lesions, bodily fluids, or respiratory secretions of infected individuals [11–14]. Indirect transmission via contaminated materials such as bedding, clothing, or shared objects is also possible [11–13, 15]. The prolonged incubation period of up to 21 days poses significant challenges for containment efforts [16]. During this relatively long period, infected individuals may unknowingly spread the virus, complicating contact tracing and early intervention strategies [16]. This extended asymptomatic period increases the risk of widespread transmission before symptoms become apparent [16]. The latter is particularly concerning in some specific environments, e.g. the sporting environment, where athletes are typically in contact with each other on a daily basis, let alone the crowds that gather to attend sporting competitions. Indeed, research has highlighted the potential for asymptomatic or pre-symptomatic transmission of mpox, which could have significant implications for sports settings [17]. The rising transmission rates of mpox are of growing concern for the sports world. Football, as a high-contact sport with global appeal, serves as an ideal case study for examining the potential impact of mpox on sports. The frequent physical interactions between players, shared equipment, and mass gatherings associated with football events can create unique challenges for disease prevention and control [17]. While, as of late September 2024, it's less infectious than coronavirus disease 2019 (COVID-19), the potential for viral mutations [18] and increased infectivity could have severe implications for athletic activities [19]. The transmission methods of mpox are particularly worrisome in sports contexts. Skin-to-skin contact, common in contact sports and among some spectators, presents a higher risk compared to the primarily respiratory transmission of COVID-19, and mass gathering events, both for athletes and fans, and creates environments conducive to viral spread [17]. Unlike COVID-19, where wearing face masks provided some protection, the skin contact transmission route of mpox makes such measures ineffective [17].

The sports community faces unique challenges in addressing the mpox threat. While lessons learned from COVID-19 could provide valuable insights, their applicability may be limited due to the differing transmission mechanisms of mpox [17]. Contact sports, in particular, might face significant risks due to the frequent skin-to-skin contact between athletes. Although vaccines show promise, vaccine hesitancy remains high, partly due to concerns stemming from COVID-19 vaccine side effects [20]. The potential for a mpox pandemic raises questions about the feasibility and impact of lockdowns on sporting events and athlete training regimens [21].

To the best of the authors' knowledge, this study presents the first comprehensive conceptual framework for understanding the potential impact of mpox on the sports world. Addressing the identified research gaps, including the lack of sport-specific transmission data, limited understanding of the virus's behaviour in the athletic environments, and absence of tailored prevention strategies for sports settings, our conceptual study aims to: *(i)* analyse the pathophysiology and transmission mechanisms of mpox in sports environments, with a particular emphasis on football as a representative of high-contact sport; *(ii)* develop and evaluate tailored epidemiological strategies for sports, including risk assessment, testing protocols, hygiene measures, return-to-play policies, and spectator management; *(iii)* examine the potential impact of mpox on sports activities, encompassing physical health, performance considerations, and implications for events and training regimens; and *(iv)* assess the public health implications and propose preparedness strategies for managing potential pandemics in sports settings, drawing on experiences from the COVID-19 pandemic.

PATHOPHYSIOLOGY AND TRANSMISSION OF MPOX

Mpox follows a complex pathophysiological progression [13]. The disease course can be divided into three distinct phases: *i)* incubation (lasting 5–21 days), *ii)* prodromal (1–5 days), and *iii)* exanthem (2–4 weeks) [22]. The prodromal phase is characterized by systemic

symptoms including fever, malaise, myalgia, and lymphadenopathy [22]. The exanthem phase involves the development of a characteristic rash, progressing from macular lesions to papules, vesicles, and pustules before crusting and desquamation [23]. This prolonged disease course and the potential for asymptomatic transmission create potential challenges challenges for containment in sports settings.

The virus spreads primarily through close contact with infected persons, animals, or contaminated materials, entering the body via broken skin, the respiratory tract, and/or mucous membranes [24]. Football, as the world's most popular sport, with extensive global participation and spectatorship, serves as an ideal model for examining the potential impact of mpox in sports settings. Its widespread practice, high-contact nature, and the lessons learned from COVID-19 management in football provide a comprehensive framework for analysis [25]. Importantly, transmission can occur through skin-to-skin contact even before visible lesions appear, significantly increasing the risk in sports settings. In football, the frequent close physical contact during tackles, aerial duels, or on-field celebrations could potentially facilitate virus transmission, even in asymptomatic cases [26]. This risk extends to other contact sports, including combat (e.g. boxing, karate, silat, and wrestling) and team (e.g. rugby, hockey, volleyball, and basketball) sports with similar levels of physical interaction [26].

Direct physical contact with skin, regardless of visible lesions, or bodily fluids of an infected individual is a key transmission route. This applies to football, where players frequently come into close physical contact during matches and training sessions. The risk then extends beyond obvious skin lesions to include contact with seemingly healthy skin of infected individuals [27]. Moreover, MPXV can persist on surfaces and objects, creating the potential for indirect transmission [28]. In football, shared equipment such as balls, training bibs, or even goalposts could become vectors for the virus, emphasizing the need for rigorous cleaning protocols in training facilities and stadiums. Figure 1 summarizes the various transmission pathways of MPXV including zoonotic transmission from animals to humans, and both horizontal and vertical transmission between humans.

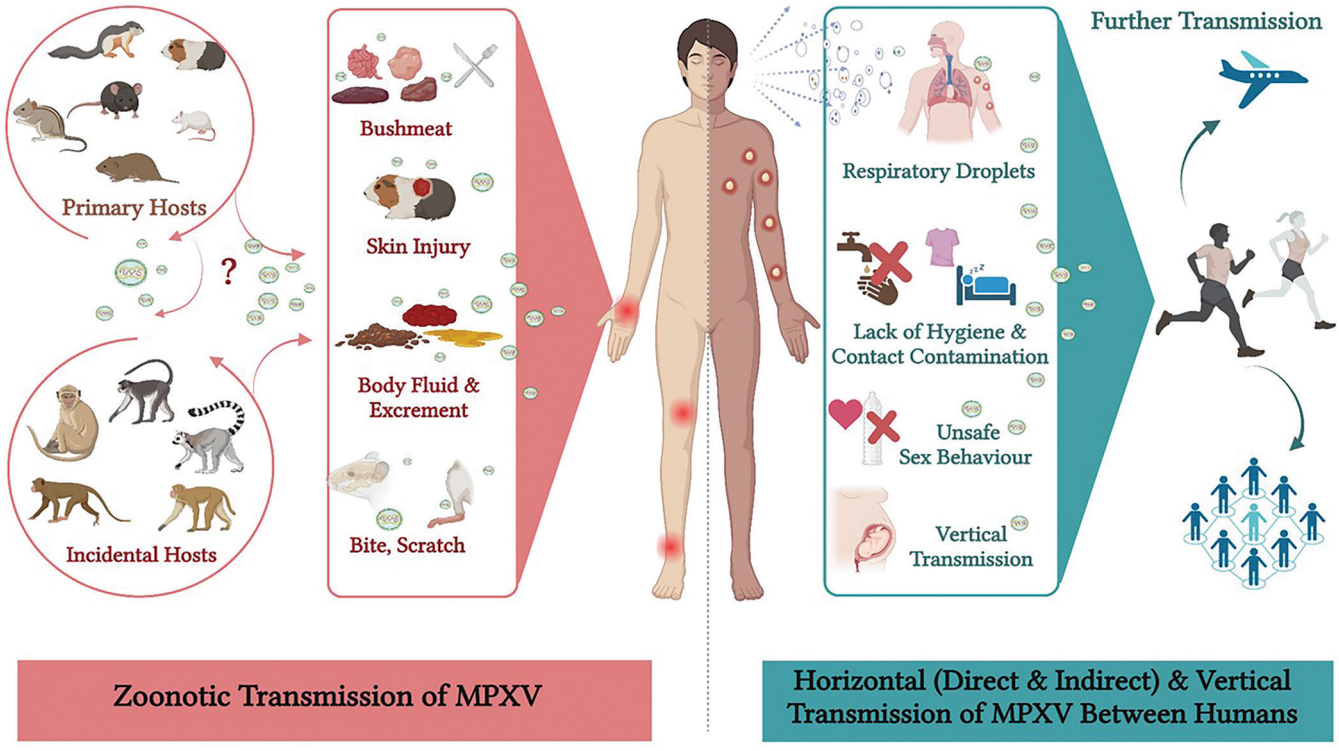


FIG. 1. Zoonotic and human-to-human transmission of mpox virus (MPXV) (created with Biorender.com) [11-13].
This figure illustrates the transmission pathways of mpox, including both zoonotic and human-to-human routes.
Zoonotic transmission occurs when humans encounter infected animals (primarily rodents and primates) through direct interaction, animal bites, scratches or exposure to bodily fluids, as well as through the consumption of contaminated bushmeat.
Human-to-human transmission can be categorized into horizontal and vertical routes. Horizontal transmission includes skin-to-skin contact, exposure to contaminated materials, and inhalation of respiratory droplets. Vertical transmission refers to the transfer of the virus from mother to fetus. The understanding of these transmission pathways is crucial for the development and implementation of effective prevention and control strategies (see Figure 2).

While both mpox and COVID-19 are contagious diseases, their transmission mechanisms differ substantially [29]. COVID-19 spreads primarily through respiratory droplets and aerosols, with very few prospective risks in the sports environment [30], whereas mpox relies more on direct physical contact, including skin-to-skin contact without visible symptoms [31]. This distinction is crucial for developing targeted prevention strategies in football and other sports environments. Notably, the COVID-19 pandemic caught the sports world largely unprepared, as there was no recent precedent for such a global health crisis in early 2020 [32]. In contrast, we expect that the experience gained from managing COVID-19 has better equipped sports organizations and policymakers to respond to the potential threat of mpox [32, 33]. Table 1 provides a detailed comparison of COVID-19 and mpox, highlighting key differences relevant to transmission, management, and preparedness in sports settings.

The incubation period for mpox ranges from 5 to 21 days, with most cases showing symptoms within 7 to 14 days [34]. This extended period creates challenges for containment, as players or staff may unknowingly spread the virus before any symptoms or skin lesions appear [34]. These factors complicate the management of sporting events, tournaments, and training schedules across all contact sports, necessitating careful monitoring and preventive measures even for seemingly healthy individuals [35]. While our analysis focuses on football as a representative example, the principles and challenges discussed apply to a wide range of sports, particularly those involving close physical contact [36]. For football clubs and organizations, this approach emphasizes the importance of comprehensive prevention strategies that account for asymptomatic transmission, alongside adaptive measures to mitigate the potential spread of mpox while maintaining competitive activities.

EPIDEMIOLOGICAL CONSIDERATIONS IN SPORTS

Risk assessment and contact analysis

In football, the close-contact nature of play presents unique challenges for controlling MPXV transmission. To address this, we can adapt advanced epidemiological tools and integrate them with existing sports technology [37]. Enhanced global positioning system tracking systems, augmented with proximity sensors and biometric data, can create detailed, multi-dimensional contact matrices that account for the intensity, duration, and physiological context of player interactions [38]. These matrices can be analysed using machine learning algorithms and social network analysis to identify potential transmission hotspots and "super-spreader" positions. Machine learning algorithms can play a dual role: first, in research settings to analyse and identify patterns of transmission in sports environments, and second, in the development of systems that can be integrated into competitive

TABLE 1. Comparison of coronavirus disease 2019 (COVID-19) and mpox in sports settings.

Characteristic	COVID-19	Mpox
Primary transmission	Respiratory droplets and aerosols	Direct physical contact, including skin-to-skin
Incubation period	2-14 days (average 5-6 days)	5-21 days (average 7-14 days)
Infectiousness	1-2 days before symptom onset	Primarily after symptom onset, but possibly before rash appears
Main symptoms	Fever, cough, fatigue, loss of taste/smell	Fever, rash, lymphadenopathy
Risk in sports	High in indoor, close-contact settings	High in all contact sports, including outdoor
Surface transmission	Possible, but not primary route	More significant risk from contaminated items
Asymptomatic spread	Common	Less common, but possible before the rash appears
Vaccination	Widely available No sport-specific protocols	Limited availability No sport-specific protocols yet (Late September 2024)
Isolation period	Typically, 5-10 days from symptom onset	Until all lesions have crusted and fallen off (2-4 weeks)
Impact on sports events	Widespread cancellations and adaptations	Limited impact so far (Late September 2024), but potential for significant disruption
Prior pandemic experience	No recent precedent, the sports world unprepared	COVID-19 experience should better inform preparedness and decision-making
Risk of mutation	High, led to multiple variants of concern	Low, but the potential exists for increased transmissibility
Policy readiness	Policies developed reactively	Opportunity for proactive policy development and preventative measures mechanisms implementation based on COVID-19 experience

games and tournaments [37]. These systems could be used for real-time monitoring of player interactions, helping to identify potential transmission hotspots during matches and practices, thereby enabling more responsive and targeted interventions [37]. The SEIRS-V (for susceptible-exposed-infected-recovered-susceptible-vaccinated) model is an epidemiological compartmental model that includes vaccination status, allowing for more nuanced predictions in partially immunized populations [39]. A football-specific SEIRS-V model, incorporating factors such as varying transmission rates between training and matches, player positions, and crowd presence, can be developed to estimate position-specific and situation-specific R0 values [40]. Environmental sampling for fomite transmission risk can be integrated into spatiotemporal models.

Testing protocols and symptom monitoring

Mpox testing and monitoring in football should follow a tiered, risk-based approach triggered by specific epidemiological indicators. Initial efforts should focus on enhanced symptom vigilance and basic skin examinations by trained medical staff. If mpox cases are reported in the general population or sports communities, a more intensive protocol should be activated [41]. Mpox infection diagnosis relies on both direct and indirect methods. Nucleic acid amplification tests, particularly reverse transcription polymerase chain reaction (RT-PCR), are widely used for direct detection of viral DNA sequences [41]. In resource-limited settings, pooled sample RT-PCR offers a cost-effective surveillance approach, building on the widespread availability of RT-PCR technology from the COVID-19 pandemic. Indirect tests, which detect the patient's immune response, include lateral flow assays (LFAs) for detection of Orthopoxvirus immunoglobulins M and G. However, these tests have limitations, such as undetected convalescent samples and cross-reactivity with poxvirus vaccines [41, 42]. While LFAs are rapid and suitable for point-of-care use, they are less accurate than laboratory-based methods such as enzyme-linked immunosorbent assay (ELISA) and chemiluminescent immunoassay (CLIA). ELISA and CLIA offer higher sensitivity and specificity for antibody and antigen detection but require specialized laboratory infrastructure and low-temperature logistics, which may be challenging in low-resource countries [41]. LFAs for mpox antigen detection show promise as a low-cost, rapid alternative but require rigorous validation before widespread implementation in public health surveillance and diagnosis [41, 42].

When handling mpox specimens in the laboratory, strict biosafety measures are essential to prevent accidental exposure and contamination [43]. Samples from identical lesion types can be combined, but those from different types should be kept separate. It is beneficial to gather various lesion types from multiple sites simultaneously. In addition to skin lesions, swabs from the oropharynx, anus, and rectum can be used to detect mpox. However, oropharyngeal results should be interpreted with caution due to limited clinical data [44].

This could include periodic random sampling using polymerase chain reaction (PCR) tests on skin lesion samples or throat swabs from a subset of players and staff [45], prioritizing those with higher risk exposures. Serological surveys might be conducted quarterly to assess team immunity levels, detecting antibodies against mpox [46]. Advanced techniques such as artificial intelligence (AI)-powered dermatological imaging or CRISPR (for clustered regularly interspaced short palindromic repeats)-based diagnostics would only be deployed if cases were confirmed within the football community or if there was a significant outbreak in the surrounding area [47]. This adaptive strategy will ensure that resources are used efficiently, scaling up monitoring efforts only when epidemiological data justify increased vigilance, thus balancing cost-effectiveness with comprehensive disease surveillance.

Hygiene measures and surface decontamination

To address the prolonged surface persistence of MPXV in football environments, a multi-layered decontamination strategy is essential. High-touch areas and shared equipment should be prioritized, using EPA (environmental protection agency)-registered disinfectants effective against enveloped viruses [48]. Ultraviolet C irradiation systems could be installed in locker rooms and training facilities for overnight sanitization [49]. For textiles, implementing rigorous laundry protocols with high-temperature washing and the addition of virucidal laundry sanitizers is crucial. To reduce reliance on frequent cleaning, antimicrobial surfaces such as copper alloys could be strategically implemented in high-contact areas. For medical staff and players, a risk-stratified approach to personal protective equipment (PPE) should be adopted, with standard precautions for routine interactions and enhanced protection, including respirators, for close-contact treatments or when handling potentially infectious materials [50].

A decontamination strategy for sports facilities in low-resource countries should include regular disinfection of high-touch surfaces, education on hygiene practices, and tracking cards to monitor cleaning schedules. Providing basic protective equipment and raising awareness about proper disposal of contaminated materials are also crucial for effective implementation. Table 2 outlines decontamination strategies for sports facilities that are applicable in all settings, including resource-constrained countries [51–60].

Gradual return to play and adaptive policies

A phased return-to-play protocol, similar to those used after COVID-19 [26, 61], but tailored to mpox's longer incubation period (up to 21 days), might be necessary. This approach could involve extended quarantine periods for exposed individuals and a gradual reintegration process monitored by sports medicine professionals. Policies should be adaptive, potentially utilizing Bayesian decision-making frameworks that can quickly incorporate new epidemiological data. Mpox's longer incubation period necessitates a carefully structured return-to-play protocol in football [62]. This protocol should be risk-stratified, considering the player's exposure level, vaccination status, and team outbreak situation. A minimum 21-day observation period for

TABLE 2. Inclusive decontamination strategies for indoor sports facilities [51-60].

Strategy	Details
Enhance ventilation	• Open windows/doors • Use low-cost fans • Improve air circulation • Increase heating, ventilation, and air conditioning filter changes
Establish equipment sanitization protocols	• Create schedules for cleaning shared equipment using affordable disinfectants with clear instructions
Install handwashing stations and/or hand sanitizers	• Place stations at key locations • Use portable stations with foot operation if water is limited
Use disinfectant mats at entrances	• Install durable mats for footwear decontamination • Regularly replace the disinfectant solution
Manage facility capacity	• Implement staggered scheduling • Occupancy limits • Extend hours to reduce crowding
Implement proper waste management	• Place labelled, covered bins for waste • Regularly empty and sanitize receptacles
Create designated "clean" and "used" areas	• Implement a system for collecting, cleaning, and redistributing shared items like towels • Encourage personal hygiene behavior
Choose easily cleanable surfaces	• Opt for smooth, non-porous equipment surfaces or apply cleanable coatings
Conduct regular staff training and periodic assessments	• Provide training on cleaning, personal protective equipment usage, and safety protocols, with periodic updated courses • Regularly audit decontamination measures and seek feedback for improvements
Display clear, multilingual signage	• Use graphic-based instructions for hygiene protocols • Place signs in key areas
Utilize ultraviolet-C light disinfection	• Use ultraviolet-C light for small items or hard-to-clean areas if budget allows
Develop a contact tracing system	• Maintain facility usage logs and implement a check-in process for outbreak management

exposed individuals is advisable, with a gradual reintegration process involving staged increases in training intensity and group size [63]. A multidisciplinary team including infectious disease specialists and sports medicine professionals should oversee this process. To ensure flexibility, the protocol could employ a Bayesian decision-making framework, allowing real-time adjustments based on new epidemiological data, testing results, and player health metrics [64].

Spectator management strategies

Unlike COVID-19, where respiratory transmission was the primary concern, mpox poses additional challenges due to potential skin-to-skin transmission. Social distancing measures in stadiums might need to be more stringent, potentially utilizing hexagonal or honeycomb seating arrangements to maximize interpersonal distance [12]. Entry screening could include visual skin checks or thermal imaging to detect fever. Stadiums might need to implement enhanced ventilation systems with HEPA filtration and ultraviolet sterilization to reduce airborne transmission risk. Spectator management for mpox in football requires innovative approaches beyond those used for COVID-19 [65]. Given the risk of skin-to-skin transmission, stadium seating could be redesigned using algorithmic models to maximize interpersonal distance while maintaining capacity. Digital ticketing systems could be used to create "social bubbles" allowing groups that regularly interact to sit together while maintaining distance from others. Recent studies have shown the effectiveness of social bubbles in reducing disease transmission [66]. Entry protocols might include non-invasive screening methods such as AI-powered visual skin anomaly detection, complemented by thermal imaging. To mitigate fomite transmission, stadiums could implement contactless technologies for all fan interactions, from entry to concessions. Environmental controls should focus on both air and surface management, potentially incorporating photocatalytic oxidation systems for continuous disinfection [67]. Fan education campaigns, emphasizing the unique transmission routes of mpox, would be crucial for compliance with these measures. While we propose various technologically advanced solutions, it is important to acknowledge that implementation may be challenging or impossible for many countries due to financial constraints or infrastructure limitations [67]. These suggestions represent ideal scenarios and should be adapted based on local resources and capabilities.

Data collection and analysis

Implementing a comprehensive syndromic surveillance system across leagues could provide early warning of potential outbreaks [68]. This approach could involve real-time data integration from multiple sources including team medical staff, local health authorities, and even crowd-sourced symptom tracking apps. Advanced machine learning algorithms could be employed to detect anomalous patterns indicative of emerging clusters [68]. A football-specific syndromic surveillance system for mpox would integrate diverse data streams to detect outbreaks early. This system could combine traditional epidemiological data with sport-specific metrics. While not directly related to mpox transmission, changes in player performance, training load tolerance, and recovery times could potentially serve as early indicators of subclinical infection or exposure [69]. Machine learning algorithms, particularly anomaly detection models, could be trained to identify subtle patterns indicative of potential mpox spread. The system could incorporate genomic surveillance, tracking viral mutations that might affect transmissibility or virulence within the football community [70]. To enhance sensitivity, a network of sentinel sites could be established across different leagues and levels of play. This approach would not only serve as an early warning system but also contribute to our understanding of mpox transmission dynamics in high-performance athletic settings [71]. The surveillance system should be designed with data privacy in mind, using secure, anonymized data sharing protocols to protect player and team confidentiality while still allowing for an effective public health response.

International coordination

Given the potential for cross-border transmission, establishing a global football-specific health information system could be vital. This could function similarly to the WHO's global outbreak alert and response network, but tailored to the specific needs and rapid movement patterns of international football [72]. A global football-specific health information system for mpox would need to address the challenges presented by the sport's international nature. This system could leverage existing football networks such as the Fédération Internationale de Football Association (FIFA) and continental confederations to create a rapid alert mechanism for potential outbreaks [73]. It should incorporate real-time travel data of teams and officials, allowing for quick contact tracing across borders. The system could utilize blockchain technology to ensure secure, transparent sharing of health data while maintaining player privacy. A standardized risk assessment tool, tailored to football-specific scenarios, could be integrated to help decision-makers evaluate the safety of international matches and tournaments [74]. This global system should also facilitate rapid sharing of best practices and emerging research relevant to mpox in sports settings [75]. To ensure effectiveness, it should be designed with input from epidemiologists, sports medicine experts, and football governing bodies, creating a collaborative approach to global health security in football.

Mental health support

The psychological impact of another disease outbreak could be significant. Implementation of regular mental health screenings using validated tools such as the Athlete Psychological Strain Questionnaire could be beneficial [76, 77]. Telepsychiatry services could be made readily available to players and staff. Addressing the mental health implications of an mpox outbreak in football requires a proactive, multifaceted approach. Beyond regular screenings, a comprehensive mental health strategy could include the development of a sport-specific psychological resilience training programme [78], focusing on coping mechanisms for disease-related stress and uncertainty. This could be integrated into regular team training sessions [79]. Peer support networks could be established, leveraging the team dynamics to create a culture of openness about mental health. To address potential stigma associated with mpox, educational programmes should be implemented, emphasizing factual information and dispelling myths. While advanced technologies such as AI-driven chatbots for mental health support may not be immediately implementable in many contexts, especially in developing countries, it is crucial to consider more accessible and cost-effective alternatives [80]. For instance, establishing a network of trained peer support volunteers within sports organizations could provide initial mental health triage and guidance to appropriate resources. Collaboration with local mental health professionals, including sports psychologists and psychiatrists familiar with infectious disease-related trauma, could help develop tailored interventions for athletes dealing with pandemic-related anxiety or depression [81]. These strategies, while ambitious, are designed with long-term preparedness in mind, recognizing that implementation may vary significantly based on resources and infrastructure available in different regions [82, 83].

Vaccination strategies

Vaccination strategies for mpox in football face significant challenges, largely stemming from the contentious experiences with COVID-19 vaccines [84]. The football community's hesitancy is deeply rooted in the aftermath of the previous pandemic, where widespread concerns about vaccine side effects and long-term impacts emerged [81]. During the COVID-19 vaccination campaigns, reports of adverse events among athletes garnered significant attention. Cases of myocarditis, particularly in young male athletes, sparked intense debate and concern [85]. While rare, these incidents were highly publicized, leading to amplified fears within the sports community [86]. Some players reported experiencing fatigue, reduced performance, and prolonged post-vaccination recovery times, further fuelling scepticism [87].

The rapid development and emergency authorization of COVID-19 vaccines led to concerns about insufficient long-term safety data [88]. This worry is particularly acute among athletes, whose careers depend on peak physical condition and longevity [88]. The notion of introducing a novel medical intervention into finely tuned athletic bodies has met resistance from players and medical staff alike [89]. Conspiracy theories and misinformation, which spread rapidly through

TABLE 3. Vaccination strategies for a potential mpox pandemic in sports.

Strategy	Implementation	Expected outcome
Tailored communication	• Athlete-specific messaging • Use player ambassadors • Share personal stories	• Increased vaccine acceptance through peer influence
Address specific concerns	• Studies on performance effects • Clear safety information • Transparent reporting	• Alleviation of fears about performance and health impacts
Cultural sensitivity	• Work with cultural leaders • Culturally appropriate info • Personal choice framework	• Improved acceptance among diverse player groups
Alternative protocols	• Robust testing for unvaccinated • Incentives for vaccinated	• Maintained team safety while encouraging vaccination
Long-term monitoring	• Ongoing health monitoring • Transparent data sharing	• Address concerns about future effects, demonstrate player welfare commitment

social media and even among some high-profile athletes, have left a lasting impact. Claims about vaccines affecting fertility, altering DNA, or being part of larger control agendas, though debunked, continue to resonate with a segment of the population, including some in the football world [90].

The perceived pressure to vaccinate during the COVID-19 pandemic, sometimes linked to ability to play or travel, led to feelings of coercion among some athletes [91, 92]. This has created a backdrop of mistrust towards health authorities and team management when it comes to vaccination policies [93]. Reports of breakthrough infections among vaccinated individuals during the COVID-19 pandemic have led some to question the efficacy of vaccines altogether. This scepticism may carry over to mpox vaccines, particularly if early data show anything less than perfect protection [94]. Moreover, the evolving nature of COVID-19 vaccines, with multiple boosters becoming necessary, has led to fatigue and scepticism about the long-term commitment required for vaccination programmes [94, 95].

The global disparity in vaccine access during the COVID-19 pandemic also created tensions, particularly in international football, where players from different countries had vastly different experiences with vaccine availability and mandates [96]. These compounding factors from the COVID-19 experience present a formidable challenge for potential mpox vaccination strategies in football. The memory of adverse events, the spread of misinformation, and a general wariness towards rapidly developed vaccines create a landscape where achieving high vaccination rates may be significantly more difficult than anticipated [97]. This hesitancy could potentially undermine efforts to establish effective herd immunity within the football community, leaving the sport vulnerable to mpox outbreaks [97]. To address these challenges, a multi-faceted approach is necessary, as outlined in Table 3.

It is important to note that while we propose various advanced technological solutions, including AI-driven mental health support, many of these recommendations may not be feasible in the immediate future, especially in resource-limited settings [98]. This framework is designed not only for potential mpox outbreaks but also as a long-term preparedness strategy for future pandemics that may emerge in the coming decades [99]. The implementation of these measures should always consider the diverse economic realities across different countries and aim for equitable, adaptable solutions [99].

POTENTIAL IMPACT OF MPOX ON SPORTS ACTIVITIES

Physical health considerations

Mpox infection bring about particular concerns to athletes' physical health, distinct from those observed with COVID-19. The primary physical health considerations include the impact of skin lesions on performance, systemic effects on endurance, and potential long-term consequences [100]. Skin lesions, a hallmark of mpox, can significantly impair athletic performance, especially in sports requiring extensive skin contact or equipment use. These lesions may affect grip strength, dexterity, and mobility, factors crucial for many sports. Moreover, the risk of secondary bacterial infections in lesions may increase due to sweating and physical contact inherent in sports activities [17].

The systemic effects of mpox, including fever, fatigue, and muscle aches, can severely influence an athlete's endurance and overall physical capacity [17]. Lymphadenopathy, typical of mpox, may affect mobility and comfort, particularly in sports requiring a full range of motion. While less prominent than in COVID-19, respiratory symptoms can occur, potentially affecting cardiovascular endurance and performance in aerobic sports [3, 17].

Dehydration and thermoregulation present additional concerns. The fever associated with mpox, combined with physical exertion, may increase the risk of heat-related illnesses. Athletes may need to pay extra attention to hydration and cooling strategies during recovery. Nutritional challenges may arise due to potential appetite loss

during infection, leading to unintended weight loss and muscle wasting [101]. This necessitates careful nutritional management during and after recovery to maintain optimal body composition and performance. Indeed, long-term physical effects of mpox in athletes remain largely unknown [17]. Potential concerns include scarring from lesions, which could affect sports with aesthetic components. Possible lingering fatigue or weakness may require extended rehabilitation periods. The stress on the immune system may also leave athletes more susceptible to other infections or injuries in the short term after recovery [102].

While less common than in COVID-19, cardiovascular complications should be monitored, especially given the high cardiovascular demands of many sports. Rare ophthalmological involvement could have significant implications for sports requiring precise vision and eye-hand coordination [103].

The physical health considerations of mpox in athletes accentuate the need for sport-specific medical protocols and individualized assessment. Gradual return-to-play strategies, taking into account the unique demands of each sport and the specific manifestations of the disease in each athlete, will be crucial.

Mental health impact

The mental health consequences of mpox for athletes result in particular difficulties, unlike other infectious diseases, particularly due to the visible nature of its symptoms and the potential stigma associated with the infection [104]. These factors could significantly affect an athlete's psychological well-being, self-image, and overall mental state.

The presence of visible skin lesions due to mpox can be particularly distressing for athletes, who often have a heightened awareness of their physical appearance. This visible manifestation of the disease may lead to increased anxiety, depression, and self-consciousness [3]. Athletes in sports with aesthetic components or those who rely heavily on sponsorships and public image may experience amplified psychological distress. Stigma and misconceptions surrounding mpox can exacerbate mental health challenges [105]. The initial association of the 2022 outbreak with specific communities may lead to unwarranted discrimination or prejudice. Athletes may fear social isolation or judgment from teammates, competitors, or the public, potentially affecting their social support systems and overall well-being [106].

The uncertainty surrounding the long-term effects of mpox on athletic performance can be a significant source of stress and anxiety. Athletes may worry about their ability to return to pre-infection performance levels, potentially leading to feelings of frustration, helplessness, or loss of identity tied to their athletic capabilities [107]. Isolation periods required for infection control can contribute to feelings of loneliness and a sense of disconnect from the team. Being away from regular training and competition environments may exacerbate existing mental health symptoms/issues or introduce new ones, particularly for athletes who rely heavily on a structured schedule and routines for their psychological well-being [33, 106].

The potential impact on career trajectories, especially for athletes in time-sensitive competitive phases or nearing the end of their careers, can lead to heightened stress and anxiety. Concerns about missed opportunities, contract negotiations, or selection for major competitions may weigh heavily on infected athletes [108].

Coping with the physical symptoms of mpox, including fever, fatigue, and pain from skin lesions, can also take a psychological toll. The discomfort and potential pain associated with the infection may lead to mood disturbances, irritability, and decreased motivation. A well-prepared medical staff should support the athletes in managing these issues.

Performance implications and training adaptations during potential infection, quarantine or lockdown

The impact of mpox on athletic performance and the necessary training adaptations present unique challenges that differ significantly from those encountered during the COVID-19 pandemic [17]. Mpox infection creates particular challenges to athletic performance, necessitating careful consideration of both immediate and long-term impacts on training and competition readiness. In the immediate aftermath of infection, athletes may experience significant deconditioning due to the systemic effects of mpox, including fever, fatigue, and muscle pain [109]. This deconditioning can lead to reductions in aerobic capacity, strength, and sport-specific skills. However, the presence of skin lesions introduces an additional layer of complexity to performance management and training adaptations compared to COVID-19 for instance [110].

Indeed, skin lesions can substantially impair an athlete's ability to perform, especially in sports requiring extensive skin contact or fine motor control [111]. These lesions may cause discomfort or pain during movement, potentially altering biomechanics (technique) and increasing the risk of secondary injuries. Moreover, the psychological impact of visible lesions may affect an athlete's confidence and mental readiness to return to training and competition [112].

Training prescriptions for mpox-infected athletes must be carefully tailored to account for these skin-related challenges. Low-impact cardiovascular exercises that minimize friction on affected skin areas would become crucial. For instance, stationary cycling or rowing may be preferable to running or contact sports during the recovery phase [17]. Strength training protocols need modification to avoid putting pressure on lesions, potentially emphasizing isometric exercises or exercises that target unaffected body parts [17].

Flexibility and mobility work take on heightened importance in the context of mpox recovery. Skin lesions may lead to stiffness or a restricted range of motion in affected areas [17]. Gentle stretching and mobility exercises, carefully executed to avoid irritating healing lesions, could help maintain joint flexibility and prevent the development of compensatory movement patterns that might lead to future injuries [109].

The application of high-intensity interval training (HIIT) in mpox recovery requires careful consideration [113]. While HIIT proved

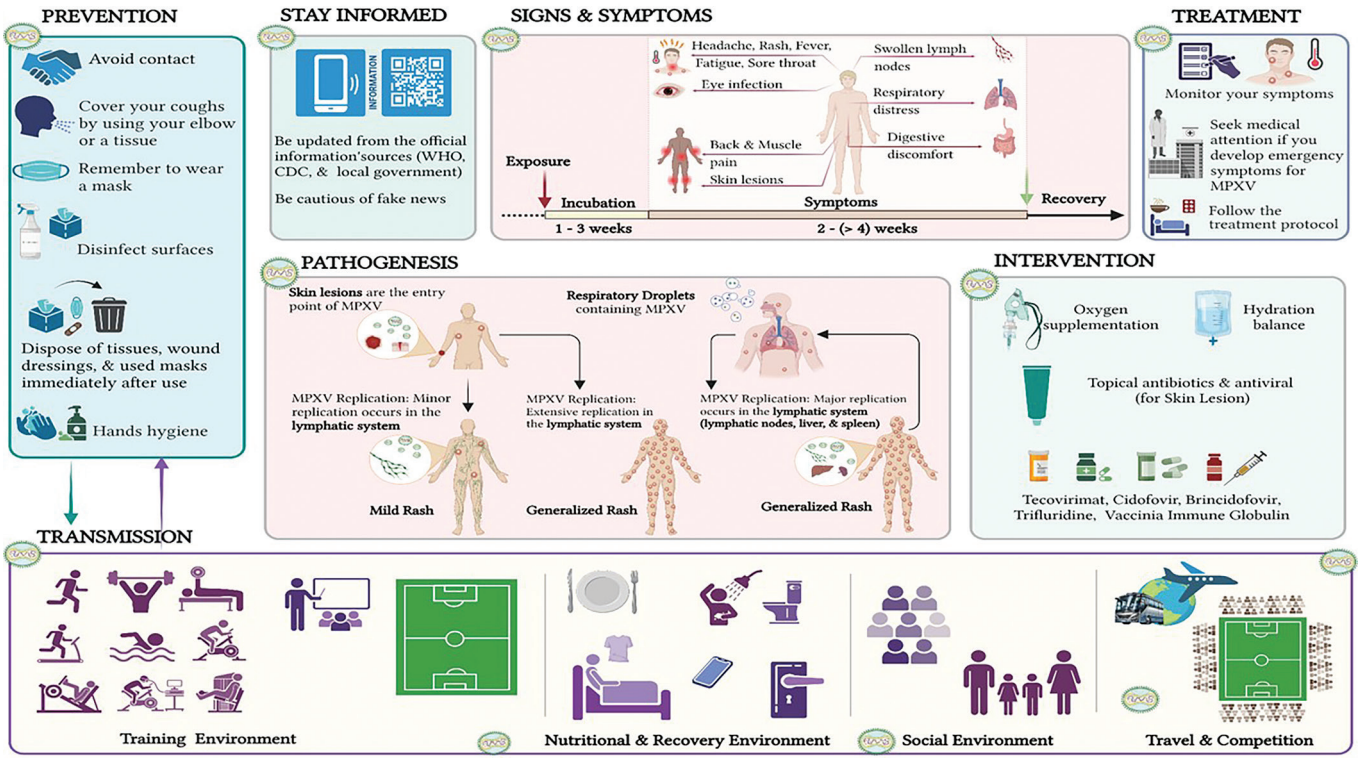


FIG. 2. Comprehensive overview of mpox virus (MPXV) transmission, symptoms, pathogenesis, prevention, and management in football players' environments (created with Biorender.com) [117-122].

CDC: Centers for Disease Control and Prevention. WHO: World Health Organization.

The figure provides a comprehensive overview of mpox transmission, clinical symptoms, pathogenesis, and management, with a specific focus on football players and sports environments.

Transmission pathways include horizontal transmission through direct human-to-human contact and indirect transmission from contaminated environments and surfaces. Football players face specific risks due to skin-to-skin contact during match play or training, respiratory droplet transmission in close quarters (e.g. locker rooms, restaurants), and indirect/fomite transmission via shared sports equipment, clothing, and surfaces.

Prevention and safety measures are crucial in mitigating the spread of mpox in sports settings. These include isolating infected individuals, using PPE, implementing proper hygiene practices, disinfecting shared equipment, and regularly sanitizing sports facilities.

Reliable information on mpox is crucial. Local government agencies, the CDC and the WHO provide up-to-date, evidence-based guidance on transmission, prevention, and management of this disease. Athletes, coaches, and sports organizations should regularly consult these official sources for the latest developments and best practices. Avoiding misinformation is essential for appropriate response and prevention strategies.

The clinical symptoms of mpox progress from initial symptoms such as fever, fatigue, and lymphadenopathy to the development of a skin rash that spreads across the body. These symptoms can significantly influence athletic performance and participation.

The pathogenesis of mpox in athletes involves viral invasion and replication in the body, leading to systemic and localized symptoms. Skin lesions and fatigue can particularly affect physical endurance and overall athletic performance.

Emergency clinical support and treatment. Athletes developing symptoms of mpox should seek immediate medical attention. Emergency clinical support may include isolation to prevent further transmission, symptomatic treatment, and oxygen supplementation if respiratory symptoms are severe, addressing dehydration through fluid replacement, administration of antivirals in severe cases, and use of vaccinia immunoglobulin for complications or severe infections. For skin lesions, topical antibiotics may be recommended to prevent secondary bacterial infections. Antiviral medications may also be applied topically in some cases. Healthcare professionals based on the individual's symptoms, medical history, and disease severity should determine the specific treatment plan. Sports medicine physicians should work closely with infectious disease specialists to provide appropriate care for athletes with mpox while considering the unique needs of sports participation. Understanding the transmission, prevention, and clinical aspects of mpox is essential for maintaining the health and safety of football players, other athletes and the support staff surrounding them. This comprehensive guide is based on research by some authors and organizations. It provides valuable information for understanding mpox's impact on football players and athletes, as well as strategies for prevention and management in sports environments.

valuable during COVID-19 lockdowns for maintaining cardiovascular fitness, its intense nature may exacerbate skin lesions or cause excessive discomfort in mpox patients [113]. A modified approach to interval training, featuring lower intensities and shorter durations, may be more appropriate. As recovery progresses, the intensity and complexity of these sessions can be gradually increased, always with close monitoring of skin condition and overall health status.

The reintroduction of sport-specific training must be approached with caution, particularly in sports involving skin-to-skin contact or shared equipment. Modified drills that limit skin contact should be prioritized in the early stages of return to play [114]. For example, in combat sports, shadow boxing or solo technique work might precede partner drills. In team sports, individual skill work might be emphasized before full team practices resume. Continuous monitoring of skin healing and overall health status is crucial throughout the recovery and return-to-play process. This monitoring should inform a gradual progression in training intensity and complexity. The use of protective gear or specialized clothing may be necessary to shield healing skin during training and early return to competition [115].

The unique challenges presented by a potential mpox outbreak highlight the need for a flexible, individualized approach to athlete management [17]. Sports organizations must develop comprehensive protocols that address not only the physical aspects of recovery, but also the psychological impact of the disease [33]. These protocols should be adaptable, recognizing that the manifestation and recovery from mpox can vary significantly among individuals [17]. As the sports medicine community continues to learn about the long-term effects of mpox on athletic performance, ongoing research and data collection will be crucial [17, 116]. Professional sports science and sports medicine societies such as the European College of Sport Science and the American College of Sports Medicine should feature symposia on mpox at their annual meetings. This knowledge will inform the development of more refined strategies for maintaining athlete health and performance in the face of this emerging infectious disease threat [17].

Figure 2 presents a comprehensive overview of mpox transmission, symptoms, pathogenesis, prevention, and management in football players' environments [117–122].

MANAGEMENT STRATEGIES FOR SPORTS EVENTS

Risk assessment for event continuity

The process of risk assessment for sports events in the context of mpox necessitates a comprehensive and nuanced approach, building upon the valuable global experiences gained during the COVID-19 pandemic [25, 123, 124]. This assessment requires the collaboration of a multidisciplinary team comprising health experts, event organizers, and sports' governing bodies to thoroughly evaluate the potential risks and benefits associated with holding an event [125, 126].

The risk assessment process must consider several key factors, including the current epidemiological situation in both the host location and participating countries, the nature of the sport and the level of physical contact involved, the duration and scale of the event, the availability and effectiveness of preventive measures, and the capacity of local healthcare systems to manage potential outbreaks [127]. These considerations should be weighed carefully against the potential benefits of hosting the event, such as economic impact, social cohesion, and the continuation of sporting traditions.

The Amir Cup 2020 in Qatar serves as a pioneering example of event management during a pandemic [124]. Held at a time when there was no availability of vaccines and with the presence of 20 thousand spectators, it demonstrated the feasibility of safe event execution through the implementation of rigorous testing protocols, strict hygiene measures, and carefully controlled spectator numbers (half of the stadium capacity) [128, 129]. This approach provides a valuable template that can be adapted to address the unique challenges presented by mpox, with additional considerations given to the risks associated with skin-to-skin contact and shared equipment use.

Adaptation vs. cancellation protocols

The decision-making process regarding whether to adapt or cancel a sports event due to mpox should be rooted in a thorough risk-benefit analysis. This analysis must be informed by the latest scientific understanding of the disease, its transmission dynamics, and the effectiveness of available preventive measures [130]. The experiences of major sporting events during the COVID-19 pandemic offer invaluable insights into this complex decision-making process [130].

Adaptation strategies may encompass a wide range of modifications to traditional event formats and procedures. These could include altering competition structures to minimize close contact between athletes, implementing enhanced hygiene protocols and regular health screenings, utilizing controlled "bubble" environments as successfully demonstrated by the National Basketball Association (NBA) and National Hockey League (NHL) during the height of the COVID-19 pandemic, and adjusting event schedules to accommodate potential isolation periods if required [131].

The Union of European Football Associations (UEFA) Europa League's completion in a reduced format in 2020 stands as a testament to the feasibility of adapting major tournaments in the face of infectious disease threats [132]. Similarly, the Tokyo 2020 Olympics, postponed to 2021, exemplified how large-scale, multi-sport events could be conducted safely with the introduction of vaccines, albeit without spectators. These examples provide valuable blueprints for potential adaptations in the context of mpox [133].

Cancellation of an event should be considered as a last resort, to be implemented only when the associated risks demonstrably outweigh the benefits and cannot be adequately mitigated through adaptations. It is crucial to establish clear, predetermined thresholds for cancellation based on objective criteria such as infection rates, the ability to maintain a safe environment for all participants, and the potential for the event to become a vector for disease spread.

Spectator management

The management of spectators in the context of mpox requires a carefully calibrated approach that balances public health imperatives with the desire for fan engagement and the economic considerations of event organizers [134]. The gradual reintroduction of spectators during the later stages of the COVID-19 pandemic provides a valuable template for managing this critical aspect of sports events [97, 135].

Effective spectator management strategies may include a phased reintroduction of fans, beginning with reduced capacities and gradually increasing as the epidemiological situation allows. This approach should be coupled with robust health screening measures at entry points, enhanced cleaning and disinfection protocols, particularly for high-touch surfaces, and potential modifications to seating arrangements to maintain appropriate physical distancing [128]. The implementation of PPE for staff and recommendations for spectator use may also be necessary, depending on the current understanding of mpox transmission dynamics [136].

The progression from the Amir Cup 2020, held with limited spectators and stringent protocols, to the FIFA World Cup 2022 in Qatar, which successfully hosted full stadiums, illustrates the potential for a gradual return to normalcy. The World Cup demonstrated how large-scale events could be held safely, relatively shortly after the global COVID-19 pandemic [137]. This was possible by leveraging high vaccination rates and the development of herd immunity. However, it is important to note that the approach to mpox may initially need to be more conservative, given the different transmission characteristics of the disease and the current lack of a widely available specific vaccine for the general population [129, 137].

The successful management of sports events in the face of the mpox threat will require a high degree of flexibility, innovation, and an unwavering commitment to prioritizing the health and safety of all participants and spectators. By carefully adapting the lessons learned from the COVID-19 pandemic to the specific challenges caused by mpox, sports organizations can work towards maintaining the continuity of events while effectively minimizing health risks [32].

FIFA World Cup 2026: epidemiological preparedness in the context of emerging mpox threats

The forthcoming FIFA World Cup 2026, to be hosted across Canada, Mexico, and the United States, presents a complex epidemiological challenge, particularly in light of recent mpox developments and insights gleaned from the Paris 2024 Olympics. As of this writing, just a few weeks after the conclusion of the Paris Games, the global health community finds itself in a state of heightened vigilance regarding the mpox situation.

It is crucial to note that while the situation in Paris did not escalate to pandemic proportions during the Olympics, the potential for future escalation remains a significant concern. The identification of a more virulent strain, Clade 1b, in the immediate post-Olympic period has raised alarms about the possibility of a more widespread outbreak in the coming months or years [138]. This temporal proximity to the Paris Games underlines the dynamic nature of infectious disease threats and the need for continual reassessment of epidemiological strategies.

The tri-national nature of the 2026 World Cup in North America introduces unique challenges in epidemiological harmonization. The event's vast geographical scope, spanning diverse ecological and climatic zones from Mexico to Canada, necessitates a comprehensive approach to disease surveillance and control. This approach must account for the potential variability in mpox transmission dynamics across different environments and population densities.

Lessons from Paris 2024, while not directly involving a full-scale pandemic response, provide valuable insights into managing large-scale international events under the shadow of emerging infectious threats. The Paris experience demonstrated the importance of robust syndromic surveillance systems, rapid molecular diagnostics, and flexible public health measures [139]. However, the post-Olympic emergence of Clade 1b highlights the need for even more advanced genomic surveillance and real-time phylodynamic analysis capabilities for future events [140].

The North American World Cup organizers should prepare for a scenario in which the current mpox situation could potentially evolve into a more serious global health threat by 2026. This necessitates the development of scalable response plans that can adapt to various levels of disease prevalence, from isolated clusters to widespread community transmission. The implementation of a continental-scale genomic surveillance network, capable of rapidly identifying and characterizing new viral variants, will be crucial [141].

Risk assessment and communication strategies for the 2026 World Cup must be designed with the understanding that the global mpox landscape may be significantly different from the present. This includes preparing for the possibility of a pandemic-level event, even if such a scenario has not yet materialized. The development of adaptive threshold criteria for implementing various levels of public health interventions, based on real-time epidemiological data, will be essential [142].

The potential for mpox to affect a broader demographic by 2026, beyond the currently observed high-risk groups, must be considered in all preparedness plans. This shift in epidemiology, if it occurs, would necessitate a re-evaluation of targeted screening and prevention strategies [143].

ECONOMIC IMPACT AND MITIGATION STRATEGIES

The potential resurgence of mpox, particularly in the context of the global sports calendar, presents a multifaceted economic challenge that extends far beyond individual events. The interconnected nature of the international sports ecosystem, encompassing events such as the FIFA World Cup 2026, various continental and domestic football leagues, and numerous other sports competitions worldwide, necessitates a comprehensive analysis of the potential economic impact and the development of robust mitigation strategies [25].

The financial implications for the global sports industry are profound and far-reaching. The emergence of more virulent mpox strains, such as Clade 1b, introduces a level of uncertainty that permeates all aspects of sports economics. Revenue streams across multiple events and leagues could face potential disruption, with the possibility of crowd restrictions, schedule alterations, or, in extreme cases, event cancellations [17]. This uncertainty extends to broadcasting rights, sponsorship deals, and merchandise sales, potentially leading to a sector-wide re-evaluation of the financial models underpinning professional sports.

Major football tournaments (e.g. the 2025–26 UEFA Champions League) may face significant revenue challenges if mpox outbreaks necessitate operational changes. The impact could cascade through domestic leagues worldwide, from Europe's top-tier competitions to emerging markets in Asia and Africa, potentially destabilizing club finances, player transfer markets, and wage structures [144]. The 2026 Winter Olympics in Milan-Cortina presents its own set of challenges, given the close-contact nature of many winter sports and the indoor environments of several venues. Any restrictions or outbreaks could severely affect not only the event's direct revenues but also the long-term economic benefits to the host regions. It is important to note that while mpox has historically been endemic to certain regions of Africa, recent outbreaks have shown potential for global spread through international travel and contact [145].

The potential impact on broadcasting rights and media contracts, which are primary revenue sources for many sports, could be substantial. This could lead to complex liability issues and financial challenges across the sports industry [146]. Insurance and liability considerations in this multi-sport context become increasingly complex. The insurance landscape for sports events will likely undergo significant changes to account for the broadened risk profile. Event organizers across different sports may find it increasingly challenging to secure comprehensive coverage, particularly for communicable disease risks. Multi-sport organizations such as the International Olympic Committee and global governing bodies such as FIFA and UEFA may need to consider creating their own insurance pools or self-insurance mechanisms to manage the increased risk across their portfolio of events [147].

Liability issues become more nuanced when considering the variety of sports and their differing risk profiles. Contact sports may face higher liability risks compared to non-contact sports, potentially leading to a tiered approach in legal and insurance considerations. The global nature of sports tourism adds another layer of complexity, with organizers potentially needing to consider liability not just for the events themselves, but also for associated travel and accommodations [148].

Developing economic resilience in this complex, multi-sport environment requires a coordinated, adaptable approach. Cross-sport collaboration becomes crucial, with the potential establishment of a global sports resilience forum where different sports governing bodies can share best practices, coordinate responses, and potentially pool resources for research and development of safety measures [149]. This collaborative approach could lead to the development of standardized protocols that can be adapted to the specific needs of different sports and events.

Flexible scheduling and format innovations will be essential in navigating the uncertain landscape. Sports organizations must develop adaptive competition formats that can be quickly implemented across various sports [150]. This could include provisions for regional bubbles, extended but less intensive schedules, or hybrid in-person/virtual events. Such flexibility will be crucial in maintaining competitive integrity and financial viability in the face of potential disruptions [151].

Diversification of revenue models emerges as a key strategy for economic resilience. This includes accelerating the development of virtual and augmented reality experiences across all sports, creating new digital assets, and exploring novel competition formats that are less reliant on physical attendance [152]. The integration of technology not only serves as a risk mitigation strategy but also opens up new avenues for fan engagement and monetization [153].

Investment in biosecurity infrastructure becomes a priority, with the development of multi-use venues featuring advanced health screening capabilities, adaptable space configurations, and state-of-the-art ventilation systems.

CONCLUSIONS

This comprehensive analysis of the potential impact of an mpox outbreak on the sports world, with a particular focus on football, offers a proactive framework for addressing emerging infectious disease threats in athletic settings. Mpox may not be a pandemic today (as of late September 2024), but neither was COVID-19 when it first appeared. The real question is not "Why study this now?" but rather, "What happens if we do not?" The COVID-19 research was not just about understanding the virus, but also about preparedness. It helped us manage the crisis, but, more importantly, it taught us that early action could prevent worse scenarios. The time to act is before a crisis, not when it is too late. This research represents a forward-thinking effort to anticipate and prepare for potential challenges, using the valuable lessons learned from the COVID-19 pandemic.

The study's approach aligns with the call for action in sports epidemiology, encouraging the scientific community to gather and share data on post-event infection rates in large sporting events. We highlight the distinct characteristics of mpox compared to COVID-19, underlining the need for tailored strategies in sports settings. By examining the unique risks caused by close-contact sports such as football, this research proposes innovative approaches to risk assessment, including the potential use of COVID-19 specific applications for health tracking, and suggests tailored testing protocols and hygiene measures that could be implemented proactively.

A key strength of this framework is its foundation in the experiences gained from managing COVID-19 in sports. Unlike the situation faced at the onset of the COVID-19 pandemic, the sports world

is now better equipped with knowledge, infrastructure, and adaptive strategies to handle potential global health threats. This preparedness allows for more nuanced and effective approaches to issues such as spectator management, international coordination, and mental health support. Further, the limitations observed in previous research on mpox transmission, such as the lack of information on the type of person-to-person contact and the potential bias introduced by post-exposure prophylaxis and vaccination, have been avoided. We have also addressed the critical aspect of vaccination strategies, acknowledging the challenges of vaccine hesitancy stemming from the COVID-19 experience. By recognizing these challenges and constraints", sports early, sports organizations can develop (i) communication that is more effective and (ii) prevention implementation plans.

Declaration

The authors wish to disclose that an artificial intelligence tool (ChatGPT 3.5) was utilized to enhance the clarity and coherence of the manuscript writing. The tool was used for language refinement purposes only, ensuring that the text was clear and coherent without altering the scientific content or generating any new text [154, 155].

Funding

This research received no specific grant from any funding agency in the public, commercial, or non-profit sectors.

Conflicts of interest

We have no financial or personal relationships that could potentially influence or bias the content of this paper.

Acknowledgments

The authors would like to express their sincere gratitude to the two reviewers for their excellent feedback, which has substantially improved the quality of this manuscript.

REFERENCES

1. Karagoz A, Tombuloglu H, Alsaeed M, Tombuloglu G, AlRubaish AA, Mahmoud A, et al. Monkeypox (mpox) virus: Classification, origin, transmission, genome organization, antiviral drugs, and molecular diagnosis. J Infect Public Health. 2023; 16(4):531–41. doi: 10.1016/j.jiph.2023.02.003.
2. World health organization. WHO recommends new name for monkeypox disease. Link: https://www.who.int/news/item/28-11-2022-who-recommends-new-name-for-monkeypox-disease. (Last visit: September 29, 2024).
3. Wang X, Lun W. Skin Manifestation of Human Monkeypox. J Clin Med. 2023; 12(3):914. doi: 10.3390/jcm12030914.
4. Reardon S. Mpox is spreading rapidly. Here are the questions researchers are racing to answer. Nature. 2024; 633(8028):16–7. doi: 10.1038/d41586-024-02793-9.
5. Haque MA, Halder AS, Hossain MJ, Islam MR. Prediction of potential public health risk of the recent multicountry monkeypox outbreak: An update after the end declaration of global public health emergency. Health Sci Rep. 2024; 7(6):e2136. doi: 10.1002/hsr2.2136.
6. World health organization. WHO declares mpox virus a public health emergency of international concern. 2024. Link: https://news.un.org/en/story/2024/08/1153176 (Last visit: September 29, 2024)
7. World health organization. 2022–24 Mpox (Monkeypox) Outbreak: Global Trends. Produced on 24 September 2024. Link: https://worldhealthorg.shinyapps.io/mpx_global/#3_Global_situation_update (Last visit: September 29, 2024).
8. Luna N, Ramirez AL, Munoz M, Ballesteros N, Patino LH, Castaneda SA, et al. Phylogenomic analysis of the monkeypox virus (MPXV) 2022 outbreak: Emergence of a novel viral lineage? Travel Med Infect Dis. 2022; 49:102402. doi: 10.1016/j.tmaid.2022.102402.
9. Islam MA, Mumin J, Haque MM, Haque MA, Khan A, Bhattacharya P, et al. Monkeypox virus (MPXV): A Brief account of global spread, epidemiology, virology, clinical features, pathogenesis, and therapeutic interventions. Infect Med (Beijing). 2023; 2(4):262–72. doi: 10.1016/j.imj.2023.11.001.
10. Beeson A, Styczynski A, Hutson CL, Whitehill F, Angelo KM, Minhaj FS, et al. Mpox respiratory transmission: the state of the evidence. Lancet Microbe. 2023; 4(4):e277-e83. doi: 10.1016/S2666-5247(23)00034-4.
11. Farahat RA, Abdelaal A, Shah J, Ghozy S, Sah R, Bonilla-Aldana DK, et al. Monkeypox outbreaks during COVID-19 pandemic: are we looking at an independent phenomenon or an overlapping pandemic? Ann Clin Microbiol Antimicrob. 2022; 21(1):26. doi: 10.1186/s12941-022-00518-2.
12. Wang Y, Leng P, Zhou H. Global transmission of monkeypox virus-a potential threat under the COVID-19 pandemic. Front Immunol. 2023; 14:1174223. doi: 10.3389/fimmu.2023.1174223.
13. Niu L, Liang D, Ling Q, Zhang J, Li Z, Zhang D, et al. Insights into monkeypox pathophysiology, global prevalence, clinical manifestation and treatments. Front Immunol. 2023; 14:1132250. doi: 10.3389/fimmu.2023.1132250.
14. Venkatesan P. Monkeypox transmission-what we know so far. Lancet Respir Med. 2022; 10(11):e101. doi: 10.1016/S2213-2600(22)00386-1.
15. Teo CT, Wu JS, Chan K, Ng SWB, Somani J, Loh W. What does the anesthesiologist need to know about monkeypox? Can J Anaesth. 2023; 70(5):893–900. doi: 10.1007/s12630-023-02441-2.
16. Wang Y, Zheng K, Gao W, Lv J, Yu C, Wang L, et al. Asymptomatic and pre-symptomatic infection in Coronavirus Disease 2019 pandemic. Med Rev (2021). 2022; 2(1):66–88. doi: 10.1515/mr-2021-0034.
17. Smoliga JM. Mpox and Monkeypox Virus: Special Considerations for Athletes in Contact Sports. Sports Med. 2023; 53(7):1301–13. doi: 10.1007/s40279-023-01812-5.
18. Hughes DC, Orchard JW, Partridge EM, La Gerche A, Broderick C. Return to exercise post-COVID-19 infection: A pragmatic approach in mid-2022. J Sci Med Sport. 2022; 25(7):544–7. doi: 10.1016/j.jsams.2022.06.001.
19. Nathanielsz J, Toh ZQ, Do LAH, Mulholland K, Licciardi PV.

SARS-CoV-2 infection in children and implications for vaccination. Pediatr Res. 2023; 93(5):1177–87. doi: 10.1038/s41390-022-02254-x.
20. Taylor BG, Mumford EA, Kaplan AM, Liu W. Concerns about COVID-19 Vaccine Hesitancy among Law Enforcement Officers: Prevalence and Risk Factor Data from a Nationally Representative Sample in the United States. Vaccines (Basel). 2023; 11(4). doi: 10.3390/vaccines11040783.
21. Washif JA, Farooq A, Krug I, Pyne DB, Verhagen E, Taylor L, et al. Training During the COVID-19 Lockdown: Knowledge, Beliefs, and Practices of 12,526 Athletes from 142 Countries and Six Continents. Sports Med. 2022; 52(4):933–48. doi: 10.1007/s40279-021-01573-z.
22. Saied AA, Dhawan M, Metwally AA, Fahrni ML, Choudhary P, Choudhary OP. Disease History, Pathogenesis, Diagnostics, and Therapeutics for Human Monkeypox Disease: A Comprehensive Review. Vaccines (Basel). 2022; 10(12). doi: 10.3390/vaccines10122091.
23. Drago F, Ciccarese G, Merlo G, Trave I, Javor S, Rebora A, et al. Oral and cutaneous manifestations of viral and bacterial infections: Not only COVID-19 disease. Clin Dermatol. 2021; 39(3):384–404. doi: 10.1016/j.clindermatol.2021.01.021.
24. Pinto P, Costa MA, Goncalves MFM, Rodrigues AG, Lisboa C. Mpox Person-to-Person Transmission-Where Have We Got So Far? A Systematic Review. Viruses. 2023; 15(5). doi: 10.3390/v15051074.
25. Farahat RA, Setti MO, Benmelouka AY, Ali I, Umar TP, Alabdallat Y, et al. Monkeypox emergence and hosting a safe FIFA World Cup 2022 in Qatar: Challenges and recommendations. Int J Surg. 2022; 106:106935. doi: 10.1016/j.ijsu.2022.106935.
26. Schumacher YO, Tabben M, Hassoun K, Al Marwani A, Al Hussein I, Coyle P, et al. Resuming professional football (soccer) during the COVID-19 pandemic in a country with high infection rates: a prospective cohort study. Br J Sports Med. 2021; 55(19):1092–8. doi: 10.1136/bjsports-2020-103724.
27. Faude O, Muller S, Schreiber S, Muller J, Nebiker L, Beaudouin F, et al. A video-based analysis of situations bearing the risk of respiratory disease transmission during football matches. Sci Rep. 2022; 12(1):3034. doi: 10.1038/s41598-022-07121-7.
28. Taha AM, Katamesh BE, Hassan AR, Abdelwahab OA, Rustagi S, Nguyen D, et al. Environmental detection and spreading of mpox in healthcare settings: a narrative review. Front Microbiol. 2023; 14:1272498. doi: 10.3389/fmicb.2023.1272498.
29. Khamees A, Awadi S, Al-Shami K, Alkhoun HA, Al-Eitan SF, Alsheikh AM, et al. Human monkeypox virus in the shadow of the COVID-19 pandemic. J Infect Public Health. 2023; 16(8):1149–57. doi: 10.1016/j.jiph.2023.05.013.
30. Vogel L. Is monkeypox airborne? CMAJ. 2022; 194(32):E1121. doi: 10.1503/cmaj.1096013.
31. Panda K, Mukherjee A. Is monkeypox a threat to another pandemic? Front Microbiol. 2022; 13:983076. doi: 10.3389/fmicb.2022.983076.
32. AlSamhori JF, Alshrouf MA, AlSamhori ARF, Alshadeedi FM, Madi AS, Alzoubi O. Implications of the COVID-19 pandemic on athletes, sports events, and mass gathering events: Review and recommendations. Sports Med Health Sci. 2023; 5(3):165–73. doi: 10.1016/j.smhs.2023.07.006.
33. Washif JA, Hettinga FJ, Ammar A, van Rensburg DCJ, Materne O, Trabelsi K, et al. Supporting athletes during a challenging situation: recommendations from a global insight of COVID-19 home-based training experience. BMC Sports Sci Med Rehabil. 2024; 16(1):83. doi: 10.1186/s13102-024-00869-7.
34. Koenig KL, Bey CK, Marty AM. Monkeypox 2022 Identify-Isolate-Inform: A 3I Tool for frontline clinicians for a zoonosis with escalating human community transmission. One Health. 2022; 15:100410. doi: 10.1016/j.onehlt.2022.100410.
35. Gibson OR, James CA, Mee JA, Willmott AGB, Turner G, Hayes M, et al. Heat alleviation strategies for athletic performance: A review and practitioner guidelines. Temperature (Austin). 2020; 7(1):3–36. doi: 10.1080/23328940.2019.1666624.
36. Impellizzeri FM, Menaspa P, Coutts AJ, Kalkhoven J, Menaspa MJ. Training Load and Its Role in Injury Prevention, Part I: Back to the Future. J Athl Train. 2020; 55(9):885–92. doi: 10.4085/1062-6050-500-19.
37. Ferraz A, Duarte-Mendes P, Sarmento H, Valente-Dos-Santos J, Travassos B. Tracking devices and physical performance analysis in team sports: a comprehensive framework for research-trends and future directions. Front Sports Act Living. 2023; 5:1284086. doi: 10.3389/fspor.2023.1284086.
38. De Fazio R, Mastronardi VM, De Vittorio M, Visconti P. Wearable Sensors and Smart Devices to Monitor Rehabilitation Parameters and Sports Performance: An Overview. Sensors (Basel). 2023; 23(4). doi: 10.3390/s23041856.
39. Tamasiga P, Onyeaka H, Umenweke GC, Uwishema O. An extended SEIRDV compartmental model: case studies of the spread of COVID-19 and vaccination in Tunisia and South Africa. Ann Med Surg (Lond). 2023; 85(6):2721–30. doi: 10.1097/MS9.0000000000000627.
40. Szigeti G, Schuth G, Revisnyei P, Pasic A, Szilas A, Gabbett T, et al. Quantification of Training Load Relative to Match Load of Youth National Team Soccer Players. Sports Health. 2022; 14(1):84–91. doi: 10.1177/19417381211004902.
41. Zhou Y, Chen Z. Mpox: a review of laboratory detection techniques. Arch Virol. 2023; 168(8):221. doi: 10.1007/s00705-023-05848-w.
42. Jones T, Jones S, Hicks B, Selman H, Rowe C, Otter AD. Limitations of mpox lateral flow tests in assessing orthopoxvirus immunity. Lancet Infect Dis. 2024. doi: 10.1016/S1473-3099(24)00556-5.
43. World health organization. Surveillance, case investigation and contact tracing for mpox (monkeypox): Interim guidance, 20 March 2024. Link: https://www.who.int/publications/i/item/WHO-MPX-Surveillance-2024.1#:~:text=The%20overall%20goal%20of%20surveillance%2C%20case%20investigation%20and,progress%20towards%20elimination%20of%20human-to-human%20transmission%20of%20mpox (Last visit: September 29, 2024).
44. World health organization. Diagnostic testing for the monkeypox virus (MPXV): interim guidance, 10 May 2024. Link: https://www.who.int/publications/i/item/WHO-MPX-Laboratory-2024.1 (Last visit: September 29, 2024).
45. Tsang NNY, So HC, Ng KY, Cowling BJ, Leung GM, Ip DKM. Diagnostic performance of different sampling approaches for SARS-CoV-2 RT-PCR testing: a systematic review and meta-analysis. Lancet Infect Dis. 2021; 21(9):1233–45. doi: 10.1016/S1473-3099(21)00146-8.
46. Hou CW, Williams S, Taylor K, Boyle V, Bobbett B, Kouvetakis J, et al. Serological survey to estimate SARS-CoV-2 infection and antibody seroprevalence at a large public university: A cross-sectional study. BMJ Open. 2023; 13(8):e072627. doi: 10.1136/bmjopen-2023-072627.
47. Dixit S, Kumar A, Srinivasan K, Vincent P, Ramu Krishnan N. Advancing genome editing with artificial intelligence: opportunities, challenges, and future directions. Front Bioeng Biotechnol. 2023; 11:1335901. doi: 10.3389/fbioe.2023.1335901.

48. Redmond SN, Cadnum JL, Silva SY, Pearlmutter BS, Jencson AL, Alhmidi H, et al. Evaluation of a continuously active disinfectant for decontamination of portable medical equipment. Infect Control Hosp Epidemiol. 2022; 43(3):387–9. doi: 10.1017/ice.2021.66.
49. Pereira AR, Braga DFO, Vassal M, Gomes IB, Simoes M. Ultraviolet C irradiation: A promising approach for the disinfection of public spaces? Sci Total Environ. 2023; 879:163007. doi: 10.1016/j.scitotenv.2023.163007.
50. Khalid Ijaz M, Nims RW, McKinney J, Gerba CP. Virucidal efficacy of laundry sanitizers against SARS-CoV-2 and other coronaviruses and influenza viruses. Sci Rep. 2022; 12(1):5247. doi: 10.1038/s41598-022-08259-0.
51. Morawska L, Tang JW, Bahnfleth W, Bluyssen PM, Boerstra A, Buonanno G, et al. How can airborne transmission of COVID-19 indoors be minimised? Environ Int. 2020; 142:105832. doi: 10.1016/j.envint.2020.105832.
52. Kampf G. Efficacy of biocidal agents and disinfectants against the monkeypox virus and other orthopoxviruses. J Hosp Infect. 2022; 127:101–10. doi: 10.1016/j.jhin.2022.06.012.
53. World health organization. Hand hygiene: Why, how, and when? Patient safety. 2009 Link: https://www.who.int/publications/m/item/hand-hygiene-why-how-when#:~:text=Overview%201%20Hands%20are%20the%20main%20pathways%20of,explains%20how%20and%20when%20to%20practice%20hand%20hygiene (Last visit: September 29, 2024).
54. Hornig KJ, Burgess BA, Saklou NT, Johnson V, Malmlov A, Van Metre DC, et al. Evaluation of the Efficacy of Disinfectant Footmats for the Reduction of Bacterial Contamination on Footwear in a Large Animal Veterinary Hospital. J Vet Intern Med. 2016; 30(6):1882–6. doi: 10.1111/jvim.14576.
55. Huneau-Salaun A, Scoizec A, Thomas R, Martenot C, Schmitz A, Pierre I, et al. Avian influenza outbreaks: evaluating the efficacy of cleaning and disinfection of vehicles and transport crates. Poult Sci. 2022; 101(1):101569. doi: 10.1016/j.psj.2021.101569.
56. Brauner JM, Mindermann S, Sharma M, Johnston D, Salvatier J, Gavenciak T, et al. Inferring the effectiveness of government interventions against COVID-19. Science. 2021; 371(6531). doi: 10.1126/science.abd9338.
57. Boyce JM, Pittet D, Healthcare Infection Control Practices Advisory C, Force HSAIHHT. Guideline for Hand Hygiene in Health-Care Settings. Recommendations of the Healthcare Infection Control Practices Advisory Committee and the HICPAC/SHEA/APIC/IDSA Hand Hygiene Task Force. Society for Healthcare Epidemiology of America/Association for Professionals in Infection Control/Infectious Diseases Society of America. MMWR Recomm Rep. 2002; 51(RR-16):1–45, quiz CE1-4.
58. Centers for disease control and prevention. Healthcare-associated Infections. Cleaning supplies and equipment. Best practices for environmental cleaning in global healthcare facilities with limited resources. Link: https://www.cdc.gov/healthcare-associated-infections/hcp/cleaning-global/supplies-and-equipment.html (Last visit: September 29, 2024).
59. Ramos CCR, Roque JLA, Sarmiento DB, Suarez LEG, Sunio JTP, Tabungar KIB, et al. Use of ultraviolet-C in environmental sterilization in hospitals: A systematic review on efficacy and safety. Int J Health Sci (Qassim). 2020; 14(6):52–65.
60. Clack L, Stuhlinger M, Meier MT, Wolfensberger A, Sax H. User-centred participatory design of visual cues for isolation precautions. Antimicrob Resist Infect Control. 2019; 8:179. doi: 10.1186/s13756-019-0629-9.
61. Chamari K, Dergaa I, Mujika I, Schumacher YO, Tabben M, Ben Saad H. Football in Times of COVID-19: A Recapitulation of Preventive Measures and Infection Control Policies Aiming at a Safe Game Environment. Int J Sports Physiol Perform. 2022; 17(9):1448–51. doi: 10.1123/ijspp.2022-0254.
62. Peebles LA, Aman ZS, Kraeutler MJ, Mulcahey MK. Impact of the COVID-19 Pandemic on Sports Medicine Patient Care. Arthroscopy. 2023; 39(2):161–5. doi: 10.1016/j.arthro.2022.11.003.
63. Desrichard O, Moussaoui L, Ofosu N. Reduction of Precautionary Behaviour following Vaccination against COVID-19: A Test on a British Cohort. Vaccines (Basel). 2022; 10(6). doi: 10.3390/vaccines10060936.
64. Srinivas V, Choubey U, Motwani J, Anamika F, Chennupati C, Garg N, et al. Synergistic strategies: Optimizing outcomes through a multidisciplinary approach to clinical rounds. Proc (Bayl Univ Med Cent). 2024; 37(1):144–50. doi: 10.1080/08998280.2023.2274230.
65. Galy O, Washif JA, Wattelez G, Farooq A, Hue O, Sandbakk O, et al. Training strategies of 10,074 athletes from 121 countries based on human development index in early COVID-19 lockdown. Sci Rep. 2024; 14(1):8866. doi: 10.1038/s41598-024-59375-y.
66. Leng T, White C, Hilton J, Kucharski A, Pellis L, Stage H, et al. The effectiveness of social bubbles as part of a Covid-19 lockdown exit strategy, a modelling study. Wellcome Open Res. 2020; 5:213. doi: 10.12688/wellcomeopenres.16164.2.
67. Qu Y, Meng Y, Fan H, Xu RX. Low-cost thermal imaging with machine learning for non-invasive diagnosis and therapeutic monitoring of pneumonia. Infrared Phys Technol. 2022; 123:104201.doi: 10.1016/j.infrared.2022.104201.
68. Alowais SA, Alghamdi SS, Alsuhebany N, Alqahtani T, Alshaya AI, Almohareb SN, et al. Revolutionizing healthcare: the role of artificial intelligence in clinical practice. BMC Med Educ. 2023; 23(1):689. doi: 10.1186/s12909-023-04698-z.
69. Impellizzeri FM, Shrier I, McLaren SJ, Coutts AJ, McCall A, Slattery K, et al. Understanding Training Load as Exposure and Dose. Sports Med. 2023; 53(9):1667–79. doi: 10.1007/s40279-023-01833-0.
70. Vilain M, Aris-Brosou S. Machine Learning Algorithms Associate Case Numbers with SARS-CoV-2 Variants Rather Than with Impactful Mutations. Viruses. 2023; 15(6). doi: 10.3390/v15061226.
71. Lai R, Chen E, Gao W, Cheng C, Xie Q. Sentinel surveillance strategies for early detection of coronavirus disease in fever clinics: experience from China. Epidemiol Infect. 2020; 148:e205. doi: 10.1017/S0950268820001892.
72. Salmon S, Brinkwirth S, Loi G, Basseal JM. Global Outbreak Alert and Response Network deployments during the COVID-19 pandemic, WHO Western Pacific Region. Western Pac Surveill Response J. 2024; 15(5 Spec edition):1–7. doi: 10.5365/wpsar.2024.15.5.1060.
73. Branda F, Romano C, Ciccozzi M, Giovanetti M, Scarpa F, Ciccozzi A, et al. Mpox: An Overview of Pathogenesis, Diagnosis, and Public Health Implications. J Clin Med. 2024; 13(8). doi: 10.3390/jcm13082234.
74. Thangamani R, Kamalam GK, Vimaladevi M. Revolutionizing Healthcare Processes: The Dynamic Role of Blockchain Innovation. In: Kumar P, Kumari A, editors. Blockchain for Biomedical Research and Healthcare. Interdisciplinary Biotechnological Advances. Singapore: Springer Nature Singapore2024. p. 229–67.
75. Eager D. Benefit–Risk Assessment in Sport and Recreation: Historical Development and Review of AS ISO 4980:2023. Standards. 2024; 4(2):66–78. doi: 10.3390/standards4020005.

76. Souissi A, Dergaa I, Romdhani M, Ghram A, Irandoust K, Chamari K, et al. Can melatonin reduce the severity of post-COVID-19 syndrome? EXCLI J. 2023; 22:173–87. doi: 10.17179/excli2023-5864.
77. Trabelsi K, Ammar A, Masmoudi L, Boukhris O, Chtourou H, Bouaziz B, et al. Globally altered sleep patterns and physical activity levels by confinement in 5056 individuals: ECLB COVID-19 international online survey. Biol Sport. 2021; 38(4):495–506. doi: 10.5114/biolsport.2021.101605.
78. Daley MM, Shoop J, Christino MA. Mental Health in the Specialized Athlete. Curr Rev Musculoskelet Med. 2023; 16(9):410–8. doi: 10.1007/s12178-023-09851-1.
79. Li H, Glecia A, Kent-Wilkinson A, Leidl D, Kleib M, Risling T. Transition of Mental Health Service Delivery to Telepsychiatry in Response to COVID-19: A Literature Review. Psychiatr Q. 2022; 93(1):181–97. doi: 10.1007/s11126-021-09926-7.
80. Mirbahaeddin E, Chreim S. Transcending technology boundaries and maintaining sense of community in virtual mental health peer support: a qualitative study with service providers and users. BMC Health Serv Res. 2024; 24(1):510. doi: 10.1186/s12913-024-10943-y.
81. Brown KR, Quinton ML, Tidmarsh G, Cumming J. Athletes' access to, attitudes towards and experiences of help-seeking for mental health: a scoping review protocol. BMJ Open. 2023; 13(4):e062279. doi: 10.1136/bmjopen-2022-062279.
82. Haque MDR, Rubya S. An Overview of Chatbot-Based Mobile Mental Health Apps: Insights From App Description and User Reviews. JMIR Mhealth Uhealth. 2023; 11:e44838. doi: 10.2196/44838.
83. Khawaja Z, Belisle-Pipon JC. Your robot therapist is not your therapist: understanding the role of AI-powered mental health chatbots. Front Digit Health. 2023; 5:1278186. doi: 10.3389/fdgth.2023.1278186.
84. Swed S, Bohsas H, Alibrahim H, Rakab A, Hafez W, Sawaf B, et al. Monkeypox Post-COVID-19: Knowledge, Worrying, and Vaccine Adoption in the Arabic General Population. Vaccines (Basel). 2023; 11(4). doi: 10.3390/vaccines11040759.
85. Krishna BA, Metaxaki M, Sithole N, Landin P, Martin P, Salinas-Botran A. Cardiovascular disease and covid-19: A systematic review. Int J Cardiol Heart Vasc. 2024; 54:101482. doi: 10.1016/j.ijcha.2024.101482.
86. Modica G, Bianco M, Sollazzo F, Di Murro E, Monti R, Cammarano M, et al. Myocarditis in Athletes Recovering from COVID-19: A Systematic Review and Meta-Analysis. Int J Environ Res Public Health. 2022; 19(7). doi: 10.3390/ijerph19074279.
87. Bruyere O, Martens G, Demonceau C, Urhausen A, Seil R, Leclerc S, et al. Impact of COVID-19 Vaccination on Short-Term Perceived Change in Physical Performance among Elite Athletes: An International Survey. Vaccines (Basel). 2023; 11(4). doi: 10.3390/vaccines11040796.
88. Kaur U, Fatima Z, Maheshwari K, Sahni V, Dehade A, KI A, et al. Long-Term Safety Analysis of the ChAdOx1-nCoV-19 Corona Virus Vaccine: Results from a Prospective Observational Study in Priority Vaccinated Groups in North India. Drug Saf. 2023; 46(6):553–63. doi: 10.1007/s40264-023-01301-8.
89. Bardosh K, de Figueiredo A, Gur-Arie R, Jamrozik E, Doidge J, Lemmens T, et al. The unintended consequences of COVID-19 vaccine policy: why mandates, passports and restrictions may cause more harm than good. BMJ Glob Health. 2022; 7(5):e008684. doi: 10.1136/bmjgh-2022-008684.
90. Zace D, La Gatta E, Petrella L, Di Pietro ML. The impact of COVID-19 vaccines on fertility-A systematic review and meta-analysis. Vaccine. 2022; 40(42):6023–34. doi: 10.1016/j.vaccine.2022.09.019.
91. Chiampas GT, Ibiebele AL. A Sports Practitioner's Perspective on the Return to Play During the Early Months of the COVID-19 Pandemic: Lessons Learned and Next Steps. Sports Med. 2021; 51(Suppl 1):89–96. doi: 10.1007/s40279-021-01503-z.
92. Onyeaka H, Anumudu CK, Al-Sharify ZT, Egele-Godswill E, Mbaegbu P. COVID-19 pandemic: A review of the global lockdown and its far-reaching effects. Sci Prog. 2021; 104(2):368504211019854. doi: 10.1177/00368504211019854.
93. Sobierajski T, Krzywanski J, Mikulski T, Pokrywka A, Krysztofiak H, Kuchar E. Sports Elite Means Vaccine Elite? Concerns and Beliefs Related to COVID-19 Vaccines among Olympians and Elite Athletes. Vaccines (Basel). 2022; 10(10). doi: 10.3390/vaccines10101676.
94. Stevens CW, Neely SR, Scacco JM. Breakthrough infections and acceptance of COVID-19 vaccine boosters: A survey analysis. PEC Innov. 2023; 2:100167. doi: 10.1016/j.pecinn.2023.100167.
95. Musa S, Dergaa I, Abdulmalik MA, Ammar A, Chamari K, Saad HB. BNT162b2 COVID-19 Vaccine Hesitancy among Parents of 4023 Young Adolescents (12–15 Years) in Qatar. Vaccines (Basel). 2021; 9(9). doi: 10.3390/vaccines9090981.
96. Tatar M, Shoorekchali JM, Faraji MR, Seyyedkolaee MA, Pagan JA, Wilson FA. COVID-19 vaccine inequality: A global perspective. J Glob Health. 2022; 12:03072. doi: 10.7189/jogh.12.03072.
97. Excler JL, Saville M, Privor-Dumm L, Gilbert S, Hotez PJ, Thompson D, et al. Factors, enablers and challenges for COVID-19 vaccine development. BMJ Glob Health. 2023; 8(6). doi: 10.1136/bmjgh-2023-011879.
98. Thakkar A, Gupta A, De Sousa A. Artificial intelligence in positive mental health: a narrative review. Front Digit Health. 2024; 6:1280235. doi: 10.3389/fdgth.2024.1280235.
99. Williams BA, Jones CH, Welch V, True JM. Outlook of pandemic preparedness in a post-COVID-19 world. NPJ Vaccines. 2023; 8(1):178. doi: 10.1038/s41541-023-00773-0.
100. Qiu Y, Fernandez-Garcia B, Lehmann HI, Li G, Kroemer G, Lopez-Otin C, et al. Exercise sustains the hallmarks of health. J Sport Health Sci. 2023; 12(1):8–35. doi: 10.1016/j.jshs.2022.10.003.
101. Nichols AW. Heat-related illness in sports and exercise. Curr Rev Musculoskelet Med. 2014; 7(4):355–65. doi: 10.1007/s12178-014-9240-0.
102. Harapan H, Ophinni Y, Megawati D, Frediansyah A, Mamada SS, Salampe M, et al. Monkeypox: A Comprehensive Review. Viruses. 2022; 14(10). doi: 10.3390/v14102155.
103. Faghy MA, Ashton REM, Parizher G, Smith A, Arena R, Gough LA, et al. COVID-19 and elite sport: Cardiovascular implications and return-to-play. Prog Cardiovasc Dis. 2023; 76:61–8. doi: 10.1016/j.pcad.2022.11.014.
104. Sethi Y, Agarwal P, Murli H, Waheed S, Matar SG, Baklola M, et al. Neuropsychiatric manifestations of monkeypox: A clinically oriented comprehensive review. Brain Behav. 2023; 13(4):e2934. doi: 10.1002/brb3.2934.
105. Adebisi YA, Ezema SM, Bolarinwa O, Bassey AE, Ogunkola IO. Sex Workers and the Mpox Response in Africa. J Infect Dis. 2024. doi: 10.1093/infdis/jiae435.
106. Brandt L, Liu S, Heim C, Heinz A. The effects of social isolation stress and discrimination on mental health. Transl Psychiatry. 2022; 12(1):398. doi: 10.1038/s41398-022-02178-4.
107. Aroyewun TF, Olaleye SO, Adebisi YA, Yusuf M. Mental health implications of

monkeypox: An urgent need for action. Ann Med Surg (Lond). 2022; 82:104771. doi: 10.1016/j.amsu .2022.104771.
108. Gabrys K, Wontorczyk A. Sport Anxiety, Fear of Negative Evaluation, Stress and Coping as Predictors of Athlete's Sensitivity to the Behavior of Supporters. Int J Environ Res Public Health. 2023; 20(12). doi: 10.3390 /ijerph20126084.
109. Nyame J, Punniyakotti S, Khera K, Pal RS, Varadarajan N, Sharma P. Challenges in the treatment and prevention of monkeypox infectionA comprehensive review. Acta Trop. 2023; 245:106960. doi: 10.1016 /j.actatropica.2023.106960.
110. Vancini RL, Andrade MS, Viana RB, Nikolaidis PT, Knechtle B, Campanharo CRV, et al. Physical exercise and COVID-19 pandemic in PubMed: Two months of dynamics and one year of original scientific production. Sports Med Health Sci. 2021; 3(2):80–92. doi: 10.1016 /j.smhs.2021.04.004.
111. Furrer R, Hawley JA, Handschin C. The molecular athlete: exercise physiology from mechanisms to medals. Physiol Rev. 2023; 103(3):1693–787. doi: 10.1152/physrev.00017.2022.
112. Romero-Morales C, Lopez-Lopez D, Almazan-Polo J, Mogedano-Cruz S, Sosa-Reina MD, Garcia-Perez-de-Sevilla G, et al. Prevalence, diagnosis and management of musculoskeletal disorders in elite athletes: A mini-review. Dis Mon. 2024; 70(1):101629. doi: 10.1016 /j.disamonth.2023.101629.
113. Rasmussen IE, Lok M, Durrer CG, Foged F, Schelde VG, Budde JB, et al. Impact of high-intensity interval training on cardiac structure and function after COVID-19: an investigator-blinded randomized controlled trial. J Appl Physiol (1985). 2023; 135(2):421–35. doi: 10.1152 /japplphysiol.00078.2023.
114. Hughes D, Saw R, Perera NKP, Mooney M, Wallett A, Cooke J, et al. The Australian Institute of Sport framework for rebooting sport in a COVID-19 environment. J Sci Med Sport. 2020; 23(7):639–63. doi: 10.1016/j.jsams.2020.05.004.
115. Seçkin AÇ, Ateş B, Seçkin M. Review on Wearable Technology in Sports: Concepts, Challenges and Opportunities. Applied Sciences. 2023; 13(18):10399. doi: 10.3390/app 131810399.
116. Asaad A, El-Sokkary R. The current monkeypox outbreak: Knowledge gaps and research priorities. J Infect Public Health. 2023; 16(1):78–9. doi: 10.1016/j.jiph.2022.12.002.
117. Reynolds MG, McCollum AM, Nguete B, Shongo Lushima R, Petersen BW. Improving the Care and Treatment of Monkeypox Patients in Low-Resource Settings: Applying Evidence from Contemporary Biomedical and Smallpox Biodefense Research. Viruses. 2017; 9(12). doi: 10.3390/v9120380.
118. Mitja O, Ogoina D, Titanji BK, Galvan C, Muyembe JJ, Marks M, et al. Monkeypox. Lancet. 2023; 401(10370):60–74. doi: 10.1016 /S0140-6736(22)02075-X.
119. Ahmed SK, El-Kader RGA, Abdulqadir SO, Abdullah AJ, El-Shall NA, Chandran D, et al. Monkeypox clinical symptoms, pathology, and advances in management and treatment options: an update. Int J Surg. 2023; 109(9):2837–40. doi: 10.1097/JS9 .0000000000000091.
120. World health organization. Mpox (Monkeypox) fact sheet. World health organization. 2023. Link: https://www.who.int/news-room/fact-sheets/detail/mpox (Last visit: September 29, 2024).
121. Centers for disease control and prevention. What to do if you are sick. CDC. 2023. Link: https://www .cdc.gov/coronavirus/2019-ncov /if-you-are-sick/steps-when-sick.html (Last visit: September 29, 2024).
122. World health organization. Coronavirus disease (COVID-19) pandemic. World health organization. 2024. Link: https://www.who.int/emergencies /diseases/novel-coronavirus-2019 (Last visit: September 29, 2024).
123. Dergaa I, Varma A, Tabben M, Malik RA, Sheik S, Vedasalam S, et al. Organising football matches with spectators during the COVID-19 pandemic: What can we learn from the Amir Cup Football Final of Qatar 2020? A call for action. Biol Sport. 2021; 38(4):677–81. doi: 10.5114/biolsport .2021.103568.
124. Dergaa I, Ben Saad H, Zmijewski P, Farhat RA, Romdhani M, Souissi A, et al. Large-scale sporting events during the COVID-19 pandemic: insights from the FIFA World Cup 2022 in Qatar with an analysis of patterns of COVID-19 metrics. Biol Sport. 2023; 40(4):1249–58. doi: 10.5114 /biolsport.2023.131109.
125. Dergaa I, Musa S, Romdhani M, Souissi A, Abdulmalik MA, Chamari K, et al. FIFA World Cup 2022: What can we learn from the inspiring Tokyo 2020 Olympic Games held in COVID-19 times? Biol Sport. 2022; 39(4):1073–80. doi: 10.5114 /biolsport.2022.113293.
126. Dergaa I, Abdelrahman H, Varma A, Yousfi N, Souissi A, Ghram A, et al. COVID-19 Vaccination, Herd Immunity and The Transition Toward Normalcy: Challenges with The Upcoming Sports Events. Annals of Applied Sport Science. 2021; 9(3):0. doi: 10.52547 /aassjournal.1032.
127. Alhussaini NWZ, Elshaikh UAM, Hamad NA, Nazzal MA, Abuzayed M, Al-Jayyousi GF. A scoping review of the risk factors and strategies followed for the prevention of COVID-19 and other infectious diseases during sports mass gatherings: Recommendations for future FIFA World Cups. Front Public Health. 2022; 10:1078834. doi: 10.3389 /fpubh.2022.1078834.
128. Khan NA, Al Musleh AA, Abdurahiman S, Asim M, El-Menyar A, Al-Thani H. Recommencement of football competition with spectators during the active phase of the COVID-19 pandemic in a Middle Eastern country. BMC Sports Sci Med Rehabil. 2022; 14(1):112. doi: 10 .1186/s13102-022-00504-3.
129. Saidarakath J, Joravarsinh Gadhavi B, Osman Awad M, AlSaadi MM, Chovar Kattil M, Alnuaimi AS. Anti-SARS-CoV-2 Antibody Response Among Spectators of Amir Cup 2020 With a History of Recovery From COVID-19 in Qatar: A Historic Cohort Study. Cureus. 2024; 16(2):e54406. doi: 10 .7759/cureus.54406.
130. Amer F, Khalil HES, Elahmady M, ElBadawy NE, Zahran WA, Abdelnasser M, et al. Mpox: Risks and approaches to prevention. J Infect Public Health. 2023; 16(6):901–10. doi: 10.1016/j.jiph.2023.04.001.
131. Cossich VRA, Carlgren D, Holash RJ, Katz L. Technological Breakthroughs in Sport: Current Practice and Future Potential of Artificial Intelligence, Virtual Reality, Augmented Reality, and Modern Data Visualization in Performance Analysis. Applied Sciences. 2023; 13(23):12965. doi: 10.3390 /app132312965.
132. Beebeejaun K, Pebody R, Ciobanu S, Pukkila J, Smallwood C, Perehinets I. UEFA Euro 2020: lessons from the first multi-city international mass gathering during the COVID-19 pandemic. Epidemiol Infect. 2022; 150:e182. doi: 10.1017/S095026882200156X.
133. Yao Y, Wang P, Zhang H. The Impact of Preventive Strategies Adopted during Large Events on the COVID-19 Pandemic: A Case Study of the Tokyo Olympics to Provide Guidance for Future Large Events. Int J Environ Res Public Health. 2023; 20(3):2408. doi: 10.3390/ijerph20032408.
134. Dubey T, Chakole S, Agrawal S, Gupta A, Munjewar PK, Sharma R, et al. Enhancing Nursing Care in Monkeypox (Mpox) Patients: Differential

Diagnoses, Prevention Measures, and Therapeutic Interventions. Cureus. 2023; 15(9):e44687. doi: 10.7759/cureus.44687.
135. Dergaa I, Ben Saad H, Souissi A, Musa S, Abdulmalik MA, Chamari K. Olympic Games in COVID-19 times: lessons learned with special focus on the upcoming FIFA World Cup Qatar 2022. Br J Sports Med. 2022; 56(12):654–6. doi: 10.1136/bjsports-2021-105276.
136. Manirambona E, Felicilda Lopez JC, Nduwimana C, Okesanya OJ, Mbonimpaye R, Musa SS, et al. Healthcare workers and monkeypox: The case for risk mitigation. Int J Surg Open. 2023; 50:100584. doi: 10.1016/j.ijso.2022.100584.
137. Al-Thani H, Al Musleh AA, Khan NA, Asim M, Abdurahiman S, Morad YA, et al. FIFA Arab Cup tournament with full capacity of spectators during the COVID-19 pandemic: a cross-sectional study. Sci Med Footb. 2023; 7(4):337–46. doi: 10.1080/24733938.2022.2110276.
138. Müller M, Gogishvili D, Wolfe SD, Gaffney C, Hug M, Leick A. Peak event: the rise, crisis and potential decline of the Olympic Games and the World Cup. Tourism Management. 2023; 95:104657. doi: 10.1016/j.tourman.2022.104657.
139. Maddah N, Verma A, Almashmoum M, Ainsworth J. Effectiveness of Public Health Digital Surveillance Systems for Infectious Disease Prevention and Control at Mass Gatherings: Systematic Review. J Med Internet Res. 2023; 25:e44649. doi: 10.2196/44649.
140. Luna N, Munoz M, Bonilla-Aldana DK, Patino LH, Kasminskaya Y, Paniz-Mondolfi A, et al. Monkeypox virus (MPXV) genomics: A mutational and phylogenomic analyses of B.1 lineages. Travel Med Infect Dis. 2023; 52:102551. doi: 10.1016/j.tmaid.2023.102551.
141. Struelens MJ, Ludden C, Werner G, Sintchenko V, Jokelainen P, Ip M. Real-time genomic surveillance for enhanced control of infectious diseases and antimicrobial resistance. Frontiers in Science. 2024; 2. doi: 10.3389/fsci.2024.1298248.
142. Wang Y, Sun K, Feng Z, Yi L, Wu Y, Liu H, et al. Assessing the feasibility of sustaining SARS-CoV-2 local containment in China in the era of highly transmissible variants. medRxiv. 2022. doi: 10.1101/2022.05.07.22274792.
143. Banuet-Martinez M, Yang Y, Jafari B, Kaur A, Butt ZA, Chen HH, et al. Monkeypox: a review of epidemiological modelling studies and how modelling has led to mechanistic insight. Epidemiol Infect. 2023; 151:e121. doi: 10.1017/S0950268823000791.
144. Sah R, Alshahrani NZ, Head MG, Abdelaal A, Mohanty A, Padhi BK, et al. Major sporting events amid monkeypox and COVID-19 outbreaks: Considering the impact upon the traveller. Int J Surg Open. 2022; 49:100576. doi: 10.1016/j.ijso.2022.100576.
145. Bunge EM, Hoet B, Chen L, Lienert F, Weidenthaler H, Baer LR, et al. The changing epidemiology of human monkeypox-A potential threat? A systematic review. PLoS Negl Trop Dis. 2022; 16(2):e0010141. doi: 10.1371/journal.pntd.0010141.
146. Loerbroks L, Kersten LJ, Freund PA. Staying physically active during the COVID-19 pandemic: Assessing the roles of motivation, basic psychological needs, goal orientation and anticipatory sport persistence. Front Psychol. 2023; 14:1057178. doi: 10.3389/fpsyg.2023.1057178.
147. Bayle E. A model for the multi-centered regulation of world sport. International Journal of Sport Policy and Politics. 2023; 15(2):309–27. doi: 10.1080/19406940.2023.2205868.
148. Carvache-Franco M, Hassan T, Orden-Mejia M, Carvache-Franco O, Carvache-Franco W. Motivations and satisfaction of sports tourists during the FIFA world cup in Qatar 2022. Heliyon. 2024; 10(5):e26682. doi: 10.1016/j.heliyon.2024.e26682.
149. Den Hartigh RJR, Meerhoff LRA, Van Yperen NW, Neumann ND, Brauers JJ, Frencken WGP, et al. Resilience in sports: a multidisciplinary, dynamic, and personalized perspective. Int Rev Sport Exerc Psychol. 2024; 17(1):564–86. doi: 10.1080/1750984X.2022.2039749.
150. Hussain T, Wang D, Li B. Psychological resilience in athletes during the COVID-19 pandemic: A qualitative insight. Acta Psychol (Amst). 2023; 240:104050. doi: 10.1016/j.actpsy.2023.104050.
151. Betz UAK, Arora L, Assal RA, Azevedo H, Baldwin J, Becker MS, et al. Game changers in science and technology – now and beyond. Technological Forecasting and Social Change. 2023; 193:122588. doi: 10.1016/j.techfore.2023.122588.
152. Dwivedi YK, Hughes L, Baabdullah AM, Ribeiro-Navarrete S, Giannakis M, Al-Debei MM, et al. Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. International Journal of Information Management. 2022; 66:102542. doi: 10.1016/j.ijinfomgt.2022.102542.
153. Emrouznejad A, Abbasi S, Sıcakyüz Ç. Supply chain risk management: A content analysis-based review of existing and emerging topics. Supply Chain Analytics. 2023; 3:100031. doi: 10.1016/j.sca.2023.100031.
154. Dergaa I, Chamari K, Zmijewski P, Ben Saad H. From human writing to artificial intelligence generated text: examining the prospects and potential threats of ChatGPT in academic writing. Biol Sport. 2023; 40(2):615–22. doi: 10.5114/biolsport.2023.125623.
155. Dergaa I, Ben Saad H. Artificial Intelligence and Promoting Open Access in Academic Publishing. Tunis Med. 2023; 101(6):533–6.

Articles published in the Biology of Sport are licensed under an open access Creative Commons CC BY 4.0 license.





DOFINANSOWANO ZE ŚRODKÓW BUDŻETU PAŃSTWA

Program Ministerstwa Nauki i Szkolnictwa Wyższego
Rozwój Czasopism Naukowych
RCN/SP/0003/2021/1

DOFINANSOWANIE
92 000,00 zł

CAŁKOWITA WARTOŚĆ
109 600,00 zł

DATA PODPISANIA UMOWY
20 stycznia 2023