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Biological maturity vs. relative age: Independent impact on physical performance in male and female youth handball players

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ABSTRACT: Maturity status and relative age are two of the determining factors in talent development. The aim of the study was to analyze the influence of biological maturity status and relative age on physical performance in young male and female handball players. The sample included 48 males (14.11 ± 1.17 years) and 41 females (14.25 ± 1.64 years) players from one Spanish professional handball academy. Anthropometric data (height, sitting height, body mass and self-reported biological parent heights) and physical performance data (CMJ, DJ, 20 m speed, T-test and throwing velocity) were collected. Biological maturity status was determined as the percentage of predicted adult height, while relative age was estimated in birth quartiles based on biennial age grouping (Q1–Q8). The results showed a positive correlation between maturity status and CMJ in male players ($p < 0.01$). Differences in CMJ performance according to maturity status were identified ($p < 0.05$), with higher jump heights being recorded especially in early maturing boys ($p < 0.01$) and first lines and wings ($p < 0.05$). The variance in CMJ test scores could be explained by the maturity status by 42.90% in U–15 ($p < 0.05$) and 72.60% in U–16 male players ($p < 0.001$). By contrast, no differences were found in girls ($p > 0.05$). Moreover, no relationships were found between relative age and indices of physical performance ($p > 0.05$). Overall, maturity status had greater impacts on the tests of physical performance than relative age. Stakeholders should monitor the maturity status of young handball players to avoid physical performance biases that do not allow them to develop their sporting potential.

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INTRODUCTION

Recruiting players for talent pathways with the aim of developing them towards high performance is one of the main purposes of handball academies between the ages of 7–8 and 15–16 years [1]. Young talents often enjoy a wide range of high quality sporting experiences with a positive impact on both the player (e.g., increased technical-tactical level) and the club (e.g., reputational gain) [2]. However, there are some influential factors in the talent development process that may modify the transition from the handball academy to high performance contexts, such as relative age and maturity status [3–5]. Whilst relative age and maturity status are two different constructs that are often used interchangeably, they are easily confused in the talent identification and development systems implemented by team sports academies [6].

The difference in chronological age between athletes of an age group according to their birthdate is known as 'relative age' [7]. This concept reflects the age difference between athletes born in the same selection year or biennial cycle, delimited by a previously established cut-off date, and its consequences are known as 'Relative Age Effects' (RAE or RAEs) [8]. This phenomenon has been analysed in different handball contexts with different results [9, 10]. However, the majority of research has identified a higher prevalence of RAEs in males and in formative categories (age groups 10/12–16/18 years),

attenuating as players get older and with some variance relative to playing position or the demands of the sport [11].

Biological maturation is defined as the rate of progress towards adulthood and can be considered through the concepts of 'status', 'timing', and 'tempo' [12]. The 'when' and at what rate maturational development occurs are factors that differ between young players, especially between the ages of 11 to 16 years for boys and 10 to 15 years for girls [13, 14] with the potential for substantial variance in age of peak high velocity (i.e., some children maturing well in advance or delay of their same age peers). Therefore, the maturity status of young players of the same chronological age could differ considerably, as Johnson [14] demonstrated by identifying a five-to-six-year differential between athletes of the same age group in relation to skeletal age and somatic maturity. Individual differences in maturity timing are largely governed by a combination of genetic and environmental factors, and are of particular relevance from early adolescence when pubertal changes in size and athleticism can afford specific (dis)advantages [15].

Individual differences in growth and maturation are critical for the identification and development of talented young athletes. Thus, early maturational timing increases the likelihood of selection for talent programmes in sport compared to peers in the same age group with later maturation [4]. For example, Johnson et al. [16] identified that early maturing football players were more likely to be selected into England's elite academies as the player progressed through the different age groups and, consequently, selection bias increased. Furthermore, this same study reported that players with a more advanced maturity status tended to be retained in the system around 20 times more than on-time and late maturers. One of the main reasons for this is the relevance of anthropometric and physical factors in performance. Thus, on-time or late maturers tend to be less tall and have less lean muscle mass [17], perform lower on strength and power tests [18], and develop 20% lower sprint speed than early maturers [19].

Considering the impact of the RAE on talent identification and development programmes, it is worth asking whether maturity status and relative age converge and whether one of them is more prevalent throughout the process, especially associated with physical performance. A study by Parr et al. [5] concluded, with a sample of 84 football players aged 11–16 years, that the mixed impact of relative age and maturity status on physical performance was *differential* but *small*, not considering both factors mutually influential. Moreover, separate analysis yielded different correlation values between physical performance and RAEs ($r = 0.19 – 0.23$; *weak*) and maturity status ($r = 0.71 – 0.75$; *strong*). Cumming et al. [20] and Sweeney et al. [3] went one step further affirming that relative age should not be treated as a proxy indicator for biological maturation because older age within an age group would not necessarily imply more advanced maturation. In the same line, Hill et al. [21] and Johnson et al. [16] argued, not only that RAE and maturity status operate separately, but that there is a time lag in their onset and evolution. Thus, while RAEs appear in late childhood and persist into adolescence and decline with age, differences with regard to maturity status do not emerge until puberty and increase with age. For example, Radnor et al. [4] found in a study of young English footballers that 33% of players born in Q4, although fewer in absolute terms, had early maturity status compared to Q1, Q2 and Q3 (10–30%).

In women' sport, the impact of maturity status and relative age on physical performance is less clear-cut. Girls' physical qualities (e.g., strength), although they develop earlier than boys' due to earlier maturation, do not increase as markedly throughout the sport development process as boys' [15]. Furthermore, early maturation (i.e., increased body size and/or fat mass levels) may be detrimental in sports with high agility and coordination requirements [17]. These differences could influence performance in sports where physical attributes are decisive, such as handball [22]. With regard to RAE, there is no homogeneity of results. [23]. Factors such as the depth of competition, popularity or the number of active participants could be determinants for the lack of impact of relative age on player recruitment processes and competition performance in women' sport [24].

A number of studies in different sports have considered the relationships between relative age, maturity status, and physical performance in young male athletes [25, 26]. To the best of our knowledge, no study in handball incorporating the female gender has been carried out. Moreover, this phenomenon is yet to be explored in the context of handball, which is a sport characterised by physical attributes and thus leaves young athletes vulnerable to the aforementioned biases. Therefore, the aim of the present study was to analyze the influence of biological maturity status and relative age on physical performance in young male and female handball players. According to previous research, the hypothesis of this study was that the biological maturity status of Spanish handball academy players had a greater impact than relative age on physical fitness tests performed.

MATERIALS AND METHODS

Sample

A total of 89 handball players (males: $n = 48$; females: $n = 41$) belonging to U–13 ($n = 30$), U–14 ($n = 17$), U–15 ($n = 18$), U–16 ($n = 15$) and U–17 ($n = 9$) age groups of the Spanish Handball Academy volunteered to participate in the cross-sectional study. According to playing position, the players were distributed as goalkeepers ($n = 7$), wings ($n = 30$), first lines (center backs and backs) ($n = 35$), and pivots ($n = 17$). The inclusion criteria comprised of belonging to the structured training programme implemented by the academy's qualified coaches whose development starts between the ages of 6 and 8 years in the club's schools. Furthermore, none of the players reported being injured at the testing time or having suffered a disabling injury or pathology in the previous three months. The parents and/or legal guardians of the minor players were duly

informed by means of an informed consent in order to be able to extract, record, and use the data derived from the study. The project and the scientific use of the data was approved by the Ethics Committee of the Universidad Politécnica de Madrid (2020-089; 2020-090; 2020-091) in compliance with the Declaration of Helsinki.

Procedures

The physical performance tests were conducted based on the recommendations established by the National Strength and Conditioning Association (NSCA) [27], with all players at rest before completing the tests in the following order: (a) anthropometric measurements, (b) physical fitness tests, and (c) sport-specific tests. Anthropometric data were used to calculate the biological maturity status.

Anthropometric Assessment

Standing height was measured with a stadiometer to the nearest 0.1 cm. (SECA, 216, Vogel & Halke, Hamburg, Germany). In addition, a 40 × 50 × 30 cm wooden anthropometric box (Smart Met, Jalisco, Mexico) was used for sitting height. Body mass was measured to the nearest 0.1 kg. on a digital scale (SECA, 876, Vogel & Halke, Hamburg, Germany). Parental stature was provided in centimetres for each father and mother and then converted to inches to adjust for overestimation [28]. The following adjustment factor was used for males ($y = 2.316 + 0.955x$) and for females ($y = 2.803 + 0.953x$), where '*y*' was the adjusted height and '*x*' was the self-reported value. All the measurements were carried out according to the International Standards for Anthropometric Assessment (ISAK) [29] by accredited staff (level 2).

Biological Maturity Status

The biological maturity status was calculated from the Khamis-Roche equation validated especially for white Caucasian children. This equation provides the predicted adult height (PAH) using a regression formula based on gender-specific coefficients [30]. Estimated biological maturity status was expressed as a z-score relative to age-specific reference values for males and females, using the percentage of predicted adult height (% PAH) attained at the time of measurement and half-year age and sex-specific means and standard deviations from the Berkeley Guidance Study [31]. These maturity status classifications have shown a moderate correlation with other maturational classifications based on skeletal age in both males and females [32]. The z-scores associated with the % PAH were used to classify handball players as "late maturers"(z-score < – 0.5), "on-time maturers" (-0.5 < z-score < + 0.5), or "early maturers" (z-score > + 0.5), as in other studies of youth team players. This less conservative and more sensitive criterion was used in order to reduce the differences derived from categorising players according to notably different maturity status, as with the traditional criterion (± 0.99 z-score) we could find a larger differential in growth and maturation determinants factors such as skeletal age (approximately two years) [21, 33].

Relative Age

Players were categorised into eight quartiles (Q) according to relative age based on their birthdate and cut-off date for the respective biennial cycle established by the International Handball Federation (IHF). The players were grouped as follows according to even/odd-numbered years: Quartile 1/5 (Q1/Q5): January 1–March 31; Quartile 2/6 (Q2/Q6): April 1–June 30; Quartile 3/7 (Q3/Q7): July 1–September 30; Quartile 4/8 (Q4/Q8): October 1–December 31.

Physical Fitness Tests

The countermovement jump (CMJ) and drop jump (DJ) test were performed to evaluate the elastic-explosive manifestation and reactive strength of the lower body strength respectively. The tests were carried out on a contact platform (Chrono Jump Bosco System ®, Spain) and the jump height was measured in centimetres. The margin of error of the microcontroller was 0.1% and the validity of the fiberglass platform was 0.95 (ICC) [34]. Prior to the test, the players were instructed in each of the jumping technique [35]. Both tests were preceded by a warm-up jump at 50% and 75% of the self-determined maximum effort of the players and each of them performed a practice jump for familiarisation. Three attempts were made with a 60-seconds passive recovery [36]. If the range of jump height variation was ^{3} 0.4 cm, additional jumps were performed until the threshold was satisfied and the mean height was taken. The difference in variances between groups (two vs. three attempts) was tested by means of a t-test with a significance level of $p > 0.05$.

The T-test was conducted to examine the timed agility of the players according to Pauole et al. [37] protocol. Players were instructed to finish the 'T' circuit (9.14 m × 4.47 m on both sides) in the shortest time. Prior to test, all players completed warm-up efforts at 75% of their self-determined maximum and were allowed to perform a familiarisation attempt with the circuit. Two attempts were made, with a 2-minute passive recovery between them, taking the average time of both as the final test result measured by a photoelectric cell gate (Chrono Jump, Bosco System, Barcelona, Spain) with almost perfect reliability (*ICC* = 0.999–1.000) [34].

The 20 m linear speed test was used to evaluate the running speed of players. The course will consist of a straight-line run asking the players to run at the maximum possible speed to cross two photoelectric cell gates (Chrono Jump, Bosco System, Barcelona, Spain; *ICC* = 0.999–1.000) [34] separated by 20 m. Time and speed were recorded after the completion of two attempts separated by a 3-minute passive recovery, having previously warmed up to 75% of their maximum self-perceived effort. The best 20 m time was used for further analysis.

The throwing speed test was performed to measure the speed in the specific throwing action in handball. Thus, the speed was examined in a throwing situation at a distance of 9 m with a 3-step run and a final jump with one foot. The ball used was the one established by the IHF regulations for each gender and competitive level. A radar gun (Stalker Pro Inc., Plano, TX, USA; *ICC* = 0.987–1.000 [38]),

with a sampling frequency of 100 Hz and a sensitivity of 0.045 m/s, was placed 1 m behind the goal net and perpendicular to the player with the aim to eliminate possible angle errors [39]. Prior to the test, a standardised warm-up specific to handball was performed. Each player made two attempts with a 1-minute passive recovery. The best speed result was used for further analysis.

Statistical Analysis

The analyses were conducted with SPSS (Version 26). Data are expressed as mean and standard deviation ($X \pm SD$). Absolute and relative frequency counts were used to determine the number of handball players within each quartile (Q1–Q8) and each biological maturity z-score (i.e., early, on-time, late), according to gender, playing position, and age group. The assumption of normality of each variable was assessed by Kolmogorov–Smirnov test (n ^{3} 50), and Shapiro-Wilk's test (n < 50) and Levene's test was carried out to verify the homogeneity of variances. A Pearson's correlation was run to analyse the relationship between biological maturity status and relative age and the physical fitness tests. A one-way ANOVA was conducted to test for differences in physical fitness tests between groups according to the biological maturity status and relative age. Moreover, Tukey-Kramer's post hoc test was performed to confirm the difference between biological maturity groups. Partial eta-squared (ηp^2) was used to evaluate the effect size of the differences between groups, considering small (0.01), medium (0.06), or large value (0.14) [40]. Furthermore, a linear regression was performed to examine the impact of biological maturity status and relative age on physical fitness tests scores. The value of $p < 0.05$ was set as significant for all statistical comparisons.

RESULTS

The sample descriptive statistics according to the biological maturity status and relative age of male and female players are shown in Figures 1 and 2(a-c), respectively. With regard to maturity status, 34 early (38.20%), 26 on-time (29.21%), and 29 late maturers (32.59%) were identified. In relation to relative age, the sample was distributed in the following quartiles (Q): Q1 (n = 10; 11.3%); Q2 (n = 8; 9.00 %); Q3 (n = 6; 6.70 %); Q4 (n = 8; 8.90 %); Q5 (n = 11; 12.30 %); Q6 (n = 21; 23.60 %); Q7 (n = 15; 16.90 %); and, Q8 (n = 10; 11.20 %).

The correlations between biological maturity status and relative age and the five physical fitness tests are presented in Table 1. A positive correlation between biological maturity status and CMJ ($r = 0.540$; $p < 0.001$) was identified in male players. Figure 3 presents in detail (scatter plot) the marks obtained by male and female players in the CMJ test according to the biological maturity status based on the percentage of adult height (% PAH).No significant correlations in the remaining physical fitness tests with regard to the biological maturity status and relative age were observed ($p > 0.05$, all).

Table 2 shows the performance values ($X \pm SD$) for each of the five physical fitness tests performed according to biological maturity status, relative age, and gender. The CMJ test results showed significant differences between the different maturity groups ($F_{(2,86)} = 4.55$, $p < 0.05$, $\eta^2 = 0.10$), with higher jumping height values in the early maturers ($X \pm SD = 29.99 \pm 5.96$) than late maturers ($X \pm SD = 26.07 \pm 4.62$). Analysing the sample by gender, the impact of the biological maturity status on the CMJ test was significant in boys ($F_{(2,45)} = 5.72$, $p < 0.01$, $\eta^2 = 0.20$), with higher jump scores registered in the early maturers ($X \pm SD = 33.53 \pm 5.85$) than in the late maturers ($X \pm SD = 27.06 \pm 5.65$), while in girls the effect disappeared ($p > 0.05$). According to playing position, biological maturity status influenced jump height in the CMJ test carried out by first lines ($F_{(2,32)} = 3.92$, $p < 0.05$, $\eta^2 = 0.20$), with higher values in early ($X \pm SD = 30.42 \pm 5.52$) than in late maturers ($X \pm SD = 25.04 \pm 3.67$). No significant correlation was found in the remaining physical fitness tests ($p > 0.05$). No correlation was also found between relative age and physical fitness tests ($p > 0.05$) (Table 3).

Physical fitness tests regressions carried out by gender showed biological maturity status in boys explained 27.90% of the variance obtained in the CMJ test ($R^2 = 0.28$, $F_{(1,46)} = 19.18$, $p < 0.001$), rising to 61.70% in early maturing boys ($R^2 = 0.62$, $F_{(1,13)} = 23.54$, $p < 0.001$). In girls, biological maturity status explained 31.60% of the variance registered in the CMJ test on-time maturers ($R^2 = 0.32$, $F_{(1,9)} = 5.61$, $p < 0.05$).

In relation to age group, 19.30% of the change in T-test scores achieved by U–14 players ($R^2 = 0.19$, $F_{(1,15)} = 4.83$, $p < 0.05$) and 37.40% of the change in CMJ scores performed by U–16 players ($R^2 = 0.37$, $F_{(1,13)} = 9.35$, $p < 0.01$) were explained by the biological maturity status.

In the combined gender and age group analysis, 38.50% of the variance recorded in the throwing velocity test scores in U–17 female players ($R^2 = 0.38$, $F_{(1,7)} = 6.00$, $p < 0.05$) and 31.70% of the variance in the CMJ test scores in U–13 female players ($R^2 = 0.32$, $F_{(1,14)} = 7.97$, $p < 0.05$) were explained by the biological maturity status. In U–15 and U–16 male players, the variance in CMJ test scores could be explained by the biological maturity status by 42.90% ($R^2 = 0.43$, $F_{(1,7)} = 7.02$, $p < 0.05$) and 72.60% ($R^2 = 0.73$, $F_{(1,12)} = 32.79$, $p < 0.001$), respectively.

Based on playing position, the biological maturity status explained 29.90% of the CMJ test scores performed by male first line players ($R^2 = 0.30$, $F_{(1,17)} = 8.69$, $p < 0.01$) and 50.80% of those achieved by male wing players ($R^2 = 0.51$, $F_{(1,13)} = 15.47$, $p < 0.01$).

Regression analyses showed no differences in physical fitness across the RAE groups ($p > 0.05$).

DISCUSSION

The present study aimed to analyse the impact of biological maturity status and relative age on physical fitness tests performed by male and female players belonging to a Spanish handball academy

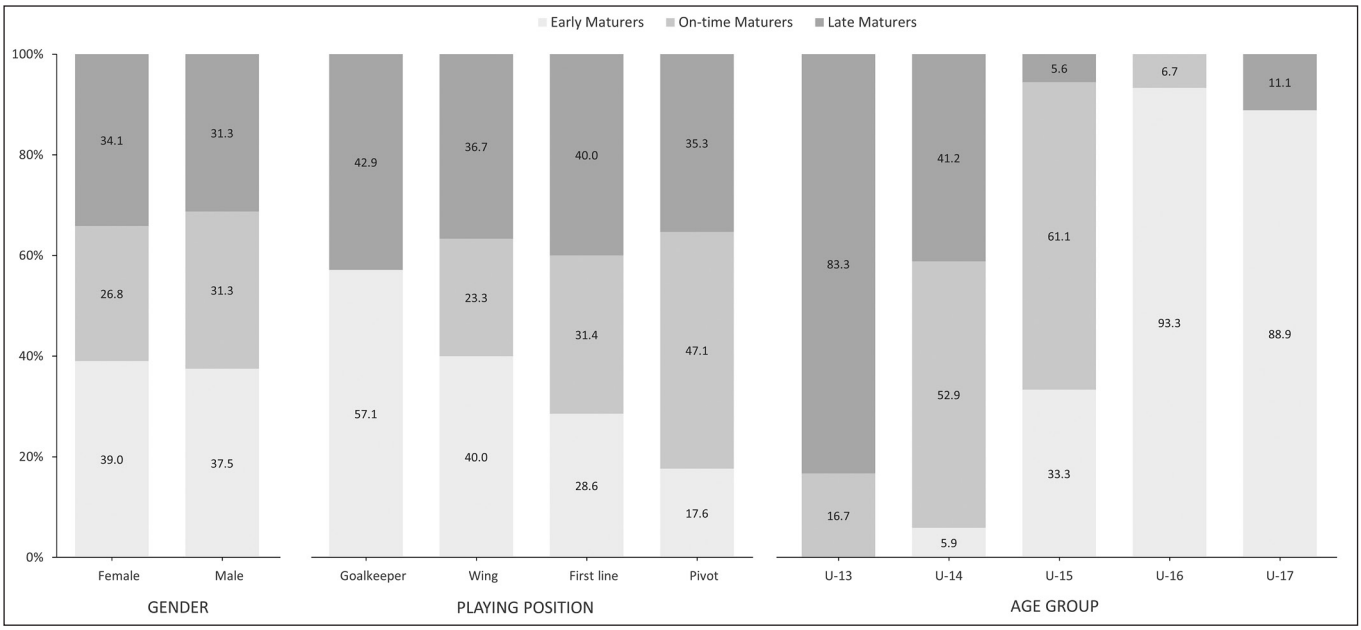


FIG. 1. Player characteristics by biological maturity status.

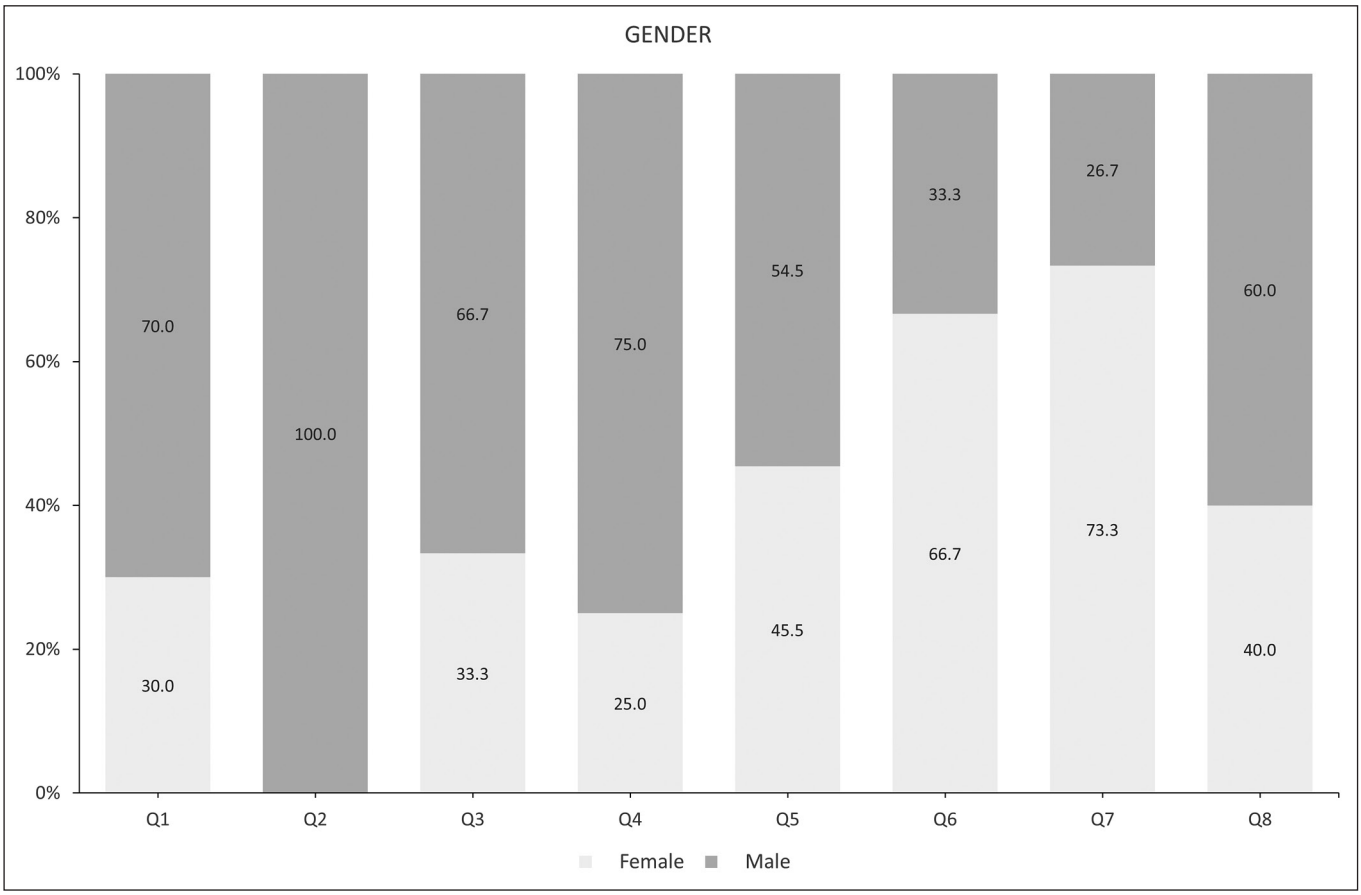


FIG. 2a. Player characteristics by relative age according to gender.

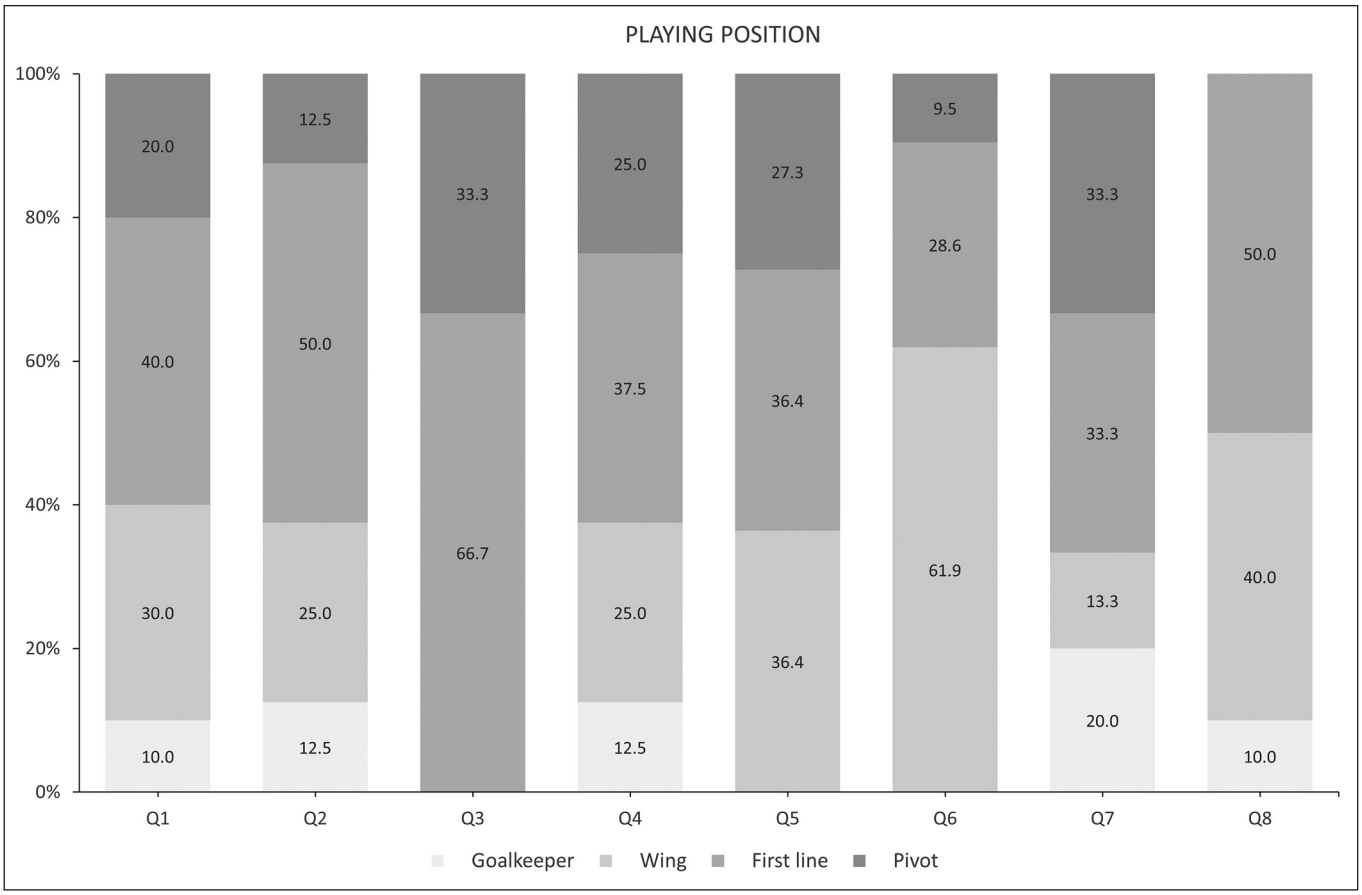


FIG. 2b. Player characteristics by relative age according to playing position.

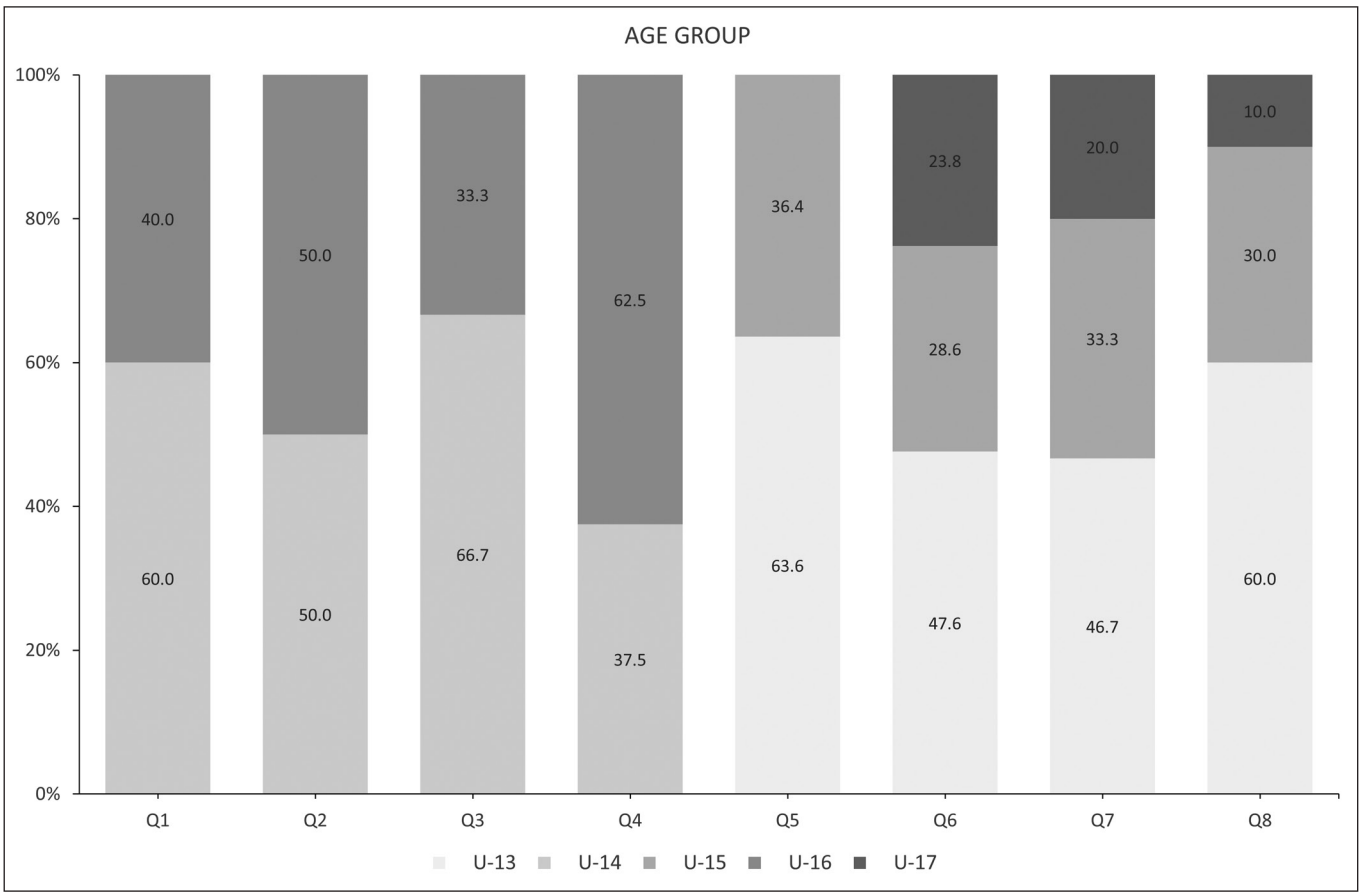


FIG. 2c. Player characteristics by relative age according to age group.

TABLE 1. Correlation between relative age/biological maturity status and physical fitness tests according to gender.

		Physical Fitness Tests				
		CMJ	**DJ**	**20 m. speed**	**T-test**	**Throwing velocity**
Women Players (n = 41)	RA	0.20	−0.15	0.18	−0.04	0.09
	BMS	0.12	0.01	0.08	0.01	0.11
Men Players (n = 48)	RA	−0.17	−0.21	−0.05	0.02	0.14
	BMS	0.54**	0.23	0.01	0.05	−0.13
All Players (n = 89)	RA	−0.19	−0.18	0.08	0.02	0.08
	BMS	0.16	0.10	0.08	0.06	−0.05

Notes: CMJ = countermovement jump; DJ = drop jump. *$p < 0.05$; **$p < 0.001$.

TABLE 2. Anthropometric characteristics and descriptive statistics ($X \pm SD$) of physical fitness tests according to the biological maturity status (early, on-time and late) of female and male handball players.

	Early Maturers		**On-time Maturers**		**Late Maturers**		***p***	***ηp²***
	X	***SD***	***X***	***SD***	***X***	***SD***		
Height								
All	167.42	7.81	162.09	7.66	162.38	7.52	-	-
Females	163.69	5.09	158.38	1.63	159.42	3.17	-	-
Males	170.91	8.43	164.80	9.18	165.01	9.23	-	-
Weight								
All	59.44	7.05	55.60	3.61	56.22	5.07	-	-
Females	58.69	4.52	52.31	2.10	52.85	4.37	-	-
Males	60.15	8.91	58.01	2.33	59.22	3.57	-	-
CMJ								
All	29.99[a]	5.96	28.20	4.87	26.07[a]	4.62	0.013*	0.10
Females	26.20	3.11	25.85	4.01	24.96	2.87	0.574	0.03
Males	33.53[a]	5.85	29.93	4.84	27.06[a]	5.65	0.006**	0.20
DJ								
All	25.56	7.15	21.84	5.33	23.18	8.37	0.154	0.04
Females	24.45	5.27	20.71	6.41	24.12	9.70	0.416	0.05
Males	26.59	8.61	22.66	4.44	22.34	7.18	0.178	0.07
20 m. speed								
All	3.47	0.31	3.46	0.20	3.43	0.28	0.881	0.00
Females	3.50	0.32	3.51	0.18	3.45	0.29	0.841	0.01
Males	3.44	0.31	3.43	0.22	3.42	0.29	0.985	0.00
T-test								
All	12.69	1.25	12.71	0.89	12.55	1.11	0.815	0.01
Females	12.70	1.24	12.92	0.79	12.63	1.19	0.806	0.01
Males	12.68	1.30	12.57	0.96	12.48	1.06	0.873	0.01
Throwing velocity								
All	69.24	9.94	70.67	9.39	70.53	10.65	0.838	0.00
Females	70.24	9.07	67.86	8.90	68.83	11.25	0.834	0.01
Males	68.31	10.93	72.72	9.49	72.04	10.16	0.445	0.04

Notes:CMJ = countermovement jump; DJ = drop jump. [a] = differences between early and late maturers; [b] = differences between early and on-time maturers; [c] = differences between on-time and late maturers *$p < 0.05$. **$p < 0.01$.

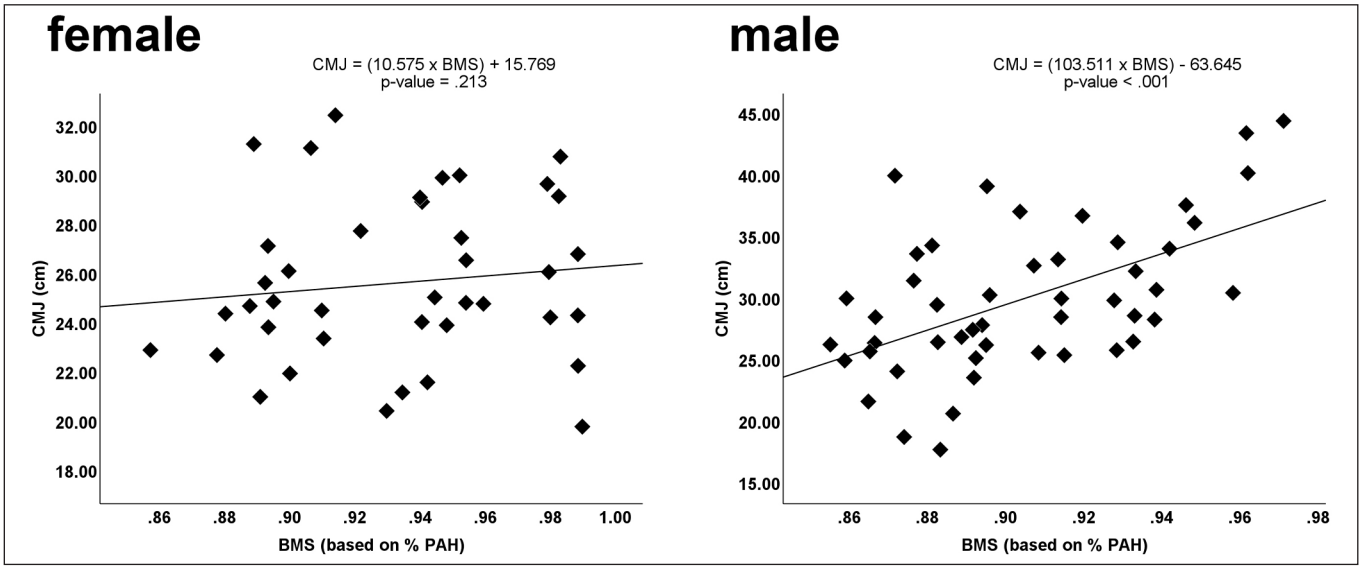


FIG. 3. CMJ test scores of male and female handball players according to biological maturity status (BMS) based on percentage of adult height (% PAH).

TABLE 3. Descriptive statistics ($X \pm SD$) of physical fitness tests according to the relative age (Q1 – Q8) of female and male handball players.

PFT	Q1		Q2		Q3		Q4		Q5		Q6		Q7		Q8		*p*	ηp^2
	X	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*	*X*	*SD*		
CMJ																		
All	28.7	7.2	30.6	6.1	27.8	6.9	30.8	6.1	28.0	6.8	26.6	3.8	27.5	4.5	26.5	3.0	0.475	0.08
Females	22.8	2.5	-	-	22.5	3.1	27.0	3.1	26.2	2.8	26.3	3.8	26.2	3.8	24.0	0.9	0.378	0.16
Males	31.3	7.1	30.6	6.1	30.5	6.9	32.1	6.5	29.5	8.9	27.2	4.1	31.1	6.2	28.1	2.8	0.862	0.07
DJ																		
All	26.3	4.8	24.2	7.4	24.1	11.2	24.4	9.4	24.6	9.5	23.5	6.7	21.2	6.1	21.9	5.7	0.802	0.05
Females	27.8	5.8	-	-	19.7	12.3	23.8	9.6	23.7	9.9	24.8	7.6	21.0	6.2	22.3	9.7	0.493	0.08
Males	25.6	4.6	24.2	7.4	26.3	11.8	24.6	10.2	25.3	10.1	20.9	3.6	21.7	6.9	21.6	1.7	0.870	0.07
20 m. speed																		
All	3.3	0.3	3.5	0.3	3.4	0.3	3.5	0.4	3.4	0.2	3.4	0.3	3.6	0.2	3.4	0.3	0.573	0.07
Females	3.2	0.2	-	-	3.6	0.1	3.6	0.6	3.4	0.2	3.5	0.3	3.5	0.2	3.6	0.4	0.633	0.10
Males	3.4	0.3	3.5	0.3	3.3	0.3	3.5	0.4	3.4	0.3	3.4	0.2	3.6	0.5	3.3	0.2	0.599	0.12
T-test																		
All	12.3	1.0	12.7	0.9	12.9	1.3	12.9	1.6	12.9	1.0	12.4	1.2	12.7	0.9	12.7	1.1	0.831	0.04
Females	12.6	0.9	-	-	13.5	0.1	13.1	2.6	12.9	0.7	12.5	1.2	12.6	0.9	13.2	1.4	0.507	0.08
Males	12.2	1.1	12.7	0.9	12.7	1.6	12.8	1.4	12.8	1.3	12.2	1.2	13.1	0.8	12.3	0.8	0.832	0.08
Throwing velocity																		
All	70.6	9.2	68.5	10.6	69.5	11.9	66.6	11.4	70.3	11.0	70.3	11.6	70.6	8.3	73.1	7.3	0.956	0.02
Females	72.0	10.5	-	-	59.2	9.5	72.0	11.3	67.2	5.9	67.4	12.6	71.1	7.8	72.6	7.0	0.644	0.10
Males	70.0	9.4	68.5	10.6	74.6	10.1	64.8	11.9	72.9	14.0	76.0	7.1	69.2	10.8	73.4	8.1	0.613	0.12

Notes: PFT = physical fitness test; CMJ = countermovement jump; DJ = drop jump. $^{*}p < 0.05$. $^{**}p < 0.01$.

based on three modulating variables (i.e., gender, playing position, and age group). Results showed biological maturity status was associated with CMJ performance in male players whereas relative age presented no relationship level with the scores obtained in the physical fitness tests. Specifically, an advanced maturity status was associated with higher performance in the CMJ test, especially in the case of early maturing boys (by gender), belonging to the U–15 and U–16 male age groups (by gender and age group), and first lines and wings (by playing position). On the other hand, no differences in physical performance were found among female players according to the biological maturity status and relative age. Nevertheless, biological maturity status functioned as a performance predictor, less powerful than for boys, in the throwing velocity test in U–17 female players and in the CMJ test in U–13 female players.

The main result indicates physical performance in young handball players was more influenced by biological maturity status than by relative age. Similar results were obtained by Parr et al. [5] in a sample of 84 male football players aged between 11.3 and 16.2 years confirming a higher correlation between biological maturity status and physical performance. Moreover, a recent study in two English football academies with male players aged between 8.1 and 18.9 years found that the impact of maturity status on sprinting ability was greater than that of relative age, with early maturers obtaining better times and velocities [4]. Therefore, this evidence would support the idea that the two constructs–biological maturity status and relative age–operate independently and the functional advantages associated with an advanced maturity status may not be attributed to RAEs [16].

It should be noted that the two factors (biological maturity status and relative age) do not coincide in the same period of children's development so the physical (dis)advantages on the talent selection process will not be the same. [6]. Thus, while RAEs operate in childhood and is maintained (although generally decreasing) throughout adolescence, the maturational bias emerges with the onset of puberty and increases in magnitude with adolescence [12, 21]. Indeed, Johnson et al. [16] identified a higher likelihood of selection to elite U–17 teams for early maturers (20 times) than for relatively older players at the start of developmental programmes (2.2 times). The most plausible explanation would lie in the temporary gain in physical and anthropometric qualities attributed to early maturers, with late maturers being excluded to a greater extent throughout the formative stages.

Although the impact of the biological maturity status on physical performance seems to be discrete, the scientific literature agrees that the CMJ is one of the tests most influenced by maturity status [4, 5], with high values of variance being in jump height [41]. Specifically, the results of the present study even explained 61.70% of the variance recorded in the CMJ for early maturing male players. Since the CMJ expresses the power of the lower limbs playing a fundamental role in the jumping actions of handball (e.g., defensive blocking) [22], it is interesting to note that male players of advanced maturity status obtained greater jump heights. A higher percentage of lean mass and larger body size (height and weight), due to a more intense adolescent growth spurt, could be the main determinants of the superior physical performance of early maturers [42]. On the other hand, it is worth noting the lack of impact of biological maturity status on sprinting ability. A training method not primarily aimed at improving sprinting ability in handball due to the lower relevance in the game to the detriment of other abilities (i.e., strength) and higher height and weight values at this age (14.17 ± 1.39 years) than other sports such as football [43], could be two of the explanations. Nevertheless, it would be appropriate to analyse this relationship separately for playing positions with a greater displacement speed (e.g., wings).

Furthermore, the impact of biological maturity status on CMJ was amplified in the U–16 male age group (72.60 % of the variance). Entering adolescence produces a series of body changes that lead to the development of higher strength levels [44]. This appears to be multiplied in children aged 11–15 years [45] as well as in early maturers [17], providing a sporting advantage over less mature peers. Neuromuscular gains due to increasingly higher intensity and volume of training as the chronological age increases could explain the performance differential in the CJM test [46]. Therefore, chronological age and biological maturity status could be playing a dual role on jumping ability of handball players in formative sporting stages. On the other hand, a notable influence of biological maturity status (50.80% of the variance) was identified in the CMJ test in wing male players. The game-specific physical demands cause this playing position to require a higher jumping ability [47]. Nevertheless, and in comparison to other playing positions where the variance in maturity status was not as wide (e.g., pivot), it is necessary to highlight that the performance differences in jumping ability is not only influenced by an advanced maturity status but also by a well-developed jumping ability throughout the training process [48].

The results are not as clear for adolescent women as in previous studies [49]. While jumping ability was influenced by biological maturity status in the U–13 age group (31.70% of the variance), throwing velocity was explained by 38.50% in the U–17 age group. This highlights the different impact of the biological maturity status on physical performance among girls throughout adolescence [33]. Early maturing girls typically experience exponential body size growth in early adolescence that allows them to develop higher strength levels in jumping or sprinting tests. However, these strength levels seem not to be as decisive in tests such as the CMJ or 20 m sprint as this stage develops, due to increases in body fat leading to a loss of agility levels [17]. Conversely, lower limb strength levels become less important in the throwing action throughout adolescence to the detriment of anthropometric perimeters and upper limb strength levels [50]. Therefore, this could mean that the impact of the biological maturity status would be greater in higher age groups such as U-17.

This study is not without its limitations. First, the research was carried out in a single academy at a handball club and with an

available sample of boys and girls aged over 12 years, so in terms of statistical testing the sample could be considered small. Second, parental heights for the PAH were self-reported, rather than measured, and subsequently adjusted for overestimation. Third, the equation generally used for the prediction of adult height was validated on Caucasian children and may not be appropriate for the calculation of biological maturity status in children of other ethnicities. Fourth, no reference data (i.e., Spanish growth reference data) was used for the calculation of the z-scores which could influence the categorisation of the players according to the biological maturity status. Finally, the non-use of force plates for the evaluation of the jumping tests (CMJ and SJ) did not allow for a full exploration of the performance strategy (e.g., direct measurement of force applied).

CONCLUSIONS

This study, considered as an initial exploration of the topic, determined the impact of biological maturity status on the physical performance of young handball players, whilst no effect was observed for relative age. Specifically, the maturity status affected the CMJ test scores, showing that the more mature players (male, U–15/U–16, and wings and first lines) performed better than the rest. The results was not as clear-cut for female handball players. These findings should serve to understand, both for stakeholders and practitioners, that these two constructs can have a different influence on the athlete physical performance. Thus, a late maturing or relatively young player should not be relegated within talent development programmes, even to the point of drop-out, but stakeholders should find the right strategy to retain him/her and develop his/her future potential by providing adapted competitive experiences. Therefore, regular growth and maturation assessment within talent development systems is necessary to monitor and track the physical performance of young male and female handball players. The implementation of training and competition strategies based on biological maturational status (e.g., bio-banding) [51] should be considered in order to reduce the player selection and retention bias according to anthropometric and physical factors. Nevertheless, it is worth noting the need for prospective studies with larger samples to analyse the impact of the maturity status and RAE on selection and performance.

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Conflict of interest declaration

The authors declare no conflict of interest

REFERENCES

1. Spinger LS. Can I Make it ? Exploring the Transition Process into a Handball Academy in Germany. University of Thessaly; 2016.
2. Sweeney L, Horan D, MacNamara Á. Premature Professionalisation or Early Engagement? Examining Practise in Football Player Pathways. Front Sport Act Living. 2021; 3:1–9. doi/10.3389/fspor.2021.660167/full.
3. Sweeney L, Cumming SP, MacNamara Á, et al. A tale of two selection biases: The independent effects of relative age and biological maturity on player selection in the Football Association of Ireland's national talent pathway. Int J Sports Sci Coach. 2022; 174795412211261. doi/10.1177/17479541221126152.
4. Radnor JM, Staines J, Bevan J, et al. Maturity Has a Greater Association than Relative Age with Physical Performance in English Male Academy Soccer Players. Sports. 2021; 9:171. doi/ 10.3390/sports9120171.
5. Parr J, Winwood K, Hodson-Tole E, et al. The main and interactive effects of biological maturity and relative age on physical performance in elite youth soccer players. J Sports Med. 2020; 2020:1–11. doi.10.1155/2020/1957636.
6. Towlson C, MacMaster C, Parr J, et al. One of these things is not like the other: time to differentiate between relative age and biological maturity selection biases in soccer? Sci Med Footb. 2022; 6:273–276. doi/full/10.1080/24733938.2021.1946133.
7. Helsen WF, Baker J, Michiels S, et al. The relative age effect in European professional soccer: Did ten years of research make any difference? J Sport Sci. 2012; 30:1665–1671. doi/abs/10.1080/02640414.2012.721929.
8. Musch J, Grondin S. Unequal Competition as an Impediment to Personal Development: A Review of the Relative Age Effect in Sport. Dev Rev. 2001; 21:147–167. doi/10.1006/drev.2000.0516.
9. Schorer J, Cobley S, Büsch D, et al. Influences of competition level, gender, player nationality, career stage and playing position on relative age effects. Scand J Med Sci Sports. 2009; 19:720–730. doi/10.1111/j.1600-0838.2008.00838.x.
10. Wrang CM, Rossing NN, Diernæs RM, et al. Relative Age Effect and the Re-Selection of Danish Male Handball Players for National Teams. J Hum Kinet. 2018; 63:33–41. doi/10.2478/hukin-2018-0004.
11. de la Rubia A. El efecto de la edad relativa: la prevalencia y el impacto sobre el rendimiento en competición en jugadores de balonmano internacionales. Universidad Politécnica de Madrid; 2021. http://oa.upm.es/67999/.
12. Malina RM, Rogol AD, Cumming SP, et al. Biological maturation of youth athletes: assessment and implications. Br J Sports Med. 2015; 49:852–859. doi/10.1136/bjsports-2015-094623.
13. Soliman A, De Sanctis V, Elalaily R, et al. Advances in pubertal growth and factors influencing it: Can we increase pubertal growth? Indian J Endocrinol Metab 2014; 18:53. doi/10.4103/2230-8210.145075.
14. Johnson A. Monitoring the immature athlete. Aspetar Sport Med J. 2015; 4:114–118.
15. Malina RM, Cumming SP, Rogol AD, et al. Bio-banding in youth sports: background, concept, and application. Sport Med. 2019; 49:1671–1685. doi.org/10.1007/s40279-019-01166-x.
16. Johnson A, Farooq A, Whiteley R. Skeletal maturation status is more strongly associated with academy selection than birth quarter. Sci Med Footb. 2017; 1:157–163. doi.org/10.1080/24733938.2017.1283434.

17. Brown KA, Patel DR, Darmawan D. Participation in sports in relation to adolescent growth and development. Transl Pediatr. 2017; 6:150–159. doi/10.21037/tp.2017.04.03
18. Figueiredo AJ, Gonçalves CE, Coelho e Silva MJ, et al. Characteristics of youth soccer players who drop out, persist or move up. J Sport Sci. 2009; 27:883–891. doi/abs/10.1080/02640410902946469.
19. Malina RM, Ribeiro B, Aroso J, et al. Characteristics of youth soccer players aged 13–15 years classified by skill level. Br J Sports Med. 2007; 41:290–295. doi/10.1136/bjsm.2006.031294.
20. Cumming SP, Searle C, Hemsley JK, et al. Biological maturation, relative age and self-regulation in male professional academy soccer players: A test of the underdog hypothesis. Psychol Sport Exerc. 2018; 39:147–153. doi/10.1016/j.psychsport.2018.08.007
21. Hill M, Scott S, Malina RM, et al. Relative age and maturation selection biases in academy football. J Sport Sci. 2020; 38:1359–1367. doi/full/10.1080/02640414.2019.1649524.
22. Massuca L, Branco B, Miarka B, et al. Physical Fitness Attributes of Team-Handball Players are Related to Playing Position and Performance Level. Asian J Sports Med. 2015; 6:2–6. doi/10.5812/asjsm.24712
23. de la Rubia A, Lorenzo-Calvo J, Lorenzo A. Does the Relative Age Effect Influence Short-Term Performance and Sport Career in Team Sports? A Qualitative Systematic Review. Front Psychol. 2020; 11:1–27. doi/10.3389/fpsyg.2020.01947/full.
24. Smith KL, Weir PL, Till K, et al. Relative age effects across and within female sport contexts: A systematic review and meta-analysis. Sport Med. 2018; 48:1451–1478. doi.org/10.1007/s40279-018-0890-8.
25. Massa M, Moreira A, A. Costa R, et al. Biological maturation influences selection process in youth elite soccer players. Biol Sport. 2022; 39:435–441. doi/10.5114/biolsport.2022.106152.
26. Arede J, Cumming SP, Leite N. David Vs. Goliath Playing Against Maturity Matched or Un-Matched Opposition Results in Distinct Physical Performance and Spatial Exploration Behavior. J Sport Psychol. 2021; 30:56–62.
27. Baechle TR, Earle RW. Essentials of strength training and conditioning. Human Kinetics; 2008.
28. Epstein LH, Valoski AM, Kalarchian MA, et al. Do Children Lose and Maintain Weight Easier Than Adults: A Comparison of Child and Parent Weight Changes From Six Months to Ten Years. Obes Res. 1995; 3:411–417. doi/10.1002/j.1550-8528.1995.tb00170.x.
29. Stewart A, Marfell-Jones M, Olds T, et al. International society for the advancement of kinanthropometry: International standards for anthropometric assessment. Int. Soc. Adv. Kinanthropometry. 2011; 115.
30. Khamis HJ, Roche AF. Predicting adult stature without using skeletal age-the Khamis-Roche Method. Pediatrics. 1994; 94:504. doi.org/10.1542/peds.94.4.504
31. Bayer LM, Bayley N. Growth diagnosis: Selected methods for interpreting and predicting physical development from one year to maturity. Oxford, England: Univer. Chicago Press; 1959.
32. Malina RM, Dompier TP, Powell JW, et al. Validation of a Noninvasive Maturity Estimate Relative to Skeletal Age in Youth Football Players. Clin J Sport Med. 2007; 17:362–368. doi/10.1097/JSM.0b013e31815400f4.
33. Drenowatz C, Wartha O, Klenk J, et al. Differences in Health Behavior, Physical Fitness, and Cardiovascular Risk in Early, Average, and Late Mature Children. Pediatr Exerc Sci. 2013; 25:69–83. doi/10.1123/pes.25.1.69
34. Pueo B, Penichet-Tomas A, Jimenez-Olmedo J. Reliability and validity of the Chronojump open-source jump mat system. Biol Sport. 2020; 37:255–259. doi/10.5114/biolsport.2020.95636.
35. Lloyd RS, Oliver JL. The Youth Physical Development Model. Strength Cond J. 2012; 34:61–72. doi/10.1519/SSC.0b013e31825760ea.
36. Read MM, Cisar C. The Influence of Varied Rest Interval Lengths on Depth Jump Performance. J. Strength Cond. Res. 2001; 15:279–283.
37. Pauole K, Madole K, Garhammer J, et al. Reliability and Validity of the T-Test as a Measure of Agility, Leg Power, and Leg Speed in College-Aged Men and Women. J. Strength Cond Res. 2000; 14:443–450. doi/10.1519/00124278-200011000-00012.
38. Romero-Franco N, Jiménez-Reyes P, Castaño-Zambudio A, et al. Sprint performance and mechanical outputs computed with an iPhone app: Comparison with existing reference methods. Eur J Sport Sci. 2017; 17:386–392. doi.org/10.1080/17461391.2016.1249031.
39. de la Rubia A, Ugalde-Ramírez A, Gutiérrez-Vargas R, et al. Does the New Resin-Free Molten d60 Ball Have an Impact on the Velocity and Accuracy of Handball Throws? Appl Sci. 2022; 13:425. doi/10.3390/app13010425.
40. Cohen J. Statistical power analysis for the behavioral science. 2nd Editio. New York: Lawrence Erlbaum Associates; 1988.
41. MacMaster C, Portas M, Parkin G, et al. The effect of bio-banding on the anthropometric, physical fitness and functional movement characteristics of academy soccer players. PLoS ONE. 2021; 16:1–16. doi.org/10.1371/journal.pone.0260136.
42. Cumming SP, Lloyd RS, Oliver JL, et al. Bio-banding in sport: Applications to competition, talent identification, and strength and conditioning of youth athletes. Strength Cond J. 2017; 39:34–47. doi.10.5152/tjsm.2019.126
43. Malina RM, Eisenmann JC, Cumming SP, et al. Maturity-associated variation in the growth and functional capacities of youth football (soccer) players 13–15 years. Eur J Appl Physiol. 2004; 91:555–562. doi/10.1007/s00421-003-0995-z.
44. Stratton G, Oliver JL. The impact of growth and maturation on physical performance. Strength and Conditioning for Young Athletes. Routledge; 2019. p. 3–20.
45. Malina RM, Reyes MEP, Eisenmann JC, et al. Height, mass and skeletal maturity of elite Portuguese soccer players aged 11–16 years. J Sport Sci. 2000; 18:685–693. doi/abs/10.1080/02640410050120069.
46. Meylan C, Cronin J, Oliver J, et al. Talent identification in soccer: The role of maturity status on physical, physiological and technical characteristics. Int J Sports Sci Coach. 2010; 5:571–592. doi/10.1260/1747-9541.5.4.571.
47. Schwesig R, Hermassi S, Fieseler G, et al. Anthropometric and physical performance characteristics of professional handball players: Influence of playing position. J Sports Med Phys Fitness. 2017; 57:1471–1478. doi.10.23736/S0022-4707.16.06413-6.
48. Krüger K, Pilat C, Ückert K, et al. Physical Performance Profile of Handball Players Is Related to Playing Position and Playing Class. J Strength Cond Res. 2014; 28:117–125. doi/10.1519/JSC.0b013e318291b713.
49. Giuriato M, Carnevale Pellino V, Lovecchio N, et al. Do maturation, anthropometrics and leg muscle qualities influence repeated change of direction performance in adolescent boys and girls? Biol Sport. 2023; 1033–1038. doi/10.5114/biolsport.2023.123322.
50. Ferragut C, Vila H, Abraldes JA, et al. Influence of Physical Aspects and Throwing Velocity in Opposition Situations in Top-Elite and Elite Female Handball Players. J Hum Kinet. 2018; 63:23–32. doi/10.2478/hukin-2018-0003.
51. de la Rubia A, Lorenzo J, Rojas-Valverde D, et al. Bio-Banding in Handball: Academy Players' Perceptions Based on Maturity Status and Gender. Int J Sports Med. 2023; 44: 871–881. doi:10.1055/a-2145-6454

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A new approach to comparing the demands of small-sided games and soccer matches

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ABSTRACT: To improve soccer performance, coaches should be able to replicate the match's physical efforts during the training sessions. For this goal, small-sided games (SSGs) are widely used. The main purpose of the current study was to develop similarity and overload scores to quantify the degree of similarity and the extent to which the SSG was able to replicate match intensity. GPSs were employed to collect external load and were grouped in three vectors (kinematic, metabolic, and mechanical). Euclidean distance was used to calculate the distance between training and match vectors, which was subsequently converted into a similarity score. The average of the pairwise difference between vectors was used to develop the overload scores. Three similarity (Sim_{kin}, Sim_{met}, Sim_{mec}) and three overload scores ($OVER_{kin}$, $OVER_{met}$, $OVER_{mec}$) were defined for kinematic, metabolic, and mechanical vectors. Sim_{met} and $OVER_{met}$ were excluded from further analysis, showing a very large correlation ($r > 0.7$, $p < 0.01$) with Sim_{kin} and $OVER_{kin}$. The scores were subsequently analysed considering teams' level (First team vs. U19 team) and SSGs' characteristics in the various playing roles. The independent-sample *t*-test showed ($p < 0.01$) that the First team presented greater Sim_{kin} ($d = 0.91$), $OVER_{kin}$ ($d = 0.47$), and $OVER_{mec}$ ($d = 0.35$) scores. Moreover, a generalized linear mixed model (GLMM) was employed to evaluate differences according to SSG characteristics. The results suggest that a specific SSG format could lead to different similarity and overload scores according to the playing position. This process could simplify data interpretation and categorize SSGs based on their scores.

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INTRODUCTION

Success in soccer is determined by the interaction of several factors, among which technical skills, physical capabilities, and tactical knowledge represent the most important performance elements [1]. Following the principle that "you should train as you play" [2], coaches should aim to develop training methods capable of replicating match intensity demands. Indeed, in the theory of training, the principle of specificity suggests that performance increases when training is able to replicate the physiological demands and movement patterns occurring during competitive matches [3]. For this reason, small-sided games (SSGs) became a very popular training method due to their ability to concomitantly train technical, tactical, and physical aspects by manipulating different variables such as pitch size, the number of players, recovery periods, the presence of goalkeepers, and playing rules [4–10].

In general, it has been reported that a greater number of players and a larger pitch area lead to higher physical demand in SSGs [11, 12]. Clemente et al. [13] observed that the 4v4 format induced players' greater distance coverage and speed compared to the 2v2 format. Similarly, Lacome et al. [14] reported a higher overall running intensity (total distance and high-speed running) during 10v10 compared with 8v8, 6v6, and 4v4 formats. Regarding the pitch area, several studies reported that, by increasing the area per player, it was possible to induce higher locomotor demands for total distance, high-speed, and very high-speed distance [15, 16]. However, by reducing the size of the pitch, Gaudino et al. [17] registered a more significant number of moderate accelerations and decelerations with a higher number of changes in velocity. For this reason, with appropriate SSG formats, coaches and physical trainers can

demand specific movements patterns and elicit players' responses according to pre-defined targets of the training session (e.g., strength, endurance, speed).

Global positioning systems (GPSs) and radio-frequency local positioning systems (LPSs) are typically used to quantify the locomotor patterns and the intensity achieved in SSGs and to compare them with the match demands. These systems can provide several workload metrics, with some studies reporting more than 80 parameters [18]. All these variables are used to quantify the locomotor patterns. They are generally classified into kinematic (i.e., the overall movement performed by players at different running speeds), metabolic (i.e., estimated energy cost of activity during training and matches) [19], and mechanical (i.e., the overall load placed on the body during accelerations and decelerations) [20]. Despite the large amount of data and information provided by GPSs, many studies are limited to using a few variables to compare SSGs and matches. For example, Beenham et al. [21] analysed differences between SSGs and match play using only player load. For the same purpose, Dalen et al. [22] investigated differences only in acceleration and high-intensity activities. Although using a few variables could ease the interpretation, the metrics selected could not capture a significant proportion of information provided by multiple load variables [23]. Conversely, Gómez-Carmona et al. [24] used a pairwise comparison to analyse differences between SSGs and official matches regarding 31 different variables. However, in this case, we can identify the following limitations: (1) risk of "data overload" [23]; (2) increasing the number of variables also increases the difficulty in interpretation; (3) a larger number of variables makes data visualization and communication with the coach difficult; (4) complexity in the staff decision-making processes.

To avoid losing important information from multiple variables, while attempting to overcome the "data overload" problem, we want to present a new approach to provide a practical and easy quantification of training efforts compared to a match. To quantify the similarity between SSGs and soccer match locomotor demands (kinematic, metabolic, mechanical), Euclidean distance calculation was employed. Euclidean distance is a very simple similarity metric which reflect the distance between the vectors being analysed. In the current study, we considered two different vectors: the SSG vector and the match vector. If the Euclidean distance is very small, then the values in each vector are very similar, and this suggests a high similarity between the two vectors. Therefore, the Euclidean distance offers several advantages within the context of the current study: (1) it allows multiple variables to be treated as vectors (GPS metrics), thereby avoiding the risk of "data overload"; (2) it is easy to implement; (3) it is straightforward to interpret. However, also knowing the similarity between training and match play is not enough. Indeed, according to the principle of training, it is necessary to create a progressive overload to elicit adaptation processes in the physiological systems [25]. To achieve this goal, the average of the pairwise difference between the two vectors was calculated.

Therefore, the main purpose of the current study was to introduce a similarity and overload score to compare SSG and match demands based on external load variables. Particularly, for each SSG, three similarity scores and three overload scores were calculated for kinematic, metabolic, and mechanical variables. In addition, we evaluated whether and how these similarity and overload scores changed according to the SSGs' characteristics (i.e., area per player, type of drills) in the different playing roles.

MATERIALS AND METHODS

Participants

A total of fifty-one elite soccer players were involved in the present study: twenty-six from the First team (age: 24.5 ± 5.5; body mass: 80.9 ± 6.9; height: 184.9 ± 6.1) and twenty-five from the U19 team (age: 17.4 ± 0.9; body mass: 73.9 ± 6.6; height: 181.4 ± 6.5). All participants were classified according to their playing position: defenders (n = 20), midfielders (n = 17), and forwards (n = 14). The goalkeepers were excluded from the data collection. Data were obtained from daily monitoring of the routine over the course of the competitive season. Therefore, the usual appropriate ethics committee clearance was not required [26]. Nevertheless, to guarantee team and player confidentiality, all data were anonymized before analysis, and the study was conducted following the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Experimental Approach

The study was conducted during the 2021/22 soccer season, involving players from a First team and a U19 team competing in the Italian Serie B and Primavera 2 championships, respectively, and belonging to the same Italian professional soccer club. The two teams trained five days per week and competed once a week. In all, 128 training sessions were monitored, with a total of 3290 individual observations. Only players free from injury involved in the full training schedules were considered. In the end, 147 different SSGs were selected for further analysis. All SSGs were performed under the supervision and motivation of the coaching staff to keep the work rate high. The different SSGs were classified based on the type of drill:

- Game Simulations: games performed with two goals (regular size) and the presence of goalkeepers.
- Possession Games: possession drills performed without goalkeepers.
- Tactical Games: games performed with two goals (regular size) and specific tactical rules (e.g., presence of time constraints, pressing rules, presence of limitations in the playing space).

The area per player (ApP) [27, 28]:

- Small Games: ApP ≤ 100 m^2
- Medium Games: 100 m^2 < ApP ≤ 200 m^2
- Large Games: ApP > 200 m^2

TABLE 1. Kinematic, metabolic, and mechanical variables selected for similarity and overload score estimation.

KINEMATIC	METABOLIC	MECHANICAL
Total Distance	Energy Expenditure	Number of accelerations above 2.5 m/s^2
Distance above 7.2 km/h	Average Metabolic Power	Number of accelerations above 3.5 m/s^2
Distance above 14.4 km/h	Distance covered from 5 to 10 W	Number of accelerations above 4.5 m/s^2
Distance above 19.8 km/h	Distance covered from 10 to 20 W	Number of decelerations below -2.5 m/s^2
Distance above 25.2 km/h	Distance covered from 20 to 35 W	Number of decelerations below -3.5 m/s^2
Max Speed	Distance covered from 35 to 55 W	Number of decelerations below -4.5 m/s^2
	Distance covered above 55 W	

Following the purpose of the study, the players' efforts during SSGs were subsequently compared with players' efforts elicited during matches. Twenty-eight different matches were monitored for the First team, and twenty-two for the U19 team.

Data Collection

The players' external training/match load was collected using a 10-Hz GPS (WIMU PRO; RealTrack Systems SL) with an integrated 100 Hz tri-axial accelerometer, gyroscope, and magnetometer. Data were subsequently analysed using the system-specific software (WIMU Software; RealTrack Systems SL). The GPS system showed good accuracy for measures of running speed, acceleration, and deceleration in previous studies [29, 30]. The GPS devices were placed between the players' scapulae through a tight vest. Among the numerous GPS variables, 19 different metrics were extracted and classified as kinematic, metabolic, and mechanical [20]. All the variables that constitute the vectors are presented in Table 1.

Similarity Score and Overload Score Estimation

As previously mentioned, we grouped GPS variables into three classes we identified as our three vectors. The different GPS metrics were normalized according to training duration to allow the comparison with matches. Therefore, each SSG was characterized by three different vectors that were compared with the benchmark match vectors. The three benchmark match vectors (kinematic, metabolic, mechanical) were calculated for each player as the average (μ_p) and standard deviation (σ_p) of the different GPS variables. The vectors were calculated for the 90-minute time window of the match. If 90-minute data were unavailable, calculations were made based on the time played. In this case, only players' matches with a time of play over 45 minutes were considered. Also in this case, data were expressed per minute played. The benchmark match vectors and SSG vectors were generated for the various subjects, thereby enabling a comparative analysis of each player with oneself.

The average and standard deviation calculated for the matches were used to centre and scale training data using the following formula:

$$Ci = \frac{(Ti - \mu i)}{\sigma i}$$

Ci = centred and scaled training data

Ti = training data

μ_i = average match data

σi = standard deviation match data

Then, the Euclidean distance (= L2-Norm) of each drill vector was calculated:

$$Di = || Ci||_2$$

At this stage, the distance value obtained was converted to a similarity score using the following formula:

$$Simk = \frac{1}{1 + \frac{Di}{Ni}}$$

Where Ni represents the number of variables that constitute the vector. Therefore, for each drill and each player, we identified three different similarity scores for the kinematic vector (Sim_{kin}), metabolic vector (Sim_{met}), and mechanical vector (Sim_{mec}). The similarity score could range from 0, which means "inability to replicate match demands", to 1, which stands for the "maximum ability to replicate match demands".

In addition, to determine whether the training (SSG) was globally more demanding or less demanding than the match, the average of the pairwise difference between the training vectors and benchmark match vectors was calculated:

$$\Delta 0 = Avg(Ci)$$

Also in this case, for each drill and each player, we identified three different overload scores for the kinematic vector ($OVER_{kin}$), metabolic vector ($OVER_{met}$), and mechanical vector ($OVER_{mec}$). A negative value indicates a lower overall intensity of the SSG compared with the match; conversely, a positive value indicates a higher overall intensity.

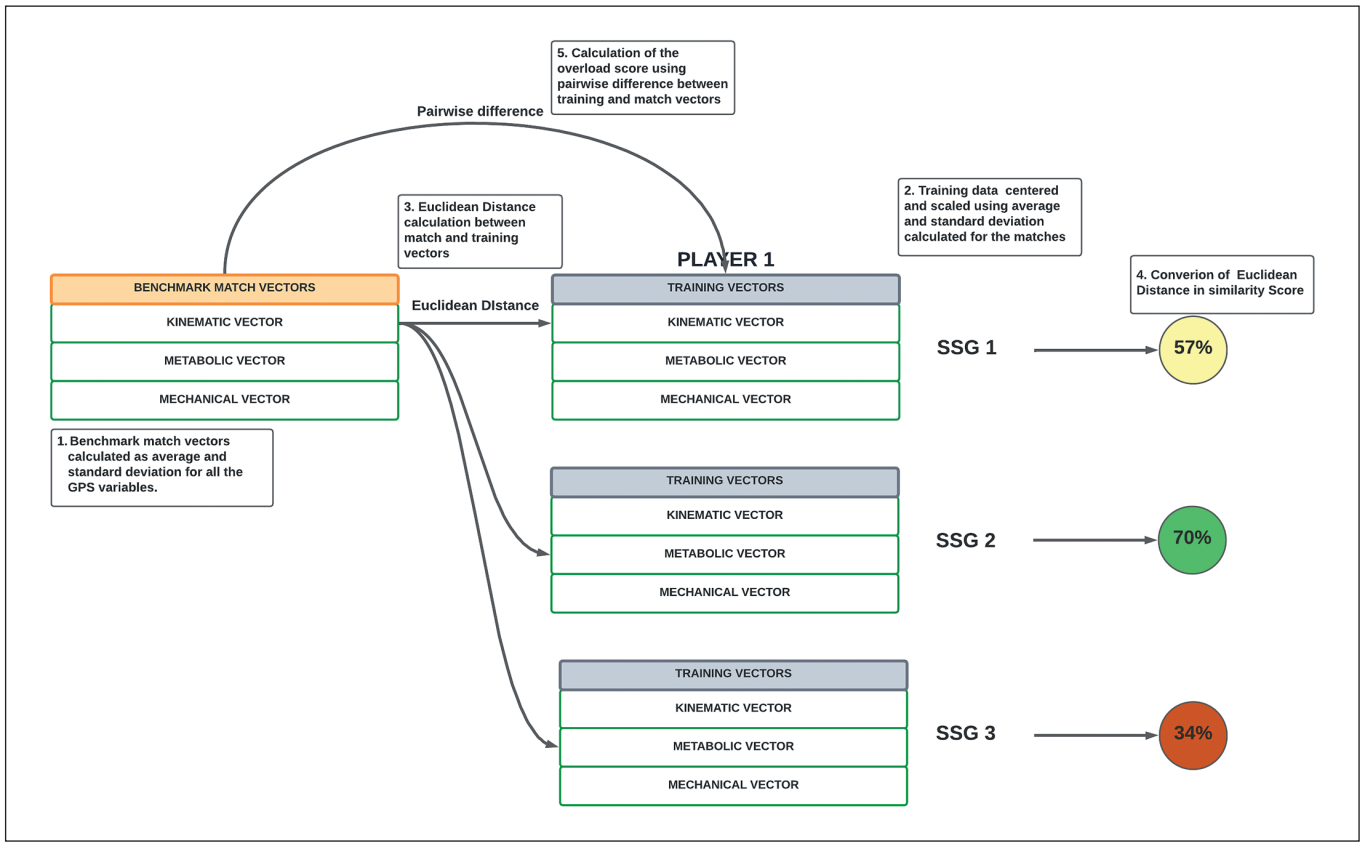


FIG. 1. Summary of the steps to calculate similarity score and overload score.
Note: SSG = small-sided game

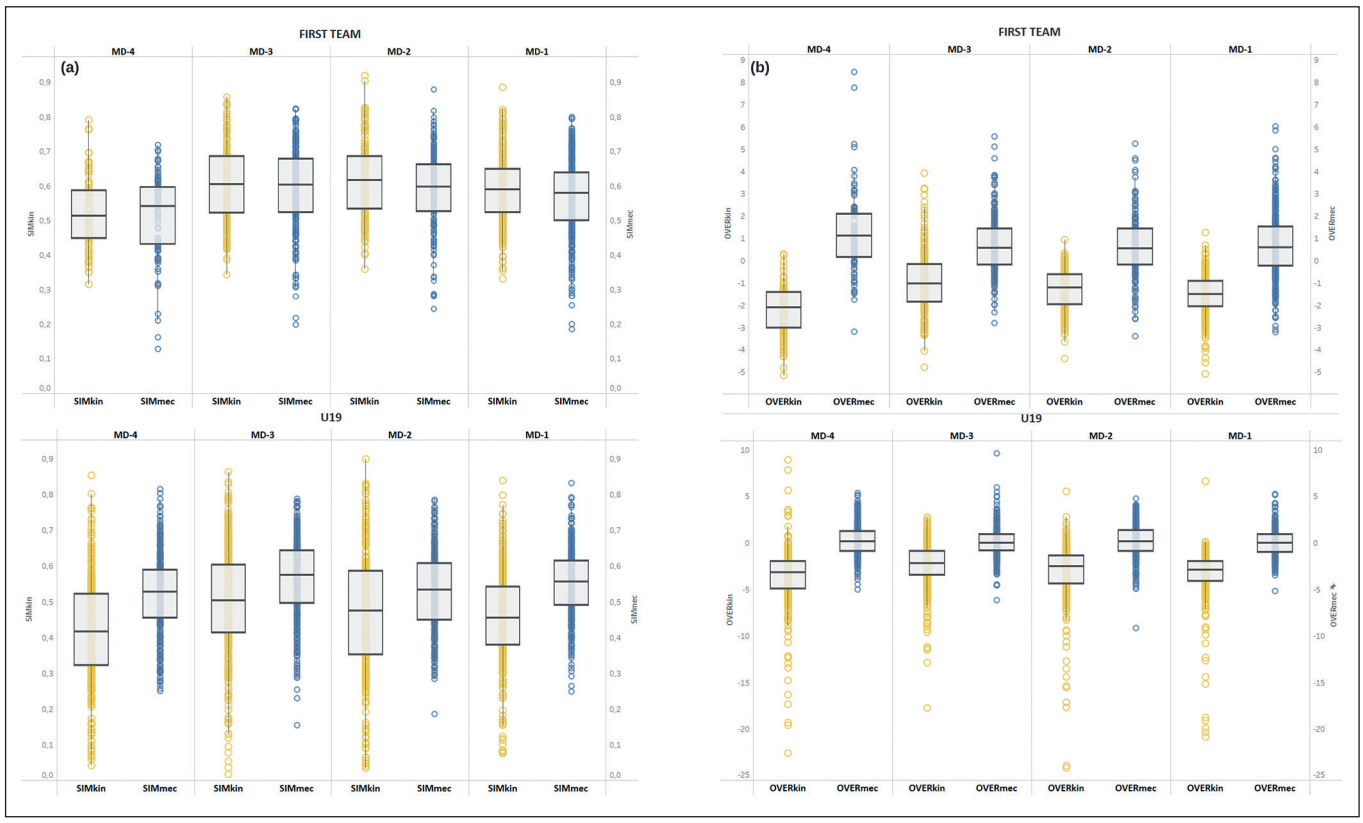


FIG. 2. Weekly distribution of similarity (a) and overload (b) scores for the First team and U19 team.
Note: MD = Match Day Simkin = similarity score for the kinematic vector OVERkin = Overload score for the kinematic vector Simmec = Similarity score for the mechanical vector OVERmec = Overload score for the mechanical vector

Therefore, the general demand of each drill was quantified according to the ability to replicate the match effort (similarity score) and the ability to overload players regarding match locomotor requests (overload score).

The different steps followed to calculate the two scores are summarized in Figure 1.

Statistical Analyses

Pearson's correlation coefficient was used to evaluate the relationship between the different similarity scores and overload scores calculated. Correlation coefficient magnitudes were rated 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 ($0.7 < r < 0.9$), and nearly perfect ($r > 0.9$) and perfect ($r = 1.0$) [31]. An independent-sample *t*-test was performed to test differences in the similarity scores and overload scores between the two different teams (First team vs U19 team). Cohen's effect size was calculated and the magnitudes of the effect were interpreted according to the Hopkins criteria [32]: < 0.2 (*trivial*), 0.20–0.59 (*small*), 0.60–1.19 (*moderate*), 1.20–1.99 (*large*), 2.00–3.99 (*very large*), ≥ 4.00 (*nearly perfect*). To account for differences between similarity scores and overload scores with SSG characteristics, a generalized linear mixed model (GLMM) was employed. The characteristics of SSGs (i.e., type of the drill, ApP) were inserted into the model as fixed factors. The players' identity was inserted into the model as a random effect to take into account the repeated measurements. GLMM was employed to understand the relationship between all the possible two-way interactions, and the similarity and overload scores were identified as the dependent variables. The dataset was split into three subsets according to players' positions. Inside each subset, six GLMM were fitted, three for the similarity scores and three for the overload scores. Each standardized regression coefficient (β) was used to quantify the effect size of the individual predictors and ascertain which interaction was the most important in explaining the variation in the dependent variable [33, 34]. Data are presented as mean (± SD) and 95% confidence intervals. The significance level was set at $p < 0.05$. The software used for the statistical analysis of the data was IBM's SPSS Statistics version 27 (SPSS, Inc. Chicago, Illinois IBM Corp., Armonk, NY).

RESULTS

After correlation analysis, Sim_{kin} score showed a very large correlation ($r = 0.892$, $p < 0.01$) with Sim_{met} score, while $Over_{kin}$ score showed a very large correlation ($r = 0.708$, $p < 0.01$) with $Over_{met}$. For this reason, showing the same behaviour in relation to the SSGs, Sim_{met} score and $Over_{met}$ score were excluded from further analysis. The 147 different SSGs were reported in the supplementary material (see Table S1) with their respective average values of similarity (Sim_{kin}, Sim_{mec}) and overload scores ($OVER_{kin}$, $OVER_{mec}$). The weekly distribution of similarity and overload scores for the two different teams is presented in Figure 2. The days of the week were classified according to the days preceding a match (MD-4; MD-3; MD-2; MD-1).

The independent-sample *t*-test revealed significantly higher similarity scores and overload scores ($p < 0.01$) in the First team compared to the U19 team except for Sim_{mec}, for which no significant differences were found. A moderate effect was found for the Sim_{kin} score ($d = 0.91$), while a small effect was found for $OVER_{kin}$ ($d = 0.47$) and $OVER_{mec}$ ($d = 0.35$). Descriptive statistics for both groups are displayed in Table 2. Regarding the GLMM analysis, the results of the two-way interactions for the three different playing roles are summarized in Table 3. The two-way interactions (type of drill, ApP) produced eight different combinations (e.g., game simulations – small games, possession games – medium games) that were compared with the drill "tactical games – medium games" identified as the reference category in all the models. Tactical games – small games format was not included in the analysis as it was never recorded during the training sessions.

DISCUSSION

The study aims to develop a similarity and overload score to compare training SSGs and match effort using external load data. Particularly, the similarity score aimed to quantify the ability of SSGs to replicate match kinematic and mechanical demands. Instead, the overload

TABLE 2. Differences of similarity and overload scores between First team and U19 team after independent-sample t-test.

	Team	Mean	SD	p-value	Effect size (*d*)
Sim_{kin}	U19 team	0.460	0.158	**0.001**	**0.91**
	First team	0.586	0.114		
$OVER_{kin}$	U19 team	-3.213	5.146	**0.001**	**0.47**
	First team	-1.451	1.239		
Sim_{mec}	U19 team	0.534	0.116	0.562	
	First team	0.567	0.119		
$OVER_{mec}$	U19 team	0.066	1.929	**0.001**	**0.35**
	First team	0.675	1.510		

Sim_{kin} = similarity score for the kinematic vector; $OVER_{kin}$ = Overload score for the kinematic vector; Sim_{mec} = Similarity score for the mechanical vector; $OVER_{mec}$ = Overload score for the mechanical vector.

TABLE 3. Analysis of differences in similarity and overload scores according to SSGs characteristics and playing roles.

		SIMILARITY SCORE (KINEMATIC VECTOR)									OVERLOAD SCORE (KINEMATIC VECTOR)								
		DEFENDERS			MIDFIELDERS			FORWARDS			DEFENDERS			MIDFIELDERS			FORWARDS		
Type of the drill	ApP	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value
(Intercept)		0.365	[0.252 0.478]	*0.001*	0.457	[0.395 0.518]	*0.001*	0.430	[0.326 0.492]	*0.001*	-5.945	[-9.465 -2.426]	*0.001*	-3.220	[-4.033 -2.408]	*0.001*	-3.772	[-5.117 -2.426]	*0.001*
GS	LG	**0.189**	[0.060 0.318]	**0.001**	**0.130**	[0.062 0.198]	**0.001**	**0.174**	[0.059 0.228]	**0.003**	**5.470**	[1.517 9.423]	**0.007**	2.042	[1.143 2.940]	**0.001**	2.482	[0.988 3.976]	**0.001**
	MG	0.148	[0.019 0.277]	**0.024**	0.078	[0.010 0.145]	**0.024**	0.129	[0.0144 0.216]	**0.028**	4.027	[0.103 7.951]	**0.044**	1.072	[0.175 1.968]	**0.019**	1.727	[0.240 3.214]	**0.023**
	SG	0.046	[-0.090 0.184]	0.501	-0.024	[-0.102 0.052]	0.530	0.032	[-0.09 10.156]	0.603	1.607	[-2.779 5.994]	0.471	-0.139	[-0.164 0.886]	0.789	0.596	[-1.014 2.208]	0.464
PG	LG	-0.009	[-0.165 0.146]	0.905	-0.045	[-0.132 0.041]	0.307	0.008	[-0.141 0.159]	0.907	1.995	[-2.866 6.857]	0.419	**3.688**	[2.538 4.837]	**0.001**	**2.165**	[0.214 4.115]	**0.030**
	MG	0.110	[-0.022 0.243]	0.104	0.052	[-0.018 0.124]	0.145	0.071	[-0.04 6.189]	0.234	2.698	[-1.446 6.843]	0.200	0.912	[0.162 1.765]	**0.045**	1.400	[0.117 2.933]	**0.041**
	SG	0.002	[-0.128 0.134]	0.966	-0.076	[-0.147 -0.004]	**0.036**	-0.013	[-0.132 0.105]	0.825	-1.143	[-4.218 3.931]	0.945	-0.929	[-1.871 -0.171]	**0.042**	-0.074	[-1.618 1.469]	0.924
TG	LG	0.070	[-0.073 0.215]	0.334	0.0247	[-0.048 0.097]	0.503	0.064	[-0.063 0.192]	0.318	1.513	[-2.830 5.858]	0.492	0.473	[-0.493 1.440]	0.334	0.877	[-0.786 2.541]	0.297
	MG	0a			0a			0a			0a			0a			0a		

		SIMILARITY SCORE (MECHANICAL VECTOR)									OVERLOAD SCORE (MECHANICAL VECTOR)								
		DEFENDERS			MIDFIELDERS			FORWARDS			DEFENDERS			MIDFIELDERS			FORWARDS		
Type of the drill	ApP	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value
(Intercept)		0.487	[0.419 0.555]	*0.001*	0.547	[0.488 0.605]	*0.001*	0.539	[0.461 0.617]	*0.001*	-0.577	[-1.612 0.458]	*0.273*	0.153	[-0.651 0.957]	*0.708*	-0.421	[-1.597 0.754]	*0.478*
GS	LG	**0.085**	[0.010 0.161]	**0.026**	**0.061**	[0.011 0.125]	**0.042**	**0.073**	[0.013 0.151]	**0.046**	1.053	[0.083 2.195]	**0.047**	-0.155	[-1.033 0.723]	0.728	0.594	[-0.696 1.885]	0.362
	MG	0.025	[-0.049 0.100]	0.499	0.045	[-0.019 0.109]	0.170	0.027	[-0.056 0.111]	0.514	1.555	[0.426 2.684]	**0.007**	-0.074	[-0.949 0.800]	0.867	0.928	[-0.352 2.209]	0.153
	SG	-0.031	[-0.116 0.052]	0.458	-0.031	[-0.105 0.042]	0.403	-0.053	[-0.147 0.041]	0.268	**1.995**	[0.676 3.313]	**0.003**	0.682	[-0.332 1.698]	0.187	**1.309**	[0.211 2.899]	**0.036**
PG	LG	-0.114	[-0.189 -0.032]	**0.021**	-0.047	[-0.130 0.034]	0.255	0.002	[-0.113 0.118]	0.971	1.010	[-0.419 2.441]	0.165	0.590	[-0.546 1.728]	0.307	0.546	[-1.188 2.280]	0.534
	MG	0.007	[-0.071 0.087]	0.845	0.016	[-0.051 0.084]	0.640	0.033	[-0.055 0.121]	0.461	1.552	[0.339 2.765]	**0.012**	0.180	[-0.748 1.108]	0.702	0.836	[-0.504 2.177]	0.218
	SG	-0.020	[-0.098 0.057]	0.152	-0.034	[-0.102 0.033]	0.321	-0.055	[-0.143 0.033]	0.219	1.213	[0.026 2.400]	**0.045**	-0.369	[-1.291 0.552]	0.430	0.994	[-0.348 2.337]	0.144
TG	LG	0.026	[-0.056 0.109]	0.525	0.022	[-0.046 0.092]	0.516	0.055	[-0.037 0.148]	0.237	-0.167	[-1.400 1.065]	0.789	-0.802	[-1.738 0.134]	0.093	-0.378	[-1.798 1.040]	0.596
	MG	0a			0a			0a			0a			0a			0a		

ApP = area per player; β = standardized regression coefficient; CI = Confidence interval; GS = game simulation; PG = possession game; TG = tactical game; LG = large game; MG = medium game; SG = small game.

score was established if the SSGs were more demanding or less demanding than the match. The novelty of the study is to develop these two scores to simplify information from multiple GPS variables, to improve data communication and decision-making processes. The second purpose of the study was to analyse the behaviour of the scores in relation to the SSG characteristics in order to understand their usefulness within a real context. The main findings suggest that the similarity and overload scores were significantly higher in the First team compared to the U19 team. Moreover, significant differences were found according to the drills' format and playing position.

Development of Similarity and Overload Scores

The principal aim of the current study was to develop a similarity and overload score in order to quantify the ability of SSGs to replicate match intensity. At the end of the process, we had produced three different similarity scores (Sim_{kin}, Sim_{met}, Sim_{mec}) and three overload scores ($OVER_{kin}$, $OVER_{met}$, $OVER_{mec}$) for each SSG and each player. Before moving toward further investigations, a correlation analysis was performed to understand the relationship between the different scores. Sim_{kin} and Sim_{met} ($r = 0.892$, $p < 0.01$), as well as $OVER_{kin}$ and $OVER_{met}$ ($r = 0.708$, $p < 0.01$), showed a significant very large



FIG. 3. A real example of data visualization and communication of the similarity and overload scores for three different SSGs during a training session.
Note: Avg = average value P1 = player 1 P2 = player 2 P3 = player 3 P4 = player 4

correlation. Even in previous studies [35, 36], kinematic variables (i.e., total distance, high-speed running) showed near perfect correlation with the metabolic load (i.e., high metabolic power). The scores being highly correlated and, therefore, providing similar results, Sim_{met} and $OVER_{met}$ were excluded from further analysis. At the end of the process, the two similarity scores (Sim_{kin}, Sim_{mec}) and the two overload scores ($OVER_{kin}$, $OVER_{mec}$) were compared in relation to the team, SSG characteristics, and playing roles.

Similarity and Overload Scores Differences between Teams, SSGs, and Playing Roles

Following calculating similarity and overload scores, the second purpose of the study was to evaluate how values change according to the team (First team vs. U19 team) and according to the SSG characteristics. This last investigation was conducted for the three different roles (i.e., defenders, midfielders, and forwards) identified within the current study. The results suggest that the First team achieved higher similarity and overload scores except for Sim_{mec}, where no significant differences were identified (Table 2). To the best of our knowledge, no studies have investigated differences in SSGs between professional and youth soccer players. Houtmeyers et al. [37] only analysed differences in weekly load between U19 and First team players within a professional soccer team. Although the authors considered the overall training sessions, in line with our study, the U19 team registered a shorter distance per minute in low- and high-velocity zones. We could speculate that young soccer players, possessing less technical skills and physical capabilities, are involved in SSGs characterized by lower intensity. As proof of this, Dellal et al. [38] analysed the differences between amateur and professional players. The authors found that amateur players were able to perform less total distance in sprinting and showed lower technical abilities, as highlighted by the higher number of lost

balls and a more significant number of skill errors. In addition, Fenner et al. [39] demonstrated that the more talented young players were able to cover a greater distance at higher speeds during SSGs. For this reason, physical and technical capabilities could be crucial elements to ensure SSGs' intensity, explaining differences between the First team and the U19 team found in the current study. However, we must also consider that different coaching styles and philosophies (e.g., technical and tactical requests) could affect the way of training and, consequently, SSGs' intensity.

After analysing the differences between the First and U19 teams, our study aimed to understand how similarity and overload scores changed with SSG characteristics. Particularly, we classified SSGs based on the type of drill (game simulations, possession games, tactical games) and size of area per player (small games, medium games, large games). In general, the results suggest that the game simulations allowed the highest similarity scores to be achieved for kinematic and mechanical variables compared with the reference category "tactical games-medium games".

Game simulations appeared to elicit greater Sim_{kin} in all the playing roles. It is taken for granted that game simulations, due to the presence of goals, could most replicate the match effort. Indeed, in this type of drill, the players' movement patterns will be more linear as there is a direction to target [17]. In contrast, possession games, characterized by multidirectional movements, induced a significant reduction of the Sim_{kin} score in midfielders, as highlighted by the β coefficient. However, for the game simulations, not all the pitch sizes are able to maximize the Sim_{kin} score. As reported in Table 3, significantly higher scores were found only for medium and large games. In line with previous studies [14, 15, 40, 41], an increase in ApP leads to more space to cover, consequently allowing an increase in game intensity and higher speeds to be reached. In similar populations of both adult [27] and U19 [42] Serie A soccer players, it has been previously demonstrated that a large ApP is required as a tool to replicate official match demands. Indeed, if we consider the β coefficient, large games seem to be the most effective for increasing the Sim_{kin} in the three different playing roles. Regarding the Sim_{mec}, only game simulations performed as large games produced a significant increase in the score in the three different playing roles. A greater ApP allows for achieving very high speeds, and consequently, maximum accelerations and decelerations [17]. As in the case of Sim_{kin}, possession games (large games) caused a significant reduction in the Sim_{mec} score for defenders.

Examining the results achieved for overload scores, different information was obtained. If the similarity score was developed to understand how the SSGs were able to replicate match intensity, the overload score was integrated to understand how much the SSGs were globally more or less demanding compared to the match intensity. For the $OVER_{kin}$ score, the game simulation – large game combination was identified as the format more suitable for defenders. Interestingly, for midfielders and forwards, the combination possession game – large game was able to maximize the $OVER_{kin}$ score. Generally, due to their technical abilities, midfielders and forwards are critical players in keeping possession of the ball and applying pressure to win it back. For this reason, when the game aims to maintain possession, midfielders and forwards are more involved, consequently increasing their game intensity. By contrast, for the $OVER_{mec}$ score, the results suggest that by reducing the playing space (game simulation – small game for defenders and forwards), it is possible to have the maximum increase in the overload score. This result confirms previous studies [17] where the total number of changes in velocity (accelerations and decelerations) increased as the pitch size decreased. Consequently, small spaces could be adequate to overload mechanical work intensity compared to the match effort but failed to overload high-speed running and sprints [14, 27, 43]. In contrast, no significant differences were observed for the $OVER_{mec}$ score in the midfielders. As suggested by Riboli et al. [27], the different playing positions need different ApPs according to their specific performance model. Therefore, coaches and physical trainers should be aware that the same SSG could elicit different stimuli for different playing roles [14].

The current study has some limitations. First, the small sample size led to players being grouped in only three different playing positions (i.e., defenders, midfielders, forwards) and there being only a few observations for a specific SSG format (possession game – large game). Moreover, only two teams were included in the current study, and specific aspects such as coaching style and club philosophy could have affected the results. In addition to external load data, internal load parameters (e.g., heart rate) could provide additional comparisons between SSGs and match demands. However, it is necessary to recognize that there could be some technological limitations in constantly monitoring the internal load [16]. Another limitation concerns the SSGs' characteristics. Indeed, only the type of drill and area per player were considered in the current study. This last point opens up the opportunity for further investigations that could investigate how different SSGs' characteristics (e.g., number of players, minutes of play, number of sets, recovery time between the sets) affect similarity scores and overload scores.

Practical applications

The similarity and overload scores developed in this study could be used to classify the different SSGs throughout the season and used in the weekly microcycle in relation to the needs of coaches and physical trainers. Euclidean distance and the average of the pairwise difference between vectors proved to be effective in managing multiple GPS variables, preventing the risk of "data overload". Indeed, in this way, it is possible to use a single number to understand the general effort achieved during SSGs in relation to match intensity. Although our approach was developed using the WIMU system, it can be replicated with any other GPS system, and also by modifying the variables inserted in the training and match vectors. This method could help the coaching staff in data interpretation and decision-making strategies. To make this process clearer, we created

a visualization that could help to understand the utility of these metrics on a daily basis (Figure 3). Particularly, high overload scores could be encouraged at the beginning of the weekly microcycle and away from the match day. On the other hand, high similarity scores should be sought in all the SSGs. Coaches and physical trainers should be aware that game simulations performed in large spaces make it possible to achieve the highest similarity scores for kinematic and mechanical variables. Conversely, game simulations played in smaller spaces could induce an overload in the mechanical parameters. To overload kinematic intensity, possession games should be encouraged. However, it is important to consider that different game formats could lead to different load stimuli.

CONCLUSIONS

The similarity and overload scores developed in the current study allowed us to compare SSG and match demands. This approach could bring several advantages including the possibility to manage numerous GPS variables, and improve data interpretation and communication. The results suggested that game simulations performed in large spaces made it possible to increase similarity scores for the kinematic and mechanical variables. On the other hand, possession games and smaller play spaces could lead to higher overload scores. Coaches and physical trainers must consider that these results may change according to the level (First team vs U19 team) and role of the players (defenders, midfielders, forwards).

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Conflicts of interest/Competing interests

The authors have declared that no conflicts/competing interests exist.

Contributorship

MM, AT, and ML were responsible for the conception and design of the study. The literature review was conducted by MM, AT, AR, and ML. MM, AT SC, AR and ML conducted the data analysis and interpretation. The statistical analysis was carried out by MM, SC, and ML. The article was written by MM, AT, AR, and ML. All authors contributed to the review of the manuscript.

REFERENCES

1. Dellal A, Drust B, Lago-Penas C. Variation of activity demands in small-sided soccer games. Int J Sports Med. 2012; 33(05):370–5.
2. Dawson B, Hopkinson R, Appleby B, Stewart G, Roberts C. Comparison of training activities and game demands in the Australian Football League. J Sci Med Sport. 2004; 7(3):292–301.
3. Casamichana D, Castellano J, Castagna C. Comparing the physical demands of friendly matches and small-sided games in semiprofessional soccer players. J Strength Cond Res. 2012; 26(3):837–43.
4. Hill-Haas SV, Coutts AJ, Dawson BT, Rowsell GJ. Time-motion characteristics and physiological responses of small-sided games in elite youth players: the influence of player number and rule changes. J Strength Cond Res. 2010; 24(8):2149–56.
5. Tessitore A, Meeusen R, Piacentini MF, Demarie S, Capranica L. Physiological and technical aspects of" 6-a-side" soccer drills. J Sports Med Phys Fitness. 2006; 46(1):36.
6. Clemente F, Sarmento H. Combining small-sided soccer games and running-based methods: A systematic review. Biol Sport. 2021; 38(4):617–27.
7. Giménez JV, Liu H, Lipińska P, Szwarc A, Rompa P, Gómez MA. Physical responses of professional soccer players during 4 vs. 4 small-sided games with mini-goals according to rule changes. Biol Sport. 2018; 35(1):75–81.
8. Branquinho L, Ferraz R, Travassos B, Marinho DA, Marques MC. Effects of different recovery times on internal and external load during small-sided games in soccer. Sports Health. 2021; 13(4):324–31.
9. Branquinho L, Ferraz R, Marques MC. 5-a-Side Game as a Tool for the Coach in Soccer Training. Strength Cond J. 2021; 43(5):96–108.
10. Branquinho L, Ferraz R, Travassos B, C. Marques M. Comparison between continuous and fractionated game format on internal and external load in small-sided games in soccer. Int J Environ Res Public Health. 2020; 17(2):405.
11. 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; 18(5):693–749.
12. López-Fernández J, Sánchez-Sánchez J, Rodríguez-Cañamero S, Ubago-Guisado E, Colino E, Gallardo L. Physiological responses, fatigue and perception of female soccer players in small-sided games with different pitch size and sport surfaces. Biol Sport. 2018; 35(3):291–9.
13. Clemente FM, Wong DP, Martins FML, Mendes RS. Acute effects of the number of players and scoring method on physiological, physical, and technical performance in small-sided soccer games. Res Sports Med. 2014; 22(4):380–97.
14. 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(5):568–76.
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; 28(14):1615–23.
16. 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. 2022; 10.1519.
17. Gaudino P, Alberti G, Iaia FM. Estimated metabolic and mechanical demands during different small-sided games in elite soccer players. Hum Mov Sci. 2014; 36:123–33.
18. Rossi A, Perri E, Pappalardo L, Cintia P, Iaia FM. 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.
19. Osgnach C, Poser S, Bernardini R, Rinaldo R, Di Prampero PE. Energy cost and metabolic power in elite soccer: a new match analysis approach. Med Sci Sports Exerc. 2010; 42(1):170–8.

20. Rossi A, Pappalardo L, Cintia P, Iaia FM, Fernández J, Medina D. Effective injury forecasting in soccer with GPS training data and machine learning. PloS One. 2018; 13(7):e0201264.
21. Beenham M, Barron DJ, Fry J, Hurst HH, Figueirdo A, Atkins S. A comparison of GPS workload demands in match play and small-sided games by the positional role in youth soccer. J Hum Kinet. 2017; 57(1):129–37.
22. Dalen T, Sandmæl S, Stevens TG, Hjelde GH, Kjøsnes TN, Wisløff U. 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):2018–24.
23. Weaving D, Dalton NE, Black C, Darrall-Jones J, Phibbs PJ, Gray M, Jones B, Roe GA. The same story or a unique novel? Within-participant principal-component analysis of measures of training load in professional rugby union skills training. Int J Sports Physiol Perform. 2018; 13(9):1175–81.
24. Fernández-Cuevas I, Gomez-Carmona P, Sillero-Quintana M, Noya-Salces J, Arnaiz-Lastras J, Pastor-Barrón A. Economic costs estimation of soccer injuries in first and second spanish division professional teams. In: 15th Annual Congress of the European College of Sport Sciences ECSS, 23th 26th june. 2010.
25. Reilly T. The science of training-soccer: A scientific approach to developing strength, speed and endurance. Routledge; 2006.
26. Winter EM, Maughan RJ. Requirements for ethics approvals. 2009;
27. 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; 15(9):e0229194.
28. Owen AL, Wong DP, Paul D, Dellal A. Physical and technical comparisons between various-sided games within professional soccer. Int J Sports Med. 2014; 35(04):286–92.
29. Muyor JM, Granero-Gil P, Pino-Ortega J. Reliability and validity of a new accelerometer (Wimu®) system for measuring velocity during resistance exercises. Proc Inst Mech Eng Part P J Sports Eng Technol. 2018; 232(3):218–24.
30. 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.
31. Hopkins WG. Measures of reliability in sports medicine and science. Sports Med. 2000; 30(1):1–15.
32. 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.
33. Tribolet R, Sheehan WB, Novak AR, Watsford ML, Fransen J. A descriptive and exploratory study of factors contributing to augmented feedback duration in professional Australian football practice. Int J Sports Sci Coach. 2022; 17(3):609–18.
34. Pollard R, Armatas V. Factors affecting home advantage in football World Cup qualification. Int J Perform Anal Sport. 2017; 17(1–2):121–35.
35. Dubois R, Paillard T, Lyons M, McGrath D, Maurelli O, Prioux J. Running and metabolic demands of elite rugby union assessed using traditional, metabolic power, and heart rate monitoring methods. J Sports Sci Med. 2017; 16(1):84.
36. Castagna C, Varley M, Póvoas SC, D-Ottavio S. Evaluation of the match external load in soccer: Methods comparison. Int J Sports Physiol Perform. 2017; 12(4):490–5.
37. Houtmeyers KC, Jaspers A, Brink MS, Vanrenterghem J, Varley MC, Helsen WF. External load differences between elite youth and professional football players: ready for take-off? Sci Med Footb. 2021; 5(1):1–5.
38. Dellal A, Hill-Haas S, Lago-Penas C, Chamari K. Small-sided games in soccer: amateur vs. professional players' physiological responses, physical, and technical activities. J Strength Cond Res. 2011; 25(9):2371–81.
39. Fenner JS, Iga J, Unnithan V. The evaluation of small-sided games as a talent identification tool in highly trained prepubertal soccer players. J Sports Sci. 2016; 34(20):1983–90.
40. de Dios-Álvarez V, Castellano J, Padrón-Cabo A, Rey E. Do small-sided games prepare players for the worst-case scenarios of match play in elite young soccer players? Biol Sport. 2023; 41(1):95–106.
41. Riboli A, Esposito F, Coratella G. Technical and locomotor demands in elite soccer: manipulating area per player during small-sided games to replicate official match demands. Biol Sport. 2022; 40(3):639–47.
42. Riboli A, Olthof SB, Esposito F, Coratella G. Training elite youth soccer players: area per player in small-sided games to replicate the match demands. Biol Sport. 2022; 39(3):579–98.
43. 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; 42(06):523–8.

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Supplementary table

S1 TABLE. Small-Sided Games characteristics. Similarity and Overload scores are reported as mean ± SD.

DRILL TYPE	SSG SIZE	PLAYERS' CONTRA-POSITION	PITCH SIZE	PITCH AREA (m^2)	AREA PER PLAYER (m^2)	SIM_{kin}	$OVER_{kin}$	SIM_{mec}	$OVER_{mec}$	N° INDIVIDUAL OBSERVATIONS
Game Simulation	large	4 v 4	50 × 60	3000	375	0.57 ± 0.1	-1.35 ± 1.26	0.61 ± 0.06	-0.81 ± 0.8	14
		5 v 4	50 × 64	3200	356	0.54 ± 0.16	-1.26 ± 2.5	0.59 ± 0.09	-0.56 ± 1.16	14
		6 v 5	52 × 64	3328	303	0.42 ± 0.09	-3.69 ± 1.27	0.46 ± 0.12	0.95 ± 2.61	11
		6 v 6	48 × 52	2496	208	0.63 ± 0.07	-1.04 ± 0.76	0.55 ± 0.16	1.72 ± 1.51	13
		6 v 6	66 × 40	2640	220	0.45 ± 0.14	-3.28 ± 2.92	0.56 ± 0.1	-1.07 ± 0.85	14
		7 v 7	50 × 64	3200	229	0.52 ± 0.16	-2.66 ± 2.82	0.54 ± 0.08	0.92 ± 1.38	13
		7 v 7	52 × 64	3328	238	0.48 ± 0.13	-3.19 ± 2.95	0.56 ± 0.1	0 ± 1.54	36
		7 v 7	55 × 60	3300	236	0.5 ± 0.22	2.93 ± 10.34	0.37 ± 0.16	3.68 ± 2.58	7
		7 v 7	55 × 64	3520	251	0.55 ± 0.1	-1.93 ± 0.91	0.56 ± 0.14	0.76 ± 1.81	14
		7 v 7	60 × 52	3120	223	0.63 ± 0.1	-1.22 ± 0.92	0.61 ± 0.14	0.59 ± 1.29	15
		7 v 7	66 × 50	3300	236	0.45 ± 0.16	-4.63 ± 7.36	0.55 ± 0.09	-1.47 ± 1.09	19
		8 v 7	66 × 64	4224	282	0.54 ± 0.16	-2.38 ± 3.05	0.57 ± 0.1	0.06 ± 1.43	42
		8 v 7	75 × 64	4800	320	0.65 ± 0.16	-1.11 ± 2.48	0.57 ± 0.1	0.57 ± 1.57	14
		8 v 8	52 × 64	3328	208	0.48 ± 0.13	-3.25 ± 2.77	0.56 ± 0.09	0.3 ± 1.33	94
		8 v 8	66 × 60	3960	248	0.61 ± 0.19	0.49 ± 4.21	0.58 ± 0.12	0.81 ± 1.14	12
		8 v 8	66 × 64	4224	264	0.56 ± 0.14	-2.17 ± 2.28	0.58 ± 0.1	0.29 ± 1.33	29
		8 v 8	75 × 60	4500	281	0.45 ± 0.12	-3.51 ± 3.63	0.56 ± 0.1	-0.07 ± 1.45	19
		8 v 8	75 × 64	4800	300	0.61 ± 0.14	-0.97 ± 1.15	0.62 ± 0.08	-0.12 ± 1.12	14
		9 v 8	66 × 64	4224	248	0.6 ± 0.12	-1.7 ± 1.21	0.58 ± 0.08	0.14 ± 1.02	12
		9 v 9	100 × 50	5000	278	0.65 ± 0.11	-0.13 ± 1.16	0.62 ± 0.09	0.39 ± 0.9	14
		9 v 9	66 × 60	3960	220	0.5 ± 0.14	-2.48 ± 2.48	0.56 ± 0.07	-0.54 ± 1.35	14
		9 v 9	66 × 64	4224	235	0.57 ± 0.15	-1.8 ± 1.92	0.58 ± 0.1	0.25 ± 1.55	32
		10 v 10	105 × 60	6300	315	0.58 ± 0.16	3.67 ± 18.27	0.56 ± 0.13	1.07 ± 1.73	40
		10 v 10	105 × 64	6720	336	0.62 ± 0.13	0.39 ± 1.54	0.62 ± 0.1	-0.12 ± 1.29	99
		10 v 10	105 × 68	7140	357	0.54 ± 0.1	1.77 ± 1.07	0.62 ± 0.1	0.53 ± 1.13	19
		10 v 10	66 × 64	4224	211	0.49 ± 0.13	-2.87 ± 2.12	0.57 ± 0.11	-0.81 ± 1.36	67
		10 v 10	66 × 70	4620	231	0.68 ± 0.12	-0.14 ± 4.24	0.65 ± 0.1	0.29 ± 1.13	74
		10 v 10	66 × 78	5148	257	0.65 ± 0.12	-0.72 ± 1.07	0.67 ± 0.08	-0.15 ± 0.87	15
		10 v 10	75 × 60	4500	225	0.54 ± 0.14	-1.97 ± 1.58	0.55 ± 0.1	-0.38 ± 1.73	15

S1 TABLE. Continue.

DRILL TYPE	SSG SIZE	PLAYERS' CONTRA-POSITION	PITCH SIZE	PITCH AREA (m^2)	AREA PER PLAYER (m^2)	SIM_{kin}	$OVER_{kin}$	SIM_{mec}	$OVER_{mec}$	N° INDIVIDUAL OBSERVATIONS
Game Simulation	medium	4v4	32 × 30	960	120	0.37 ± 0.1	-4.85 ± 3.01	0.52 ± 0.07	0.18 ± 1.29	31
		4v4	34 × 30	1020	128	0.36 ± 0.08	-4.55 ± 1.41	0.37 ± 0.09	3.07 ± 1.43	8
		4v4	34 × 40	1360	170	0.33 ± 0.1	-5.64 ± 3.01	0.49 ± 0.1	-0.82 ± 1.69	14
		4v4	50 × 30	1500	188	0.59 ± 0.12	-1.33 ± 1.11	0.53 ± 0.06	1.07 ± 0.74	9
		5v2	33 × 30	990	141	0.44 ± 0.13	-3.81 ± 2.95	0.57 ± 0.09	-0.17 ± 1.42	14
		5v5	35 × 40	1400	140	0.45 ± 0.13	-3.61 ± 2.92	0.48 ± 0.1	0.85 ± 2.05	35
		5v5	35 × 45	1575	158	0.38 ± 0.14	-4.83 ± 3.58	0.46 ± 0.12	-0.82 ± 2.59	12
		5v5	40 × 32	1280	128	0.58 ± 0.11	-1.42 ± 1.18	0.48 ± 0.13	1.7 ± 1.67	45
		5v5	50 × 30	1500	150	0.57 ± 0.11	-1.78 ± 0.8	0.49 ± 0.1	1.86 ± 1.34	11
		5v5	50 × 40	2000	200	0.49 ± 0.16	-2.11 ± 6	0.55 ± 0.11	0.69 ± 2.36	50
		6v4	35 × 50	1750	175	0.4 ± 0.11	-4.04 ± 1.89	0.43 ± 0.1	1.8 ± 2.57	9
		6v5	25 × 50	1250	114	0.4 ± 0.09	-3.67 ± 1.62	0.42 ± 0.11	1.23 ± 2.42	11
		6v6	32 × 40	1280	107	0.37 ± 0.12	-5.31 ± 4.66	0.55 ± 0.1	0.19 ± 1.55	12
		6v6	40 × 32	1280	107	0.51 ± 0.07	-2.29 ± 0.86	0.56 ± 0.1	1 ± 0.98	13
		6v6	45 × 52	2340	195	0.62 ± 0.1	-0.85 ± 1.06	0.51 ± 0.15	1.82 ± 1.6	11
		6v6	50 × 40	2000	167	0.53 ± 0.13	-2.25 ± 1.47	0.51 ± 0.09	1.45 ± 1.3	12
		6v6	52 × 40	2080	173	0.64 ± 0.1	-1.2 ± 0.59	0.61 ± 0.13	1.22 ± 1.15	9
		6v6	53 × 40	2120	177	0.66 ± 0.12	-0.61 ± 0.85	0.56 ± 0.09	0.7 ± 1.12	22
		7v7	38 × 42	1596	114	0.46 ± 0.09	-3.12 ± 1.24	0.47 ± 0.12	1.33 ± 1.14	10
		7v7	40 × 52	2080	149	0.61 ± 0.1	-1.2 ± 0.98	0.56 ± 0.09	1.1 ± 1.06	27
		7v7	50 × 32	1600	114	0.4 ± 0.1	-4.19 ± 2.38	0.57 ± 0.08	-0.36 ± 0.94	13
		7v7	50 × 40	2000	143	0.44 ± 0.13	-3.67 ± 2.43	0.52 ± 0.11	0.29 ± 1.97	13
		7v7	50 × 48	2400	171	0.5 ± 0.11	-2.56 ± 1.61	0.55 ± 0.11	0.71 ± 1.33	22
		7v7	55 × 40	2200	157	0.59 ± 0.1	-1.54 ± 1.05	0.54 ± 0.15	1.16 ± 1.98	13
		7v7	55 × 50	2750	196	0.44 ± 0.11	-3.49 ± 2.29	0.57 ± 0.1	0.2 ± 1.48	27
		7v7	66 × 40	2640	189	0.54 ± 0.14	-2.1 ± 2.67	0.59 ± 0.12	0.69 ± 1.35	27
		8v8	40 × 52	2080	130	0.61 ± 0.17	-1.46 ± 1.10	0.58 ± 0.18	-0.34 ± 2.87	11
		8v8	50 × 52	2600	163	0.55 ± 0.1	-2.05 ± 0.91	0.54 ± 0.1	1.05 ± 1.19	15
		8v8	50 × 60	3000	188	0.45 ± 0.13	-3.62 ± 2.35	0.58 ± 0.09	-0.43 ± 1.09	14
		8v8	54 × 52	2808	176	0.61 ± 0.11	-1.44 ± 0.9	0.56 ± 0.09	0.79 ± 1.43	15
		8v8	66 × 40	2640	165	0.53 ± 0.12	-2.29 ± 1.02	0.57 ± 0.07	0.23 ± 0.91	11
		9v9	50 × 50	2500	139	0.57 ± 0.11	-1.96 ± 1.02	0.54 ± 0.12	0.9 ± 1.9	13
		9v9	52 × 64	3328	185	0.45 ± 0.13	-3.49 ± 2.49	0.55 ± 0.09	-0.16 ± 1.43	32
		9v9	54 × 52	2808	156	0.61 ± 0.09	-1.3 ± 0.83	0.56 ± 0.11	0.99 ± 1.29	13
		9v9	55 × 64	3520	196	0.44 ± 0.11	-3.68 ± 2.69	0.55 ± 0.08	-0.1 ± 1.21	17
		9v9	56 × 53	2968	165	0.58 ± 0.11	-1.74 ± 0.92	0.58 ± 0.13	0.03 ± 1.53	36
		9v9	60 × 52	3120	173	0.64 ± 0.09	-1.11 ± 0.72	0.54 ± 0.13	1.08 ± 1.66	19
		10v10	50 × 60	3000	150	0.47 ± 0.12	-3.29 ± 3.1	0.56 ± 0.1	-0.17 ± 1.52	31
		10v10	52 × 60	3120	156	0.61 ± 0.11	-1.09 ± 1.05	0.58 ± 0.12	0.88 ± 1.24	37
		10v10	52 × 64	3328	166	0.41 ± 0.11	-4.11 ± 3.27	0.55 ± 0.1	-0.49 ± 1.35	33
		10v10	52 × 66	3432	172	0.67 ± 0.12	-0.46 ± 0.89	0.56 ± 0.09	1.21 ± 1.25	19
		10v10	52 × 68	3536	177	0.59 ± 0.19	1.31 ± 10.46	0.59 ± 0.18	1.27 ± 2.68	15
		10v10	53 × 60	3180	159	0.58 ± 0.1	-1.74 ± 0.8	0.58 ± 0.12	0.31 ± 1.56	22
		10v10	55 × 52	2860	143	0.58 ± 0.11	-1.61 ± 1.05	0.6 ± 0.1	0.23 ± 1.29	18
		10v10	56 × 52	2912	146	0.59 ± 0.09	-1.33 ± 0.9	0.57 ± 0.12	0.78 ± 1.52	61
		10v10	56 × 53	2968	148	0.6 ± 0.11	-1.54 ± 0.88	0.55 ± 0.12	0.86 ± 1.58	42
		10v10	60 × 52	3120	156	0.59 ± 0.1	-1.5 ± 0.92	0.57 ± 0.11	0.79 ± 1.39	152
		10v10	60 × 53	3180	159	0.56 ± 0.07	-1.73 ± 0.73	0.54 ± 0.13	1.06 ± 1.47	22
		10v10	60 × 64	3840	192	0.49 ± 0.13	-2.6 ± 2.31	0.48 ± 0.13	1.55 ± 1.62	17
		10v10	62 × 53	3286	164	0.61 ± 0.12	-1.39 ± 0.91	0.53 ± 0.11	1.05 ± 1.61	42
		10v10	64 × 52	3328	166	0.59 ± 0.09	-1.64 ± 0.62	0.6 ± 0.1	0.81 ± 0.8	17
		10v10	66 × 53	3498	175	0.62 ± 0.13	-1.42 ± 1.03	0.58 ± 0.11	0.47 ± 1.39	20
		10v10	66 × 60	3960	198	0.56 ± 0.14	-1.95 ± 2.62	0.6 ± 0.1	-0.11 ± 1.35	78

S1 TABLE. Continue.

DRILL TYPE	SSG SIZE	PLAYERS' CONTRA-POSITION	PITCH SIZE	PITCH AREA (m^2)	AREA PER PLAYER (m^2)	SIM_{kin}	$OVER_{kin}$	SIM_{mec}	$OVER_{mec}$	N° INDIVIDUAL OBSERVATIONS
Game Simulation	small	3 v 3	18 × 15	270	45	0.42 ± 0.08	-3.35 ± 0.83	0.3 ± 0.09	5.18 ± 2.85	12
		4 v 4	32 × 22	704	88	0.37 ± 0.15	-5.54 ± 5.01	0.39 ± 0.08	2.45 ± 1.38	5
		4 v 4	40 × 20	800	100	0.52 ± 0.23	-3.72 ± 5.3	0.4 ± 0.09	2.72 ± 1.82	7
		5 v 5	40 × 20	800	80	0.32 ± 0.11	-6.86 ± 6.52	0.48 ± 0.08	-2.13 ± 1.24	9
		5 v 5	40 × 25	1000	100	0.41 ± 0.07	-3.65 ± 1	0.51 ± 0.06	0.42 ± 0.91	11
		7 v 7	40 × 25	1000	71	0.36 ± 0.07	-4.71 ± 1.18	0.53 ± 0.05	-0.65 ± 1.11	11
		7 v 7	40 × 32	1280	91	0.49 ± 0.09	-2.59 ± 0.96	0.54 ± 0.12	0.89 ± 1.51	44
Possession Game	large	3 v 2	52 × 64	3328	666	0.23 ± 0.09	1.85 ± 5.94	0.38 ± 0.09	0.04 ± 1.91	15
		6 v 4	52 × 64	3328	333	0.39 ± 0.18	-5.41 ± 6.44	0.46 ± 0.09	0.29 ± 2.03	8
Possession Game	medium	2 v 2	30 × 20	600	150	0.3 ± 0.11	-7.09 ± 6.62	0.43 ± 0.11	-2.08 ± 1.95	16
		5 v 5	50 × 40	2000	200	0.5 ± 0.17	-3.31 ± 3.56	0.51 ± 0.06	0.83 ± 1.33	14
		6 v 6	30 × 55	1650	138	0.57 ± 0.14	-0.1 ± 5.39	0.46 ± 0.12	2.11 ± 2.29	20
		6 v 6	35 × 40	1400	117	0.4 ± 0.15	-5.61 ± 8.01	0.47 ± 0.1	1.28 ± 1.87	19
		6 v 6	40 × 32	1280	107	0.51 ± 0.11	-2.53 ± 1.71	0.61 ± 0.1	-0.39 ± 1.29	32
		6 v 6	40 × 35	1400	117	0.49 ± 0.14	-2.77 ± 1.74	0.49 ± 0.11	1.16 ± 1.48	14
		7 v 7	50 × 40	2000	143	0.39 ± 0.13	-4.6 ± 3.52	0.52 ± 0.07	-0.96 ± 1.2	13
		9 v 8	50 × 64	3200	188	0.45 ± 0.07	-3.1 ± 1.03	0.54 ± 0.09	0.12 ± 1.46	12
		9 v 9	50 × 40	2000	111	0.45 ± 0.11	-3.3 ± 2.78	0.55 ± 0.09	0.83 ± 0.83	18
		10 v 10	35 × 60	2100	105	0.42 ± 0.15	-4.71 ± 5.4	0.61 ± 0.11	-0.56 ± 1.07	18
		10 v 10	40 × 60	2400	120	0.48 ± 0.13	-1.96 ± 3.96	0.53 ± 0.13	1 ± 1.76	30
		10 v 10	50 × 50	2500	125	0.45 ± 0.12	-3.04 ± 2.17	0.57 ± 0.08	0.27 ± 0.96	15
		10 v 10	60 × 64	3840	192	0.48 ± 0.13	-2.48 ± 2.29	0.44 ± 0.15	2.21 ± 1.99	17
Possession Game	small	4 v 4	16 × 12	192	24	0.3 ± 0.11	-7.35 ± 7.77	0.47 ± 0.09	-0.2 ± 1.85	33
		4 v 4	16 × 16	256	32	0.26 ± 0.09	-8.43 ± 6.11	0.46 ± 0.11	-0.38 ± 2.04	10
		4 v 4	20 × 18	360	45	0.26 ± 0.1	-10.31 ± 12.58	0.39 ± 0.12	-4.16 ± 2.1	10
		4 v 4	20 × 20	400	50	0.32 ± 0.06	-5.43 ± 1.59	0.41 ± 0.11	1.43 ± 2.73	10
		4 v 4	20 × 22	440	55	0.3 ± 0.09	-6.63 ± 4.97	0.44 ± 0.09	0.66 ± 2.55	19
		4 v 4	25 × 20	500	63	0.28 ± 0.12	-4.82 ± 7.4	0.3 ± 0.12	4.58 ± 4.32	8
		5 v 5	25 × 20	500	50	0.34 ± 0.1	-5.69 ± 3.94	0.46 ± 0.11	0.06 ± 2.24	17
		5 v 5	30 × 20	600	60	0.36 ± 0.1	-5.01 ± 3.51	0.53 ± 0.1	-0.02 ± 1.48	32
		6 v 3	16 × 12	192	21	0.26 ± 0.09	-8.36 ± 5.83	0.5 ± 0.07	-1.71 ± 1.18	14
		6 v 6	20 × 30	600	50	0.41 ± 0.07	-3.47 ± 1.08	0.47 ± 0.14	1.06 ± 2.18	11
		6 v 6	30 × 35	1050	88	0.46 ± 0.09	-3.01 ± 1.11	0.57 ± 0.1	-0.61 ± 1.13	15
		7 v 3	16 × 10	160	16	0.31 ± 0.12	-7.61 ± 9.3	0.48 ± 0.1	-0.95 ± 2.03	18
		7 v 7	33 × 35	1155	83	0.47 ± 0.11	-2.86 ± 1.36	0.43 ± 0.11	1.83 ± 1.88	11
		7 v 7	34 × 20	680	49	0.33 ± 0.09	-5.56 ± 2.57	0.48 ± 0.07	0.18 ± 1.3	16
		7 v 7	40 × 32	1280	91	0.48 ± 0.09	-2.56 ± 1.11	0.46 ± 0.13	1.93 ± 2.25	22
		8 v 4	20 × 15	300	25	0.3 ± 0.09	-6.95 ± 5.21	0.5 ± 0.11	0.37 ± 1.68	12
		8 v 8	30 × 25	750	47	0.36 ± 0.11	-5.11 ± 3.42	0.52 ± 0.06	-0.95 ± 1.06	13
		9 v 9	32 × 40	1280	71	0.38 ± 0.08	-4.37 ± 1.75	0.53 ± 0.1	0.38 ± 0.99	17
		10 v 5	30 × 30	900	60	0.36 ± 0.1	-5.13 ± 3.67	0.48 ± 0.12	1.09 ± 1.83	15
		10 v 10	50 × 40	2000	100	0.44 ± 0.12	-3.46 ± 1.92	0.56 ± 0.07	0.49 ± 1.29	15

S1 TABLE. Continue.

DRILL TYPE	SSG SIZE	PLAYERS' CONTRA-POSITION	PITCH SIZE	PITCH AREA (m^2)	AREA PER PLAYER (m^2)	SIM_{kin}	$OVER_{kin}$	SIM_{mec}	$OVER_{mec}$	N° INDIVIDUAL OBSERVATIONS
Tactical Game	large	4 v 2	52 × 64	3328	555	0.33 ± 0.11	-5.22 ± 3.99	0.38 ± 0.12	-0.61 ± 3.97	16
		6 v 4	52 × 64	3328	333	0.52 ± 0.12	-2.42 ± 1.3	0.52 ± 0.13	1.14 ± 1.88	16
		6 v 4	55 × 64	3520	352	0.45 ± 0.17	-4.26 ± 4.48	0.58 ± 0.1	-0.48 ± 1.2	16
		7 v 7	52 × 64	3328	238	0.4 ± 0.14	-4.77 ± 3.98	0.53 ± 0.1	-1.07 ± 1.51	41
		7 v 7	75 × 60	4500	321	0.4 ± 0.11	-4.03 ± 2.37	0.5 ± 0.09	-2.11 ± 0.93	19
		8 v 4	66 × 64	4224	352	0.47 ± 0.13	-3.07 ± 1.64	0.56 ± 0.12	-0.46 ± 1.52	16
		8 v 5	52 × 64	3328	256	0.35 ± 0.1	-5.67 ± 4.98	0.5 ± 0.12	-0.23 ± 1.63	16
		8 v 6	66 × 64	4224	302	0.58 ± 0.09	-1.54 ± 0.92	0.56 ± 0.14	1.07 ± 1.39	12
		8 v 8	52 × 64	3328	208	0.4 ± 0.12	-4.42 ± 3.61	0.51 ± 0.13	-0.47 ± 2.33	58
		8 v 8	66 × 54	3564	223	0.49 ± 0.15	-3.24 ± 3.99	0.53 ± 0.09	-0.64 ± 1.64	14
		8 v 8	66 × 60	3960	248	0.39 ± 0.11	-4.32 ± 2.83	0.53 ± 0.1	-1.32 ± 1.08	14
		9 v 9	105 × 64	6720	373	0.6 ± 0.19	-0.38 ± 3.25	0.63 ± 0.09	-0.29 ± 0.97	16
		10 v 8	66 × 64	4224	235	0.47 ± 0.15	-3.4 ± 2.85	0.57 ± 0.12	-1.17 ± 1.34	17
		10 v 9	75 × 60	4500	237	0.59 ± 0.13	-0.75 ± 1.52	0.59 ± 0.1	-0.87 ± 1.15	18
		10 v 9	75 × 64	4800	253	0.49 ± 0.14	-3.23 ± 3.51	0.56 ± 0.1	-0.91 ± 1.35	35
		10 v 10	105 × 64	6720	336	0.41 ± 0.17	-4.96 ± 8.41	0.52 ± 0.1	-1.41 ± 1.6	53
		10 v 10	66 × 64	4224	211	0.5 ± 0.14	-1.54 ± 3.48	0.58 ± 0.1	0.46 ± 1.31	18
		10 v 10	75 × 60	4500	225	0.54 ± 0.17	-2.72 ± 3.32	0.59 ± 0.1	-0.77 ± 1.21	51
		10 v 10	75 × 64	4800	240	0.53 ± 0.11	-2.19 ± 1.4	0.62 ± 0.11	-0.49 ± 1.11	16
Tactical Game	medium	6 v 6	40 × 40	1600	133	0.32 ± 0.12	-7.03 ± 6.88	0.46 ± 0.1	-0.57 ± 2.25	12
		7 v 7	50 × 48	2400	171	0.43 ± 0.11	-3.54 ± 1.55	0.54 ± 0.08	-0.55 ± 1.23	11
		7 v 7	50 × 50	2500	179	0.37 ± 0.09	-4.71 ± 2.13	0.47 ± 0.09	0.89 ± 1.11	13
		9 v 8	52 × 64	3328	196	0.49 ± 0.16	-3.22 ± 3.21	0.58 ± 0.09	-0.81 ± 1.1	17

SIM_{kin} = kinematic similarity score; $OVER_{kin}$ = kinematic overload score; SIM_{mec} = mechanicaìl similarity score; $OVER_{mec}$ = mechanical overload score.

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Playing position and match location affect the number of high-intensity efforts more than the quality of the opposition in elite football players

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ABSTRACT: This study aimed to examine the impact of playing position (PP), match location (ML), and opposition standard (OS) on team and individual acceleration (ACC) and deceleration (DEC) efforts. Fifty professional football players were monitored across 24 English Premier Development League matches during the 2020/21 season. High-intensity ACC and DEC thresholds were set at $> +3$ m·s^{-2} and < -3 m·s^{-2}, respectively. Players were divided into five PPs: centre backs (CB; n = 68), full-backs (FB; n = 24), centre midfielders (CM; n = 54), wide midfielders (WM; n = 15), centre forwards (CF; n = 27). Opposition standard was categorised as Top (1st–4th), Middle (5th–9th), and Bottom (9th–13th) based on final league ranking of the study season. Each match location was classified as Home or Away. One way analysis of variance (ANOVA) and a multivariate ANOVA analysed the independent effect of PP, ML and OS on ACC and DEC efforts, and the interaction of all contextual factors, respectively. Acceleration efforts were affected by PP and ML. FB performed 22% more ACC than WM. All players performed 6% more ACC actions during home matches compared to away fixtures. DEC efforts were only affected by PP, with FB and CM executing 26% and 32% greater DEC efforts than CB, respectively. When playing against top or middle teams at home, CB, CM, and CF tended to perform more high-intensity actions than when playing away. In contrast, when playing against top teams at home, FB and WM performed fewer high-intensity actions than when playing away. Playing position and ML affected ACC and DEC actions but not OS.

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INTRODUCTION

Acceleration (ACC) and deceleration (DEC) actions in football elicit mechanical demands, contributing 7–10% and 5–7% to the total workloads of the elite players during match-play, respectively, regardless of playing position (PP) [1]. Moreover, the number of ACC actions during competitive match-play is 3–8 times greater than that of sprint actions [2], while DEC actions occur as frequently as ACC actions inducing an even higher mechanical load [1]. Nonetheless, existing studies have predominantly focused on measuring the total distance covered and high-intensity running (physiological load) in isolation whilst not considering ACC and DEC actions (biomechanical load) [1, 3]. This potentially leads to underestimating players' biomechanical load since most ACC actions have been reported to not reach high-intensity running thresholds [2, 4].

Such underestimation of players' biomechanical load in matches may increase the potential risk of injury, given that ACC and DEC actions are highly associated with neuromuscular fatigue [5]. Specifically, high rates of force development and highly coordinated neural activation are required to execute ACC and DEC activities, leading to induced muscle damage, mechanical fatigue and reducing neural drive [6]. Furthermore, ACC actions are known to be metabolically more demanding than running at a constant velocity [4]. Additionally, high eccentric braking actions that occur when decelerating rapidly seem to constitute the greatest volume of mechanical load per metre in comparison to other high-intensity activities [1]. Thus, quantifying ACC and DEC efforts during match-play to minimise and identifying the injury risk has recently been examined [6].

Accurately and objectively quantifying players' match actions is required to improve the understanding of players' workloads during match-play. With the emergence of modern motion-tracking technologies, the biomechanical loads and corresponding physiological responses of high-intensity actions can be quantified in an objective manner [7]. Such an advance in technology has provided sports scientists and/or team's performance staff with practical insight into designing individualised recovery plans and position-specific training programmes by monitoring players' workloads [8]. However, previous studies that examined ACC and DEC efforts have reported contradictory findings [1, 8–13]. This discrepancy may be attributed to the variation in high-intensity actions according to various contextual factors [13–19], which highlights the high match-to-match variability of high-intensity actions in football [20]. Thus, an investigation of ACC and DEC efforts should incorporate contextual factors to provide a comprehensive understanding of those match-play actions.

The physical demands of football matches differ according to PP [21]. Recently, it was reported that wide midfielders covered the greatest distance during high-intensity running, with central defenders covering the least distance during match-play [22]. Moreover, Ingebrigtsen, Dalen [23] found that sprinting distance by wide midfielders was ~290 m, which is more than twice as much than covered by central defenders per match. Nonetheless, studies that examined the effect of PP on the number of ACC and DEC actions are scarce in the existing literature, while conflicting findings were observed between studies [2, 23, 24]. This necessitates more investigations to determine whether positional differences exist in ACC and DEC actions in elite development football.

The match location (ML) has been regarded as an important contextual factor that affects physical demands [3, 25, 26]. However, it seems to affect the running demands not as much, but can impact ACC and DEC. To illustrate, external load variables showed a tendency to be higher during home matches although no significant differences were found [25]. Another study revealed that ML did not influence the external load but confirmed that PP had a major impact [3]. This was also confirmed in a study that found high-intensity actions during match-play are less affected by ML compared to quality of opposition and match outcome [26]. Furthermore, less high-intensity ACC and DEC actions were performed in home matches versus away matches [22]. With the contrasting findings between running and acceleration demands and limited information on acceleration demands, it seems unclear if ML affects the number of ACC and DEC actions during match-play.

The opposition standard (OS) has been considered as another contextual factor that may influence physical demands during match-play, but the direction of influence seems inconclusive. When playing against higher-standard teams, elite football players covered a greater distance by high-intensity running (HIR), which consists of high-speed running (HSR) (≥ 19.8–25.1 km/h^{-1}) and sprinting (> 25.2 km/h^{-1}) [4], whereas other research highlighted that increased running demands were observed when playing against similar-level opponents [27]. A recent study observed that DEC (< –4 m·s^{-2}) showed higher values against top-level compared with middle- and bottom-level opponents [28]. As a limited number of studies have investigated the effect of OS on high-intensity ACC and DEC actions [12, 26, 28, 29], it restricts any definitive conclusions assessing the effect of those actions.

In the current literature, information is relatively limited on the effect of PP, ML, and OS on high-intensity ACC and DEC, and no study has investigated its effect on those actions in the English Premier Development (U23) League. Understanding the acceleration and deceleration demands in match-play supports the identification and development of talented players. Therefore, the current study aimed to determine the effects of ML, OS, and PP on the number of high-intensity ACC and DEC actions performed. A secondary aim was to examine any team and positional biomechanical demand differences. It was hypothesised that; a) positional differences appear in ACC and DEC actions, b) less high-intensity ACC and DEC actions would be performed playing at home compared to playing away, and c) greater high-intensity ACC and DEC efforts are produced when competing against higher OS compared to lower OS.

MATERIALS AND METHODS

Participants & Data Sample

This observational study involved professional football players participating in the English Premier Development League. A total of 50 elite football players (age 27 ± 5 years; height 181 ± 6 cm; body mass 75 ± 8 kg) from one academy (U23) team were monitored in the 2020/2021 season. The team played 24 matches in the English Premier League Development League. After excluding participants who played less than 90 minutes (n = 110) from the analysis, 189 player observations were included for further data analysis. Goalkeepers were excluded from the investigation due to the specific nature of the match activity and low running demands [23]. The professional club from which the participants volunteered approved the secondary data analyses. All data collected resulted from normal analytical procedures regarding player monitoring over the competitive season. Gatekeeper consent was obtained for secondary data analysis. Data from all players were compiled into a repository, and the Research Ethics Committee of Liverpool John Moores University approved secondary data analyses (Reference number: U22SPS2076).

Contextual Factors

Players were assigned to one of five playing positions as match physical demands for these differ significantly [24]. Match observations were classified according to playing positions as follows: centre backs (CB; n = 68), full-backs (FB; n = 24), centre midfielders (CM; n = 54), wide midfielders (WM; n = 15) and centre forwards (CF; n = 27). The study team consistently played in a 1-4-4-2 tactical system. To establish OS, all teams in the English Premier League Development League during the 2020/2021 season were categorised as Top (1st–4th, player observations n = 64), Middle (5th–9th, n = 67),

and Bottom (9^{th}–13^{th}, n = 57), with the reference team being classified as Middle based on the final league table of the study season [30]. Regarding ML, each match was categorised according to the location in which the game occurred (home, n = 95 and away, n = 93). To examine the independent effect of contextual factors, OS, ML, and PP were analysed separately. The factors OS, ML, and PP were also combined to determine the interactive effect.

Data Collection Procedure

The biomechanical loads were consistently monitored across the study seasons during all matches using player tracking technology with an 18 Hz global positioning system (GPS) system (Apex Pod, version 4.03, 50 g, 88 × 33 mm; STATSports; Northern Ireland, UK). StatSports devices had good reliability across sessions for high accelerations (CV = 0.0 to 4.0%), good to moderate for low accelerations (CV = 2.3 to 7.8%), moderate accelerations (CV = 1.7 to 7.5%), low decelerations (CV = 1.6 to 8.0%) and high decelerations (CV = 1.1 to 6.6%), and good to poor for moderate decelerations (CV = 4.8 to 10.2%) [31]. All devices were activated 30-minutes before data collection to allow the acquisition of satellite signals and to synchronise the GPS clock with the satellite's atomic clock [32]. To avoid potential inter-unit error, each player wore the same device during the study period [33], although the present GPS system has previously reported excellent inter-unit reliability [34]. Specifically designed vests were used to hold the devices, located on the player's upper torso, and anatomically adjusted to each player. The GPS signal quality and horizontal dilution of position (HDOP) was connected to a mean number of 21 ± 3 satellites, range 18–23, while HDOP for all seasons ranged between 0.9–1.3.

On completion of each match, GPS data were extracted using proprietary software (Apex, 10 Hz version 4.3.8, STATSports Software; Northern Ireland, UK) as software-derived data is a more simple and efficient way for practitioners to obtain data in an applied environment, with no differences reported between processing methods (software-derived to raw processed) [35]. Biomechanical loads during all matches were obtained from the GPS not from the accelerometer. Furthermore, the internal processing of the GPS units utilised the Doppler shift method to calculate both distance and velocity data which is shown to display a higher level of precision and less error compared with data calculated via positional differentiation [36]. STATSports provided written permission to allow all data to be used for research purposes. Variables analysed were selected based on previous publication [37] and in practical settings are commonly utilised by analysts in elite football. The following physical variables were quantified: the number of high-intensity accelerations ($> 3\ m \cdot s^{-2}$ with minimum duration of 0.5 s); the number of high-intensity decelerations ($< -3\ m \cdot s^{-2}$ with minimum duration of 0.5 s) [31].

Statistical Analysis

Descriptive statistics were utilised in summarising all demographic findings of this study. Data are reported as the mean ± standard deviation (SD). Statistical analyses were conducted using IBM SPSS

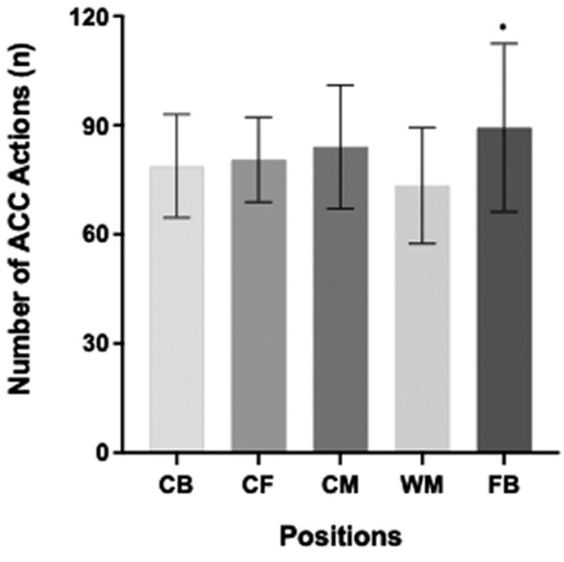


FIG. 1. The mean number of acceleration (ACC) actions performed by different playing positions. CB: centre backs; CF: centre forwards; CM: central midfielders; WM: wide midfielders; FB: full-backs. *Greater number of actions performed than WM ($P < 0.05$).

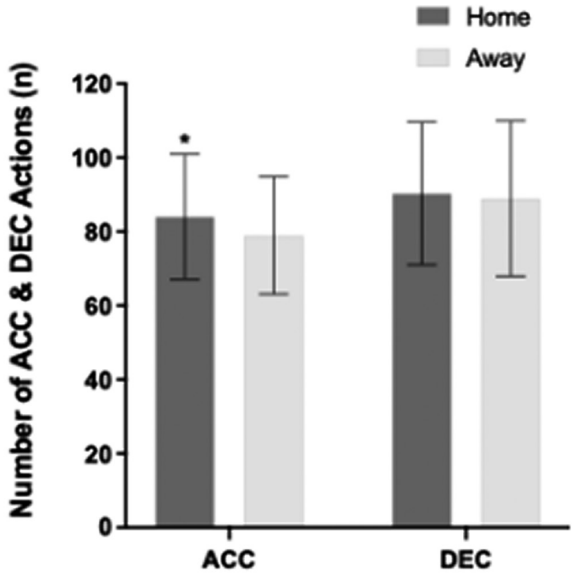


FIG. 3. The mean number of acceleration (ACC) and deceleration (DEC) actions performed by all playing positions when considering match location. *Greater number of actions performed in home than away matches ($P < 0.05$).

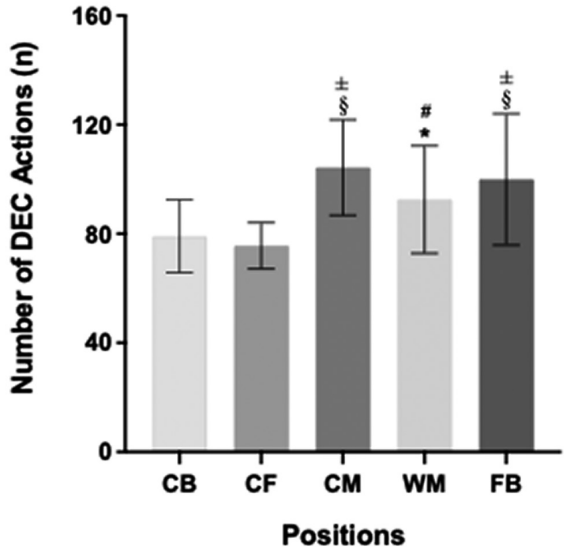


FIG. 2. The mean number of deceleration (DEC) actions performed by different playing positions. CB: centre backs; CF: centre forwards; CM: central midfielders; WM: wide midfielders; FB: full-backs. ‡ Greater number of actions than CB ($P < 0.001$); § Greater number of actions than CF ($P < 0.001$); # Greater number of actions than CB ($P < 0.05$); * Greater number of actions performed than CF ($P < 0.05$).

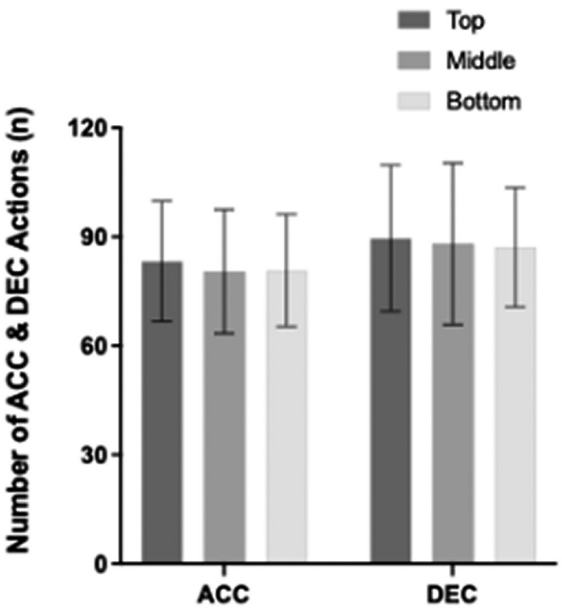


FIG. 4. The mean number of acceleration (ACC) and deceleration (DEC) actions from all playing positions whilst considering opponent standards.

Statistics for Mac OS X, version 27 (IBM Corp., Armonk, N.Y, USA). Data normality was checked using a Shapiro-Wilk test. One way analysis of variance (ANOVA) was selected to analyse the independent effect of OS, ML, and PP on ACC and DEC efforts. Bonferroni post-hoc tests were then applied when a significant difference appeared to identify any localised effects. A multivariate ANOVA (MANOVA) was utilised to determine the interaction effect of all contextual factors. Effect size (ES) for the meaningfulness of the difference was determined based on the following criterion: (≤ 0.2 = trivial), (> 0.2–0.6 = small), (> 0.6–1.2 = moderate), (> 1.2–2.0 = large), and (> 2.0–4.0 = very large) [38]. Statistical significance was set at $P \leq 0.05$.

RESULTS

The average number of ACC actions was significantly affected by different PP ($P < 0.05$; Figure 1). The highest mean ACC efforts were observed for FB (n = 89), followed by CM, CF, CB, and WM (n = 84, 81, 79, and 73, respectively). Post-hoc analysis revealed that FB performed 22% greater ACC actions than WM ($P < 0.05$; ES: 0.8), but no differences were observed for other positions.

Further, the mean number of DEC efforts were significantly affected by PP ($P < 0.001$; Figure 2). The highest DEC effort was observed in CM (n = 104), followed by FB, WB, CB, and CF (n = 100, 92, 79, and 76, respectively). Post-hoc analysis revealed that the FB, CM, and WM produced more DEC actions than the CB and CF. Specifically, the FB and CM performed 26% ($P < 0.001$; ES: 1.2) and 32% ($P < 0.001$; ES: 1.6) more DEC efforts than the CB, respectively. Similarly, FB and CM produced 32% ($P < 0.001$; ES: 1.4) and 38% ($P < 0.001$; ES: 1.9) more DEC actions than the CF, respectively. Wide midfielders executed 17% and 22% more DEC efforts compared to CB and CF, respectively ($P < 0.05$; ES: 0.9–1.3).

The mean number of ACC efforts were significantly affected by ML ($P < 0.05$; Figure 3). All players performed 6% more ACC actions in home matches compared to away matches ($P < 0.05$; ES: 0.3); whereas a non-significant difference (2%) was found in the DEC actions between home and away matches ($P = 0.635$; ES: 0.1).

The mean number of ACC ($P = 0.569$) and DEC ($P = 0.166$) efforts were not affected by OS (Figure 4). The largest number of ACC and DEC actions were performed by the study team in matches against top teams compared to those against middle and bottom teams, but this fails to reach significance.

Table 1 illustrates the mean number of ACC and DEC efforts considering OS and ML across various PP. Against top teams, CB and CF performed more ACC actions at home than away, but FB performed less ACC and DEC actions. Against middle teams, CM performed more ACC and DEC actions at home than away. When

TABLE 1. The descriptive statistics of the average acceleration and deceleration efforts when considering opposition standard and match location across different playing positions.

Contextual Factors			Acceleration			Deceleration		
Playing positions	Opposition standard	Match locations	Mean efforts (N)	Standard deviation (± SD)	Sample size (N)	Mean efforts (N)	Standard deviation (± SD)	Sample size (N)
CB	Top	Home	86.7*	15.8	13	84.1	13.4	13
		Away	72.8	12.8	11	79.7	14.1	11
	Middle	Home	76.6	15.9	12	78.1	16.4	12
		Away	77.5	11.0	12	73.8	11.1	12
	Bottom	Home	79.2	15.3	11	82.4	13.9	11
		Away	79.2	12.2	9	76.0	10.5	9
CF	Top	Home	86.5*	1.0	4	77.8	4.1	4
		Away	72.0	10.7	5	69.6	12.9	5
	Middle	Home	86.0	12.2	5	76.0	6.9	5
		Away	73.8	11.1	5	78.0	9.3	5
	Bottom	Home	86.3	12.2	4	76.8	8.3	4
		Away	81.3	13.4	4	76.5	7.5	4
CM	Top	Home	88.5	14.9	11	107.4	11.7	11
		Away	81.1	20.3	9	112.8	14.9	9
	Middle	Home	92.9*	13.2	9	119.2**	15.4	9
		Away	75.4	15.8	10	89.5	20.2	10
	Bottom	Home	78.8	18.6	8	91.5*	10.4	8
		Away	88.1	16.3	7	105.3	8.8	7
WM	Top	Home	88.5	3.5	2	97.0**	14.1	2
		Away	72.0	0	1	117.0	0	1
	Middle	Home	70.0	25.6	3	94.3	40.3	3
		Away	66.0	9.9	2	87.5	19.1	2
	Bottom	Home	85.0*	13.5	3	88.7	4.7	3
		Away	64.0	11.7	4	88.5	16.4	4
FB	Top	Home	79.0**	26.5	3	90.3**	6.8	3
		Away	101.6	22.2	5	115.0	27.2	5
	Middle	Home	88.4	36.9	5	91.8	25.6	5
		Away	91.8	5.1	4	106.0	17.8	4
	Bottom	Home	91.5	13.4	3	92.5	36.1	3
		Away	81.6	21.5	5	97.0	28.9	5
Total	Top	Home	86.7	14.6	33	92.4	15.9	33
		Away	79.7	18.9	31	94.6	24.8	31
	Middle	Home	83.4	20.3	34	92.1	25.4	34
		Away	77.3	13.0	33	83.9	18.0	33
	Bottom	Home	81.6	15.2	29	85.6	13.7	29
		Away	81.0	15.9	29	88.5	18.9	29
	Total	Home	84.0*	17.0	95	90.3	19.4	95
		Away	79.0	15.9	93	88.9	21.0	93

Abbreviations = CB: central back; CF: centre forward; CM: centre midfielder; WM: wide midfielder; FB: full-back. The symbol '*' denotes significant difference compared to away matches ($P < 0.05$); '**' denotes significant differences compared to away matches ($P < 0.001$).

playing against bottom teams at home, WM performed 33% more ACC actions ($P < 0.05$; ES: 2.0) than against bottom teams at away. However, WM performed less DEC actions against top teams at home than away.

DISCUSSION

This study aimed to determine the independent effect of PP, ML, and OS on the number of high-intensity ACC and DEC actions performed by a team competing in the English Premier Development League. Further, all contextual variables (i.e., PP, ML, and OS) were also combined to determine the interaction effect on the number of high-intensity ACC and DEC actions. The main findings of the current study were: (1) positional variations in the number of ACC and DEC actions were evident; (2) the number of ACC actions were 6% greater during home matches compared to away matches; and (3) ACC and DEC efforts were not affected by OS.

Number of Acceleration and Deceleration

In the current study, the average total number of high-intensity ACC and DEC actions performed during match-play were 82 and 90, respectively. These findings support Vigh-Larsen, Dalgas [8], who also highlighted similar numbers of ACC and DEC actions, 81 and 84 respectively. However, other research have reported more ACC and DEC actions than the current study [1, 11]. For instance, Australian A-league players accelerated and decelerated more frequently, with on average 113 and 148 times during match-play [11]. Contrary to this, Dalen, Jørgen [1] found relatively small numbers of ACC and DEC actions were performed (76 and 54, respectively) in elite Norwegian players. This may partly be attributed to the cultural differences (i.e., preferred formations or playing styles) between different European football leagues [19]. Additionally, this may be due to different speed thresholds (i.e., 2.78 vs. 2.0 vs. 3.0 $m \cdot s^{-2}$) for high-intensity ACC and DEC actions adopted by previous studies. Thus, caution should be applied when making comparisons between studies. While differences in arbitrary thresholds between studies seem negligible, researchers should utilise common arbitrary thresholds for high-intensity ACC and DEC actions [6], since this would allow researchers and practitioners to directly and easily compare match-day ACC and DEC profiles between studies and various cohorts.

Playing Position

This study has highlighted that high-intensity ACC actions were affected by the PP, which aligns with previous studies [1, 26]. It has been frequently reported that CB perform the lowest number of ACC activities during match-play, whilst WM execute the greatest compared to all other positions [23, 24]. However, Varley and Aughey [2] found that the greatest ACC effort was observed in FB, agreeing with a finding from the present study. That said, the present study also reported a contrasting result. Wide midfielders performed the lowest number of ACC actions, which was significantly lower than those performed by FB. Thus, it might be speculated that the tactical principle of the reference team during match-play pre-disposed FB to perform the lowest number of ACC. For instance, WM players perform in a more central pitch area than a lateral area when in possession. This tactical movement of WM attracts the opposition FB inside, creating more space on the flanks for FB to perform HIR (e.g., overlapping runs), which may be attributed to more high-intensity ACC performed by FB in this study. In contrast, when out of possession, FB may need to quickly recover from the opposition half to hold a dominant defensive position. Such a tactical evolution and various playing systems in modern football may require FB to be involved in offensive and defensive roles [39], that may underpin the finding of the current study, that the highest number of ACC actions were performed by FB. However, none of the justifications can be confirmed as the total distance (TD) covered and HIR and ball possession were not included in the analysis. Therefore, such examination should be considered in future studies.

Similar to ACC actions, the frequency of DEC actions during matches was position-specific. More specifically, the number of DEC actions performed by CM, FB, and WM were higher than CB, which is consistent with previous studies [2, 26], although Oliva-Lozano, Fortes [24] found no differences in those actions in CB compared to other PP, except for WM. Those inconsistent findings observed between studies may be attributed to different playing formations as positional differences in high-intensity ACC and DEC actions were considerably affected by playing formations [17]. For instance, Tierney, Young [13] found that FB in a 3-5-2 formation executed a 20% higher number of DEC actions compared to those in a 4-4-2 formation. However, investigating the effect of formations on physical demands seems to be challenging as a tactical evolution in match-play suggests that teams do not tend to adopt only one specific formation throughout the whole match, given various situational factors affecting match performance [14]. Nonetheless, a holistic approach that amalgamates physical efforts with the tactical purpose of the action still seems to be required to provide a more comprehensive understanding of physical performance that includes ACC and DEC actions [40]. This may allow the quantification of such actions to be contextualised by 'where', 'why' and 'how' for each PP performing those actions during match-play [7]. This method may be practically useful when designing position-specific training drills.

Match Location

Pertaining to ML, this study exhibited that ACC efforts of all players during home matches were higher than during away matches although small ES were observed. Further, DEC efforts between home and away matches did not differ significantly. Although ML has been reported to have less impact on the distance covered at various intensities than other contextual factors [3, 26], it may not be confirmed that this trend applies to ACC and DEC actions. One study that investigated the impact of ML on ACC and DEC efforts demonstrated that greater high-intensity ACC and DEC actions were observed in away matches rather than home matches [22], which is not

consistent with the result of this study. Goalkeeper data was not omitted from analysis in the latter study, which may have decreased the mean ACC and DEC efforts reported, thus limiting a direct comparison with the current study. Furthermore, it may be argued that ML does not have a big effect on U23 teams compared to professional level. Likely, attendance of a crowd is lower at these games and there is more a focus on development than on the consequence of winning or losing a match [41]. This may translate in similarities in ACC and DEC demands in playing home or away. Given the paucity of information on the effect of ML on ACC and DEC efforts available in the previous literature [22], a definite conclusion cannot be drawn. Hence, future research that considers these limitations is warranted.

Opposition Standard

The current study found the greatest number of ACC and DEC actions were observed in matches against higher standard opposition, but no significant difference was observed. This aligns with agrees with Rago, Silva [29] and Nobari, Ramachandran [28]. Generally, an increased density between players is expected when competing against better quality opponents, which may decrease the space available for players to run, which may predispose players to perform more high-intensity ACC and DEC actions as less time and space is available to make quick decisions to perform subsequent actions [27]. However, given the small number of player observations (low statistical power) in the current study and the research conducted by Rago, Silva [29], caution should be taken when generalising or interpreting GPS-derived ACC and DEC data.

Interaction effect of PP, ML, and OS

The current study is the first to concurrently investigate an interaction effect of OS, ML, and PP on ACC and DEC efforts. One of the main findings was that players in a central position (i.e., CB, CM, and CF) performed more high-intensity actions in games against top and middle teams at home than away. At the same time, wide players (i.e., FB and WM) performed less high-intensity actions against top teams at home than playing away. This result demonstrates the interaction between PP, OS, and ML. In home games and playing against top teams, the central players seem more engaged in high-intensity actions, whereas the wide players perform less of those efforts. This may be due to the decreased space available in the central area of the pitch by an increase in the density of opponents when playing against top teams amplified by playing at home. This may restrict the opportunity for CM to perform high-speed running, which causes these players to execute greater DEC efforts in a narrow space compared to matches against bottom teams [6]. Against bottom teams, the WM are more engaged in high-intensity efforts, again amplified by playing at home. Both of these observations, however, such a spatial constraint may be affected by the score-line [18]. This result demonstrates the interaction between PP, OS, and ML. In home games and playing against top teams, the central players engaged in high-intensity actions, whereas the wide players performed less of those efforts. The novel finding of the present study may provide sports scientists with a more comprehensive insight into designing individualised training programmes while considering PP, ML, and OS concurrently.

Limitations

Some limitations of the current study exist. Firstly, the GPS data examined in this study was from a single English Premier Development League team, thus, caution must be considered when drawing any generalisations from this study, as varying leagues have different characteristics and playing styles that may affect the physical demands during match-play [19]. Thus, these findings may potentially be different to the current study. Secondly, it has been reported that GPS metrics have a high measurement error and variation when capturing high-intensity actions (especially ACC and DEC) [42, 43], despite being previously adopted in research [44]. Therefore, using a valid and reliable accelerometer-derived device known to be more sensitive to capture ACC and DEC actions is warranted for future research, that will help improve measurement accuracy and provide more reliable data for analysis. Furthermore, the current study did not consider physical variables such as TD, HSR, and sprinting, as well as tactical variables such as formation and possession when analysing ACC and DEC efforts, similar to previous research [1, 44]. Consequently, the study produced a limited understanding of contextualised ACC and DEC actions, given these variables are reported to affect physical demands during match-play [40, 45]. Therefore, it is warranted that these variables should be considered for future research. Finally, the contextual factor of match outcome was not employed in this study analysis which should be considered for future research, since it has been proven that match outcome can affect the number of ACC and DEC [44].

CONCLUSIONS

In conclusion, the number of high-intensity efforts is influenced by playing position and match location. Playing position have a great impact on ACC and DEC efforts with large effects. The findings of this study confirm several of the hypotheses, except hypothesis (3) regarding OS. Sports scientists may utilise the findings of the current study to design position-specific physical conditioning training and individualised recovery sessions whilst considering PP, ML, and OS independently or concurrently. However, this may be of greater interest when contextualising ACC and DEC actions with tactical variables as this may help practitioners design more effective training.

Conflict of interest

The authors declare no conflict of interest.

REFERENCES

1. Dalen T, Jørgen I, Gertjan E, Havard HG, Ulrik W. Player load, acceleration, and deceleration during forty-five competitive matches of elite soccer. J Strength Cond Res. 2016; 30(2):351–9.
2. Varley MC, Aughey RJ. Acceleration profiles in elite Australian soccer. Int J Sports Med. 2013; 34(01):34–9.
3. Miguel M, Oliveira R, Brito JP, Loureiro N, García-Rubio J, Ibáñez SJ, editors. External match load in amateur soccer: the influence of match location and championship phase. Healthcare 2022; 10(4):594.
4. Rampinini E, Coutts AJ, Castagna C, Sassi R, Impellizzeri F. Variation in top level soccer match performance. International J Sports Med. 2007; 28(12):1018–24.
5. Delaney JA, Cummins CJ, Thornton HR, Duthie GM. Importance, reliability, and usefulness of acceleration measures in team sports. J Strength Cond Res. 2018; 32(12):3485–93.
6. Harper DJ, 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(12):1923–47.
7. Ade J, Fitzpatrick J, Bradley PS. High-intensity efforts in elite soccer matches and associated movement patterns, technical skills and tactical actions. Information for position-specific training drills. J Sports Sci. 2016; 34(24):2205–14.
8. Vigh-Larsen JF, Dalgas U, Andersen TB. Position-specific acceleration and deceleration profiles in elite youth and senior soccer players. J Strength Cond Res. 2018; 32(4):1114–22.
9. Opar DA, Williams MD, Shield AJ. Hamstring strain injuries. Sports Med. 2012; 42(3):209–26.
10. Russell M, Sparkes W, Northeast J, Cook CJ, Love TD, Bracken RM, et al. Changes in acceleration and deceleration capacity throughout professional soccer match-play. J Strength Cond Res. 2016; 30(10):2839–44.
11. Wehbe GM, Hartwig TB, Duncan CS. Movement analysis of Australian national league soccer players using global positioning system technology. J Strength Cond Res. 2014; 28(3):834–42.
12. Aquino R, Gonçalves LG, Galgaro M, Maria TS, Rostaiser E, Pastor A, et al. Match running performance in Brazilian professional soccer players: Comparisons between successful and unsuccessful teams. BMC Sports Sci Med Rehab. 2021; 13(1):1–9.
13. Tierney PJ, Young A, Clarke ND, Duncan MJ. Match play demands of 11 versus 11 professional football using Global Positioning System tracking: Variations across common playing formations. Hum Mov Sci. 2016; 49:1–8.
14. Carling C. Influence of opposition team formation on physical and skill-related performance in a professional soccer team. Eur J Sport Sci. 2011; 11(3):155–64.
15. Bradley PS, Carling C, Archer D, Roberts J, Dodds A, Di Mascio M, et al. The effect of playing formation on high-intensity running and technical profiles in English FA Premier League soccer matches. J Sports Sci. 2011; 29(8):821–30.
16. Sarmento H, Clemente FM, Araújo D, Davids K, McRobert A, Figueiredo A. What performance analysts need to know about research trends in association football (2012–2016): A systematic review. Sports Med. 2018; 48(4):799–836.
17. 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.
18. Redwood-Brown A, O'Donoghue P, Robinson G, Neilson P. The effect of score-line on work-rate in English FA Premier League soccer. Int J Sports Physiol Perform. 2012; 12(2):258–71.
19. Dellal A, Chamari K, Wong dP, Ahmaidi S, Keller D, Barros R, et al. Comparison of physical and technical performance in European soccer match-play: FA Premier League and La Liga. Eur J Sport Sci. 2011; 11(1):51–9.
20. Gregson W, Drust B, Atkinson G, Salvo VD. Match-to-match variability of high-speed activities in premier league soccer. Int J Sports Med. 2010; 31(4):237–42. Epub 20100215. doi: 10.1055/s-0030-1247546. PubMed PMID: 20157871.
21. 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):159–68.
22. Barrera J, Sarmento H, Clemente FM, Field A, Figueiredo AJ. The effect of contextual variables on match performance across different playing positions in professional portuguese soccer players. Int J Environ Res Public Health. 2021; 18(10):5175.
23. Ingebrigtsen J, Dalen T, Hjelde GH, Drust B, Wisloff U. Acceleration and sprint profiles of a professional elite football team in match play. Eur J Sport Sci. 2015; 15(2):101–10. Epub 20140708. doi: 10.1080/17461391.2014.933879. PubMed PMID: 25005777.
24. 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; 15(8):e0236959.
25. Nobari H, Fani M, Mainer-Pardos E, Oliveira R. Comparison of GPS derived variables based on home versus away matches in the Asian professional soccer team. Proceedings of the Institution of Mechanical Engineers, Part P: J Sports Eng Technol. 2022: 17543371221109729.
26. Teixeira JE, Leal M, Ferraz R, Ribeiro J, Cachada JM, Barbosa TM, et al. Effects of Match Location, Quality of Opposition and Match Outcome on Match Running Performance in a Portuguese Professional Football Team. Entropy. 2021; 23(8):973.
27. Hewitt A, Norton K, Lyons K. Movement profiles of elite women soccer players during international matches and the effect of opposition's team ranking. J Sports Sci. 2014; 32(20):1874–80.
28. Nobari H, Ramachandran A, Oliveira R. The influence of opponent level on professional soccer players' training and match performance assessed by using wearable sensor technology. Hum Mov. 2022; 24(1).
29. 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.
30. Castellano J, Blanco-Villaseñor A, Alvarez D. Contextual variables and time-motion analysis in soccer. I J Sports Med. 2011; 32(06):415–21.
31. Crang ZL, Duthie G, Cole MH, Weakley J, Hewitt A, Johnston RD. The inter-device reliability of global navigation satellite systems during team sport movement across multiple days. J Sci Med Sport. 2022; 25(4):340–4.
32. Maddison R, Ni Mhurchu C. Global positioning system: a new opportunity in physical activity measurement. Int J Behav Nutr Phys Act. 2009; 6(1):1–8.
33. Buchheit M, Simpson B, Mendez-Villanueva A. Repeated high-speed activities during youth soccer games in relation to changes in maximal sprinting and aerobic speeds. Int J Sports Med. 2012:40–8.
34. Beato M, de Keijzer K. The inter-unit and inter-model reliability of GNSS STATSports Apex and Viper units in measuring peak speed over 5, 10, 15, 20 and 30 meters. Biol Sport. 2019; 36(4):317–21.
35. Thornton HR, Nelson AR, Delaney JA, Serpiello FR, Duthie GM. Interunit reliability and effect of data-processing methods of global positioning systems. Int J Sports Physiol Perform. 2019; 14(4):432–8.
36. Townshend AD, Worringham CJ, Stewart IB. Assessment of speed and position during human locomotion using nondifferential GPS. Med Sci Sports Exerc. 2008; 40(1):124–32.

37. Wass J, Mernagh D, Pollard B, Stewart P, Fox W, Parmar N, et al. A comparison of match demands using ball-in-play vs. whole match data in elite male youth soccer players. Sci Med Footb. 2020; 4(2):142–7.
38. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. Int J Sports Physiol Perform. 2006; 1(1):50–7.
39. 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.
40. 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.
41. Olthof SB, Frencken WG, Lemmink KA. When something is at stake: Differences in soccer performance in 11 vs. 11 during official matches and training games. J Strength Cond Res. 2019; 33(1):167.
42. Linke D, Link D, Lames M. Validation of electronic performance and tracking systems EPTS under field conditions. PloS One. 2018; 13(7):e0199519.
43. Buchheit M, Al Haddad H, Simpson BM, Palazzi D, Bourdon PC, Di Salvo V, et al. Monitoring accelerations with GPS in football: time to slow down? Int J Sports Physiol Perform. 2014; 9(3):442–5.
44. Rhodes D, Valassakis S, Bortnik L, Eaves R, Harper D, Alexander J. The Effect of High-Intensity Accelerations and Decelerations on Match Outcome of an Elite English League Two Football Team. Int J Environ Res Public Health. 2021; 18(18).
45. Di Salvo V, Gregson W, Atkinson G, Tordoff P, Drust B. Analysis of high intensity activity in Premier League soccer. Int J Sports Med. 2009:205–12.

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Match running performance is similar in lower and higher competitive standards of Spanish professional soccer accounting for effective playing time

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ABSTRACT: This study aimed to compare match running performance of players in the top two competitive standards of Spanish professional soccer, accounting for effective playing time (the duration of play after subtracting the game interruptions). A total of 2,784 match observations from 44 teams competing in the Spanish First Division (LaLiga Santander) and the Second Division (LaLiga Smartbank) were undertaken during two consecutive seasons (from 2021/22 to 2022/23). Total distance (TD), medium-speed running (MSR, distance 14.1–21 km·h^{-1}), high-speed running (HSR, > 21 km·h^{-1}), very high-speed running (VHSR, 21.1–24 km·h^{-1}) and sprinting speed running distance (Sprint, > 24 km·h^{-1}) were analyzed using a computerized tracking system (TRACAB, Chyronhego, New York, NY). These physical performance variables were calculated for both total and effective playing time. The main results showed that the mean effective playing time was significantly higher in matches of the First Division than in the Second Division ($p < .01$). In contrast to those observed when total playing time was considered, there were no significant differences ($p > .05$) between both competitive standards on medium speed running (MSR), high speed running (HSR), very high-speed running (VHSR), and sprint distances when the effective playing time was considered. Such findings demonstrate that contrary to previous research match running performance of players was similar in lower and higher competitive standards. Thus, effective playing time should be taken into account when interpreting the match running performance of professional soccer players.

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INTRODUCTION

The match running performance of professional and amateurs' soccer players has been extensively studied over the past three decades. One of the most robust findings is that players at a higher standard of play perform more high-intensity running than peers at lower standards. For instance, Mohr et al. [1] found 28% and 58% more high-intensity running and sprinting in Italian elite players compared to sub-elite Danish players. Similarly, a greater distance covered in high-speed running has been observed in top versus middle and bottom ranking Danish teams [2].

However, to the best of our knowledge, very few studies have attempted to compare match running performances across different competitive standards of elite soccer within a single country and their results are contradictory. Additionally, it should be highly noted that the effective playing time was not considered in previous studies. While Bradley et al. [3] and Di Salvo et al. [4] found that players in lower standards of English soccer cover more total distance and high-intensity running during matches compared to those in the highest standard, other studies suggested the opposite [5–8].

These contradictory findings may be due to two different factors. Firstly, match running performance may be affected by the style of coaching and management, the characteristics of the players, team formation, and philosophy of play based on tradition of each country. That is why it is very interesting to study the physical performance within each country. More importantly, the argument of the current study is that the differences in players' match running performance in different competitive standards is nonexistent or at least substantially influenced by differences in the effective playing time of games. Effective playing time is defined as the duration of play after subtracting the time taken up by stoppages, substitutions, goals, injuries, and other incidences [9, 10]. A study of game interruptions

on elite soccer showed that there is an average of 108 interruptions per match and that matches are halted on average for 38% of the total match time [11]. Stoppages during a game have a significant impact on a player's performance. Previous studies have found that stoppages cause extended extra time and reduce players' running performance [12]; moreover, running distance in the second half of a game may decrease because of too many stoppages rather than a decrease in physical capacity [13].

Interestingly, a recent UEFA report found that the effective playing time in matches of the highest standards is higher than in lower levels and this may affect match running performances [14]. In addition, various studies have reported the amount of the effective playing time within competitive leagues [12, 13, 15, 16]. According to these studies, there exist differences in the amount of effective playing time between different leagues.

However, despite this relevant consideration, none of the aforementioned studies have compared the running performance of players across different competitive standards considering the effective playing time of games. To achieve a comprehensive analysis of the real physical demands of official soccer matches, practitioners should take into account the effective playing time, as variations on the workload of the players could not only be linked to fatigue or the level of the players. For example, Altman et al. [17] found that players covered on average 10% more total distance and performed 13% more accelerations, while sprinting 7–10% less in matches with long (> 65 min.) compared to short (< 50 min.) effective playing time. Additionally, Jerome et al. [18] suggest that the majority of sprinting distance (97%) is covered during ball-in-play.

Therefore, the aim of the current study was to compare match running performance of players in the top two competitive standards of Spanish professional soccer considering the effective playing time of matches. The research hypothesis is that differences in players' match running performance in different competitive standards is nonexistent or at least substantially influenced by differences in the effective playing time of games.

MATERIALS AND METHODS

Sample

The sample comprised 2,784 match observations from 44 teams competing in the First (LaLiga Santander; n = 1,216 records) and Second (LaLiga Smartbank; n = 1,568 records) Spanish soccer leagues over two consecutive seasons (from 2021/22 to 2022/23). Teams were classified according to their final league rankings. The classification of final league rankings was determined using 5 Tiers [19]: (A) 1^{st}–4^{th} ranking (n = 244 match observations), (B) 5^{th}–7^{th} ranking (n = 183 match observations), (C) 8^{th}–17^{th} ranking (n = 497 match observations), (D) 18^{th}–20^{th} ranking (n = 309 match observations), and (E) Second Division teams (n = 1,551 match observations). Data were retrieved from the Spanish Professional Football League (LaLiga), which allowed the use of the variables included in this investigation. In accordance with the ethical guidelines of LaLiga, this investigation does not include information that identifies soccer players (General Assembley of LaLiga, 2019). The study received the Bioethics Committee's approval from the first author´s university (application number 239/2019).

Procedure

Match running performance was recorded using a multicamera computerized optical tracking system TRACAB (ChryronHego VID, New York, NY), managed from the application Mediacoach (LaLiga, Madrid, Spain) that has a sampling frequency of 25 Hz. The validity and reliability of this system for the variables used have previously been investigated [20–22] and reported strong correlations (r > .80) and high intraclass correlation coefficients (r > .75) between Mediacoach multicamera tracking system and Global Positioning System. In addition, small (< .30) to moderate (> .60) SEs of estimate were observed in all speed categories used in this study.

Data Preparation and Variables

Match running performance was divided into the following categories: total distance covered by teams in meters (TD); medium-speed running (MSR, distance 14.1–21 $km \cdot h^{-1}$), high-speed running (HSR, > 21 $km \cdot h^{-1}$), very high-speed running (VHSR, 21.1–24 $km \cdot h^{-1}$), and sprinting speed running distance (Sprint, > 24 $km \cdot h^{-1}$). All physical performance variables were calculated as i) absolute distances during total playing time in meters (m), and ii) rates of distance covered during effective playing time and normalized to meters per unit of time ($m \cdot min^{-1}$; [12, 13]). Regarding to how were the rates of distance covered during effective playing time calculated: i) the distances covered during effective playing time were considered; ii) the rates of distance covered during effective playing time of every match normalized to meters per unit of time (m/min.) were calculated; iii) finally, the mean of this metric for each physical variable (TD, MSR, HSR, etc…) was calculated. The total playing time was defined as the duration of the match as a whole, including injury time. The effective playing time refers to the duration of play after subtracting the time taken up by stoppages, substitutions, injuries, and goals [15].

Statistical Analysis

All statistical analyses were conducted using R–Studio [23]. Considering the characteristics of the sample, organized hierarchically, nested in groups, and with a longitudinal structure, we considered that the best procedure to analyze the data was through Linear Mixed Models (LMM). LMM were used to analyze the effects of competitive standards on player activity normalized by effective playing time or total time. First, a two-level hierarchy was modeled for the analysis. The match physical demands variables (i.e., distances covered at different speed thresholds) were included as dependent variables in the models, and leagues (First and Second Division) and tiers (Tiers A, B, C, D, and E) were the independent variables included as fixed effects. The team variable was considered as the random effect in the analysis. Values were represented as coefficients and standard

error (Coeff ± SE). Statistical significance was set at $p < .05$. Finally, Cohen's d effect size was calculated and interpreted as follows: 0.00–0.19: trivial; 0.20–0.59: small; 0.60–1.19: moderate; 1.20–1.99: large; ≥ 2.00: very large [24].

RESULTS

Effective Playing Time

The mean effective playing time was significantly higher in matches of the First Division than in the Second Division (52 minutes 54 seconds ± 21 seconds vs. 51 minutes 54 seconds ± 20 seconds, $p < .01$). The mean effective playing time in matches played by Tier A (55 minutes 36 seconds ± 50 seconds) was significantly higher compared to Tier C (52 minutes 18 seconds ± 1 minutes, 10 seconds; $p < .01$), D (53 minutes 6 seconds ± 43 seconds; $p < .05$), and E (51 minutes 30 seconds ± 21 seconds; $p < .01$).

Match Running Performance

Descriptive statistics of both competitive standards are summarized in Table 1, whereas Figure 1 depicts the differences in percentage from the First Division to the Second Division. Taking into account the total playing time, First Division teams covered significantly higher sprinting distance ($p < .05$) than teams from the Second Division. No significant differences were found between both competitive standards on TD, MSR, HSR and VHSR distances.

However, when the effective playing time was considered, there were no differences in sprinting distance between First and Second Division. Contrarily, teams from the First Division covered significantly less TD compared with teams from the Second Division ($p < .05$). No significant differences were found between both competitive standards on MSR, HSR and VHSR distances.

Contextualised match running performance according to tiers

Table 2 shows the differences between ranking groups on match running performance. Taking into account the total playing time, Tiers E teams covered significantly less HSR compared to Tier A ($p < .05$) and C ($p < .01$); less VHSR than Tier C ($p < .05$); and less Sprint than Tier A ($p < .05$), C ($p < .01$), and D ($p < .05$). However, when the effective playing time was considered, Tier E teams covered significantly more TD compared to Tier A ($p < .01$) and D ($p < .05$);

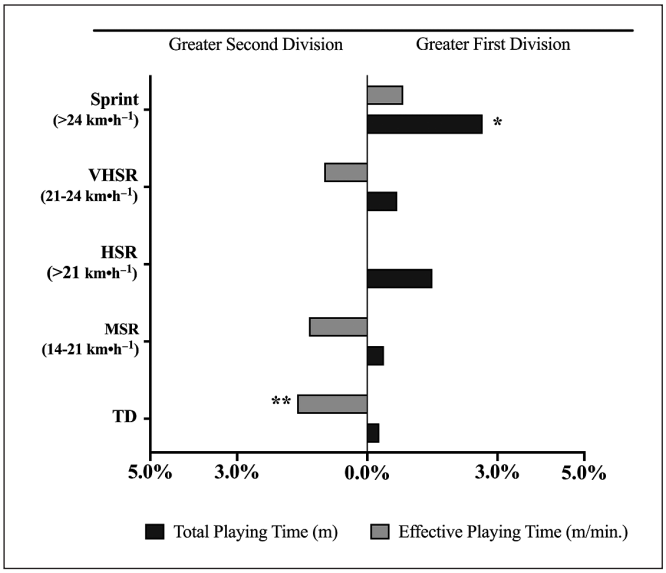


FIG. 1. Percentage of change in match running performance between First and Second Division by total or effective playing time.
Note: TD = total distance; MSR = medium-speed running; HSR = high-speed running; VHSR = very high-speed running; Sprint = sprinting speed running distance. *p < .05; **p < .01.

TABLE 1. Match running performance differences between leagues considering effective and total playing time.

	LaLiga Santander		LaLiga Smartbank		*p*	*d* ($CI_{95\%}$)
	Coeff	***SE***	***Coeff***	***SE***		
TD (m)	110,544	356	110,238	331	.387	.01
TD/min. effective ($m \times min^{-1}$)	2,104	13.8	2,138	12.9	.009	.36
MSR (m)	23,476	211	23,386	199	.623	.04
MSR/min. effective ($m \times min^{-1}$)	447	4.73	453	4.48	.127	.22
HSR (m)	6,338	72.0	6,243	67.3	.171	.37
HSR/min. effective ($m \times min^{-1}$)	121	1.54	121	1.43	.848	.14
VHSR (m)	3,182	34.2	3,160	31.9	.510	.24
VHSR/min. effective ($m \times min^{-1}$)	60.6	0.71	61.2	0.66	.346	.03
Sprint (m)	3,163	42.2	3,079	39.2	.046	.41
Sprint/min. effective ($m \times min^{-1}$)	60.3	0.90	59.8	0.83	.586	.21

Note. Coeff = Coefficient; SE = Standard Error; m = meters; $m \times min^{-1}$ = meters per minute; TD = Total distance covered; MSR = Medium-speed running; HSR = High speed running; VHSR = Very high-speed running; Sprint = Sprint speed running distance.

TABLE 2. Match running performance differences between ranking groups considering effective and total playing time.

Variables	Tier A			Tier B			Tier C			Tier D			Tier E		
	Coeff	***SE***	***p***	***Coeff***	***SE***	***p***	***Coeff***	***SE***	***p***	***Coeff***	***SE***	***p***	***Coeff***	***SE***	***p***
Effective minutes	55.6	.89	c**, d*, e***	53.1	1.02		52.3	.58	a**	53.1	.72	a*	51.5	.35	a***
TD (m)	111,314	1,007		109,399	1,163		110,617	649		110,177	789		110,294	397	
TD/min. effective ($m \times min^{-1}$)	2,015	36.8	c*, e**	2,071	42.5		2,127	23.7	a*	2,086	28.8	e*	2,153	14.5	a**, d*
MSR (m)	23,876	630		22,886	728		23,771	394		23,529	464		23,289	248	
MSR/min. effective ($m \times min^{-1}$)	433	14.05		434	16.22		457	8.78		444	10.35		454	5.53	
HSR (m)	6,590	197.3	e*	6,421	227.8		6,518	126.8	e**	6,440	153.6		6,118	77.7	a*, c**
HSR/min. effective ($m \times min^{-1}$)	119	4.32		122	4.99		125	2.78		122	3.38		119	1.70	
VHSR (m)	3,300	94.1		3,157	108.7		3,273	60.7	e*	3,203	73.7		3,111	37.1	c*
VHSR/min. effective ($m \times min^{-1}$)	59.8	2.00		59.9	2.31		62.9	1.29		60.7	1.57		60.7	0.79	
Sprint (m)	3,290	114.1	e*	3,264	131.8		3,244	74.0	e**	3,237	90.4	e*	3,008	45.0	a*, c**, d*
Sprint/min. effective ($m \times min^{-1}$)	59.6	2.50		62.0	2.88		62.5	1.62	e*	61.6	1.98		58.8	0.99	c*

Note. Coeff = coefficient; SE = Standard Error; m = meters; $m \times min^{-1}$ = meters per minute; TD = Total distance covered; MSR = Medium-speed running; HSR = High speed running; VHSR = Very high-speed running; Sprint = Sprint speed running distance; a = significant differences compared with Tier A; b = significant differences compared with Tier B; c = significant differences compared with Tier C; d = significant differences compared with Tier D; e = significant differences compared with Tier E; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

and Tier C teams covered significantly more sprinting distance compared to Tier E ($p < .05$). No significant differences were found between both competitive standards on MSR, HSR, and VHSR distances.

DISCUSSION

The aim of the present study was to compare the match running performance of players in the top two competitive standards of Spanish soccer considering the effective playing time of matches. The main findings of the study reported that: (a) the effective playing time was significantly higher in matches of the First Division than in the Second Division, (b) when the total playing time was considered, First Division teams covered significantly higher sprinting distance than teams from the Second Division, (c) however, when the effective playing time was considered, there were no differences in sprinting distance between First and Second Division. Contrarily, teams from the First Division covered significantly less TD compared with teams from the Second Division. No significant differences were found between both competitive standards on MSR, HSR and VHSR distances.

Contrary to previous research which showed differences in different competitive standards [3, 6–8], this study did not find relevant differences on match running performance when the effective playing time was considered. Only the total distance covered was different for the first and second division teams. As hypothesized, the differences in players' match running performance in different competitive standards may be influenced by differences in the effective playing time of games. Previous research demonstrated that the effective playing time is higher in highest competitive standards and consequently matches in the highest standards are more fluid than in

lower levels [14]. For example, the difference in the percentage of effective playing time between the top two competitive standards in Italy, Spain, England, France, and Germany was 3.7%, 2.8%, 3.3%, 1.5% and 4.3%, respectively [14]. Our results strongly support this finding. According to the current results, the effective playing time is 2% higher in matches of the First Division. Consequently, it seems that variations on the workload of the players could not be linked to the competitive standards of the players. Rather, it is related to differences in the effective playing time of matches.

Match analysis has shown that sprint and high-intensity efforts are the most important physical actions in soccer due to the relationship with training status and their ability to discriminate between different levels of play [25, 26]. Our results showed, under the total playing time condition, that First Division teams covered significantly higher sprinting distance than teams from the Second Division, which is likely due to significantly greater effective playing time during matches of the First Division, and the majority of sprint distance (97%) being covered during effective playing time [18]. These results are similar to those provided in previous studies. However, considering the effective playing time and normalizing the distance covered to meter per unit of time ($m \cdot min^{-1}$), the current results found that there are no significant differences between both competitive standards on MSR, HSR, VHSR, and sprint distances; and teams from the First Division covered significantly less TD. This suggests that the effective playing time gives a more representative overview of soccer players' match running performance, indicating that the total playing time could erroneously estimate match running performances in soccer.

Considering the strength of the teams according to their final league ranking, the effective playing time was lower as Tiers were lower. For example, the difference in the effective playing time between Tier A (55.6 ± .89 minutes) and Tiers B (53.1 ± 1.02 minutes), C (52.3 ± .58 minutes), D (53.1 ± .72 minutes) and E (51.5 ± .35 minutes) was + 2.5, + 3.3, + 2.5, and + 4.1 minutes, respectively. Again, it seems that matches in the highest standards are more fluid than in lower levels [14]. In fact, playing against highest quality teams involves significantly greater TD covered by teams [27]. Overall, no differences on match running performance were found between tiers according to their final league ranking. These results are different to those provided by previous research [19, 28–30]. Probably this may be due to the fact that in these studies the effective playing time was not considered. Additionally, future studies should contextualize match running performance considering simultaneously tactical and technical data. As it has been suggested recently [28], scientific literature have to understand why and how teams and players cover more or less distance depending on the game context.

Concerning the limitations of the current study, some aspects should be acknowledged: (a) previous evidence showed that physical performance of soccer players may be affected by their age. Thus, this variable should be considered in further studies; (b) different contextual-related variables, like opponent quality or scoreline [27, 31] or the playing style of each tier teams [32] should be included in future studies; (c) match performance variables should be individualized for each player rather than a general speed threshold for all of them; (d) finally, it should be noted that matches can be clustered based on the residual time and then increase the utility of the normalized data.

These findings may have a great deal of practical implications and may help coaches and strength and conditioning specialist to better understand match running performance in elite soccer. To achieve a comprehensive analysis of the real physical demands of official soccer matches, practitioners should take into account the effective playing time, as variations on the workload of the players could not only be linked to the competitive standards of the players. That means, the practitioners could know the exact workload of the players on matches considering the effective playing time and normalizing the distance covered to meter per unit of time ($m \cdot min^{-1}$). This strategy can provide information to prescribe effective stimuli to optimize the physical performance of soccer players in the training sessions [18].

CONCLUSIONS

In conclusion, to our knowledge this is the first study to date that compares the match running performance of players across different competitive standards accounting for effective playing time. The data demonstrate that the distance covered by teams was similar in lower and higher competitive standards when game interruptions are considered. Finally, future studies examining the differences in physical metrics between competitive standards should calculate the physical metrics as a rate considering effective playing time.

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Declaration of interest statement

The authors report there are no competing interests to declare.

Data availability

Restrictions apply to the availability of these data. Data was obtained from LaLiga and are available at https://www.laliga.es/en with the permission of LaLiga.

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REFERENCES

1. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sports Sci. 2003; 21:519–528. https://doi.org/10.1080/0264041031000071182
2. Ingebrigtsen J, Bendiksen M, Randers MB, Castagna C, Krustrup P, Holtermann A. Yo-Yo ir2 testing of elite and sub-elite soccer players: Performance, heart rate response and correlations to other interval tests. J Sports Sci. 2012; 30:1337–1345. https://doi.org/10.1080/02640414.2012.711484
3. Bradley P, Carling C, Gomez Diaz A, Hood P, Barnes C, Ade J, Boddy M, Krustrup P, Mohr M. Match performance and physical capacity of players in the top three competitive standards of English professional soccer. Hum Mov Sci. 2013; 32:808–821. https://doi.org/10.1016/j.humov.2013.06.002
4. Di Salvo V, Pigozzi F, González-Haro C, Laughlin M, De Witt J. Match performance comparison in top English soccer leagues. Int J Sports Med. 2013; 34:526–532. https://doi.org/10.1055/s-0032-1327660
5. Morgans R, Adams D, Mullen R, Sacramento J, McLellan C, Williams M. A comparison of physical and technical match performance of a team competing in the English Championship League and then the English Premier League following promotion. Int J Sports Sci Coach. 2015; 10:543–549. https://doi.org/10.1260/1747-9541.10.2-3.543
6. Pons E, Ponce-Bordón JC, Díaz-García J, Del Campo RL, Resta R, Peirau X, García-Calvo T. A longitudinal exploration of match running performance during a football match in the Spanish LaLiga: A four-season study. Int J Environ Res Public Health. 2021; 18:1–10. https://doi.org/10.3390/ijerph18031133
7. Modric T, Versic S, Sekulic D. Match running performance in the two different competitive standards of Croatian professional soccer. In Proceedings of the The 4th International Conference of Sports Science, AESA; 2021.
8. Sæterbakken A, Haug V, Fransson D, Grendstad HN, Gundersen HS, Moe VF, Ylvisaker E, Shaw M, Riiser A, Andersen, V. Match running performance on three different competitive standards in Norwegian soccer. Sports Med Int Open. 2019; 3:82–88. https://doi.org/10.1055/a-0943-3682
9. Castellano J, Blanco-Villaseñor A, Álvarez D. Contextual variables and time-motion analysis in soccer. Int J Sports Med. 2011; 32:415–421. https://doi.org/10.1055/s-0031-1271771
10. Zhao Y, Liu T. Factors that influence actual playing time: Evidence from the Chinese Super League and English Premier League. Front Psychol. 2022; 13. https://doi.org/10.3389/fpsyg.2022.907336
11. Siegle M, Lames M. Game interruptions in elite soccer. J Sports Sci. 2012; 30:619–624. https://doi.org/10.1080/02640414.2012.667877
12. Linke D, Link D, Weber H, Lames M. Decline in match running performance in football is affected by an increase in game interruptions. J Sports Sci Med. 2018; 17:662–667.
13. Rey E, Kalén A, Lorenzo-Martínez M, López-Del Campo R, Nevado-Garrosa F, Lago-Peñas C. Elite soccer players do not cover less distance in the second half of the matches when game interruptions are considered. J Strength Cond Res. 2020:1–6. https://doi.org/10.1519/JSC.0000000000003935
14. Poli R, Besson R, Ravenel L. Effective playing time in 37 European competitions 2018. https://www.football-observatory.com/IMG/sites/b5wp/2018/242/en/
15. Lago-Peñas C. The influence of effective playing time on physical demands of elite soccer players. Open Sports Sci J. 2012; 5:188–192. https://doi.org/10.2174/1875399X01205010188
16. Carling C, Dupont G. Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play? J Sports Sci. 2011; 29:63–71. https://doi.org/10.1080/02640414.2010.521945
17. Altmann S, Forcher L, Woll A, Härtel S. Effective playing time affects physical match performance in soccer: An analysis according to playing position. Biol Sport. 2023; 40:967–973. https://doi.org/10.5114/biolsport.2023.123320
18. Jerome BW, Stoeckl M, Mackriell B, Seidl T, Dawson CW, Fong DT, Folland JP. The influence of ball in/out of play and possession in elite soccer: Towards a more valid measure of physical intensity during competitive match-play. Eur J Sport Sci. 2023:1–23. https://doi.org/10.1080/17461391.2023.2203120
19. Bradley PS, Archer DT, Hogg B, Schuth G, Bush M, Carling C, Barnes C. Tier-specific evolution of match performance characteristics in the English Premier League: It's getting tougher at the top. J Sports Sci. 2016; 34:980–987. https://doi.org/10.1080/02640414.2015.1082614
20. 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; 19:4–13. https://doi.org/10.3390/s19194113
21. Pons E, García-Calvo T, Resta R, Blanco H, López del Campo R, Díaz García J, Pulido JJ. A Comparison of a GPS device and a multi-camera video technology during official soccer matches: Agreement between systems. PLoS One. 2019; 14. https://doi.org/10.1371/journal.pone.0220729
22. Pons E, García-Calvo T, Cos F, Resta R, Blanco H, López del Campo R, Díaz-García, J. Integrating video tracking and gps to quantify accelerations and decelerations in elite soccer. Sci Rep. 2021. https://doi.org/10.1038/s41598-021-97903-2
23. R-Studio Team RStudio: Integrated Development for R; RStudio, Ed.; Boston, 2020.
24. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41:3–12. https://doi.org/10.1249/MSS.0b013e31818cb278
25. 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; 27:159–168. https://doi.org/10.1080/02640410802512775
26. Faude O, Koch T, Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. J Sports Sci. 2012; 30:625–631. https://doi.org/10.1080/02640414.2012.665940
27. Ponce-Bordón JC, Nobari H, Lobo-Triviño D, García-Calvo T, Vicente-Giménez J, López del Campo R, Resta R, Fernández-Navarro J. Match movement profiles differences in Spanish soccer competitive leagues according to opposition's team ranking: A comparison study. Applied Sciences. 2022; 12:12635. https://doi.org/10.3390/app122412635
28. Ju W, Hawkins R, Doran D, Gómez-Díaz A, Martín-García A, Evans M, Laws A, Bradley P. Tier-specific contextualised high-intensity running profiles in the English Premier League: More on-ball movement at the top. Biol Sport. 2023; 40:561–573. https://doi.org/10.5114/biolsport.2023.118020
29. 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; 12:227–233. https://doi.org/10.1016/j.jsams.2007.10.002
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; 30:205–212. https://doi .org/10.1055/s-0028-1105950
31. Ponce-Bordón JC, Díaz-García J, López-Gajardo MA, Lobo-Triviño D, López del Campo R, Resta R, García-Calvo T. The influence of time winning and time losing on position-specific match physical demands in the top one Spanish soccer league. Sensors. 2021; 21:6843. https://doi.org/10.3390/s21206843
32. Yi Q, Gómez MA, Wang L, Huang G, Zhang H, Liu H. Technical and physical match performance of teams in the 2018 FIFA World Cup: Effects of two different playing styles. J Sports Sci. 2019; 37:2569–2577. https://doi.org/10.1080 /02640414.2019.1648120

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SUPPLEMENTAL TABLE 1. Match physical demands differences between leagues considering effective and total playing time.

	LaLiga Santander		LaLiga Smartbank		*p*
	Mean	***SD***	***Mean***	***SD***	
TD (m)	110,544	356	110,238	331	.387
TD effective (m)	83,030	488	81,465	452	.001
MSR (m)	23,476	211	23,386	199	.623
MSR effective (m)	21,989	202	21,699	191	.108
HSR (m)	6,338	72.0	6,243	67.3	.171
HSR effective (m)	6,224	71.5	6,110	66.8	.096
VHSR (m)	3,182	34.2	3,160	31.9	.510
VHSR effective (m)	3,102	33.9	3,065	31.6	.263
Sprint (m)	3,163	42.2	3,079	39.2	.046
Sprint effective (m)	3,129	41.9	3,040	38.9	.034

Note. SD = Standard Deviation; m = meters; TD = Total distance covered; MSR = Medium-speed running; HSR = High speed running; VHSR = Very high-speed running; Sprint = Sprint speed running distance.

SUPPLEMENTAL TABLE 2. Match physical demands differences between quality ranking groups considering effective and total playing time.

Variables	Tier A			Tier B			Tier C			Tier D			Tier E		
	Mean	***SD***	***p***	***Mean***	***SD***	***p***	***Mean***	***SD***	***p***	***Mean***	***SD***	***p***	***Mean***	***SD***	***p***
TD (m)	111,314	1,007		109,399	1,163		110,617	649		110,177	789		110,294	397	
TD effective (m)	85,647	1,316	e**	82,395	1,519		82,605	857		82,922	1,050		81,272	519	a**
MSR (m)	23,876	630		22,886	728		23,771	394		23,529	464		23,289	248	
MSR effective (m)	22,404	600		21,440	693		22,215	377		22,021	447		21,618	236	
HSR (m)	6,590	197.3	e*	6,421	227.8		6,518	126.8	e**	6,440	153.6		6,118	77.7	a*, c**
HSR effective (m)	6,467	196.1	e*	6,323	226.4		6,399	126.0	e**	6,319	152.6	e*	5,986	77.3	a*, c**, d*
VHSR (m)	3,300	94.1		3,157	108.7		3,273	60.7	e*	3,203	73.7		3,111	37.1	c*
VHSR effective (m)	3,216	93.6	e*	3,086	108.1		3,190	60.3	e*	3,117	73.3		3,018	36.9	a*, b*
Sprint (m)	3,290	114.1	e*	3,264	131.8		3,244	74.0	e**	3,237	90.4	e*	3,008	45.0	a*, c**, d*
Sprint effective (m)	3,251	113.4	e*	3,236	130.9		3,208	73.5	e**	3,202	89.7	e*	2,969	44.7	a*, c*, d*

Note. SD = Standard Deviation; m = meters; TD = Total distance covered; MSR = Medium-speed running; HSR = High speed running; VHSR = Very high-speed running; Sprint = Sprint speed running distance; a = significant differences compared with Tier A; b = significant differences compared with Tier B; c = significant differences compared with Tier C; d = significant differences compared with Tier D; e = significant differences compared with Tier E; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

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Physical activity shifts gut microbiota structure in aged subjects with overweight/obesity and metabolic syndrome

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ABSTRACT: We aimed to identify how physical activity (PA), within the context of a Mediterranean diet, affects metabolic variables and gut microbiota in older individuals with overweight/obesity and metabolic syndrome. Observational analysis was conducted as part of the PREDIMED-Plus study with 152 males and 145 females with overweight/obesity and metabolic syndrome. General assessments, anthropometric and biochemical measurements, and gut microbial 16S rRNA sequencing data were analyzed at baseline and 1-year of follow-up. Participants were stratified by tertiles of 1-year change in total PA-related energy expenditure ranging from -98.77 to 1099.99 METs (min/week). The total PA percentage of change was reduced in tertile 1 (-44.83 ± 24.94), increased in tertile 2 (28.96 ± 23.33) and tertile 3 (273.64 ± 221.42). Beta diversity analysis showed differences in the gut microbiota population within each tertile group. Significant differences were found at phylum, family, and genus levels in the gut microbiota of the three tertile groups at baseline and 1-year timepoint. Tertile 3, the group with the greatest increase in PA, was characterized by increases in their levels of *Sutterella*, *Bilophila*, and *Lachnospira* bacteria as well as a reduction in *Collinsella*. Moreover, this tertile showed a different pattern in its predicted metabolic capacities to the other groups. Our results have demonstrated that changes in PA such as lifestyle and Mediterranean diet induces specific variations in the gut microbiota profile. This modulation of gut microbiome populations and their metabolic capacities may contribute to the health of the aged individuals with overweight/obesity and metabolic syndrome.

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INTRODUCTION

Regular physical activity (PA) has significant health benefits, like reduction of cardiovascular risk, and improving cardiometabolic risk factors, such as reducing body mass index (BMI) and fat mass, fasting glucose, and insulin levels. Several studies have indicated that PA attenuates the risk of obesity and might be a strategy to treat obesity with numerous cardiovascular benefits [1]. However, a great increase in sedentary behaviors and physical inactivity have irrupted in the last decades, particularly in older adults [2], which is associated with weight gain and an increased incidence of obesity and obesity-related comorbidities [3]. For that reason, lifestyle interventions are of paramount importance at those ages for healthy aging. In previous work, in the frame of PREvención con DIeta MEDiterránea (PREDIMED)-Plus, a trial designed to evaluate the long-term effectiveness of an intensive weight loss lifestyle intervention on primary cardiovascular prevention [4], demonstrated that the intervention resulted in an effective increase in daily PA in older adults.

Recent findings pointed out that PA can determine changes in the gut microbiota composition, playing a positive role in energy regulation [5]. PA can enrich microbial biodiversity and enhance the number of beneficial microbial species [5] , like the phylum *Verrucomicrobia*, which includes bacteria related to better body composition and improved metabolic health [6]. Also, PA could increase the synthesis of metabolites involved in the good maintenance of intestinal health. Additionally, several studies on subjects with overweight/obesity have shown a slight increase in the abundance of *Actinobacteria*, *Firmicutes*, *Proteobacteria*, and *Verrucomicrobia* phyla and *Bacteroides* family after PA [7]. Moreover, another study suggested that an adequate PA could modulate the gut microbiota in elderly individuals [8], maintaining health, although different PA behaviors have shown diverging effects on both, the beta diversity, and the relative abundance of specific bacteria in the gut [9]. Although a growing body of evidence is pointing out the beneficial effect of PA in the modulation of gut microbiota, this intriguing pattern is still not fully elucidated, especially in older adults, when body physiology changes. We hypothesized that the increase of PA as a part of a lifestyle intervention results in changes in gut microbiota composition related to improvements in metabolic parameters. Thus, the objective of the current study is to identify how an increase in the total PA, within a context of a Mediterranean lifestyle, affects metabolic parameters and gut microbiota in older individuals with overweight/obesity and metabolic syndrome.

MATERIALS AND METHODS

Study design and participants

This sub-study in the context of the PREDIMED-Plus trial, a multicenter, randomized trial, to assess the effect of a weight-loss intervention program based on an energy-restricted traditional Mediterranean diet, PA promotion, and behavioral support, in comparison with a usual care intervention only with the energy-unrestricted Mediterranean diet. This study was registered at the International Standard Randomized Controlled Trial (ISRCT; http://www.isrctn.com/ISRCTN89898870) with the number 89898870 and the date of 24 July 2014. More details of the PREDIMED-Plus study protocol are fully described and available at http://predimedplus.com [10]. This sub-study was a longitudinal analysis focused on the baseline and 1-year timepoints.

PREDIMED-Plus eligible participants were men and women (aged 55–75 years), with overweight/obesity (body mass index (BMI) ≥ 27 and ≤ 40 kg/m^2) and metabolic syndrome (MetS). Briefly, exclusion criteria included a previous history of cardiovascular disease, any chronic medical condition, acute infectious processes, psychiatric disorders, alcohol and drug abuse, institutionalization, use of specific medications, relevant recent weight loss, any food allergy to Mediterranean diet food and the use of antibiotic therapy, probiotic or prebiotic in the previous three months. All participants provided written informed consent, and the study protocol and procedures were approved according to the ethical standards of the Declaration of Helsinki by all the participating institutions.

The present sub-study included 152 men and 145 women, from two PREDIMED-Plus recruiting centers (Malaga and Reus (Spain)) with stool samples available at baseline and after 1-year of intervention as well as available PA information. The type of activity, frequency, and duration (minutes/day) of PA were self-reported using the validated REGICOR Short Physical Activity Questionnaire [11]. PA was defined as the sum of total minutes and hours daily of 6 types of activities performed during a month (brisk walking, walking at a slow/normal place, walking in the countryside, climbing stairs, working in the garden, exercising, or playing sports at home, outdoors or in a gym). Then, total PA was determined as the sum of the total activities according to the Compendium of Physical Activities [12]. Total PA-related energy expenditure was calculated as the summed product of frequency, duration, and intensity of each activity multiplied by 7, obtaining the metabolic equivalent of tasks (METs) min/week [13].

The observational study was performed by stratifying the participants by tertiles of change in PA-related energy expenditure after 1-year intervention, with the following tertile groups T1 (n = 99), T2 (n = 99), and T3 (n = 99). The changes in the variable total PA-related energy expenditure were expressed as percentages and were calculated between basal and the 1-year differences, and divided by the basal.

Anthropometric, Laboratory Variables, and Samples Collection

At baseline, and 1-year follow-up visits, waist circumference, weight, and height were measured, and systolic blood pressure (SBP) and diastolic blood pressure (DBP) were measured using a validated semiautomatic oscillometer (Omron HEM-705CP, Kyoto, Japan). Peripheral venous blood and fecal samples were collected, at both time points, after overnight fasting. Serum glucose, total cholesterol, high-density lipoprotein (HDL) cholesterol, and triglycerides were measured by standard enzymatic methods. Low-density lipoprotein (LDL) cholesterol was calculated by the Friedewald formula. Glycated hemoglobin (HbA1c) was measured by a chromatographic method.

Fecal DNA Extraction and 16S Sequencing

DNA extraction from stools was performed using the QIAamp DNA stool Mini kit (Qiagen, Hilden, Germany) following the manufacturer's instructions. DNA concentration and purity were determined using a Nanodrop spectrophotometer (Nanodrop Technologies, Wilmington, DE, USA).

The Ion 16S Metagenomics Kit and Ion Plus Fragment Library Kit (Thermo Fisher Scientific Inc., Waltham, MA, USA) were used to build the sequencing libraries from the 16S rRNA gene. Emulsion PCR and sequencing of the amplicon libraries were performed using the Ion Chef System and Torrent S5™ system, respectively (Thermo Fisher Scientific) according to the manufacturer's instructions.

Bioinformatic Analysis

Torrent Suite™ Server software (Thermo Fisher Scientific), version 5.4.0, with default parameters for the 16S Target Sequencing (bead loading ≤ 30, key signal ≤ 30, and usable sequences ≤ 30) was used to base calling and run demultiplexing. Quality sequences were further translated into amplicon sequence variants (ASVs) using DADA2 with adapted parameters for Ion Torrent data within open-source Quantitative Insights into Microbial Ecology (QIIME2, version 2019.10) [14], which were also used for diversity analysis with the diversity plugin. Alpha diversity indexes (observed features, pielou-evenness, and faith's PD) were calculated within each group and between the groups by Kruskal-Wallis test. Weighted and Unweighted Unifrac distance matrices were calculated and permutational multivariate analysis of variance (PERMANOVA) was used looking to look for differences in group compositions. Taxonomic assignment was performed through clustering with VSEARCH and the reference base Greengenes version 13_8 at 97% of identity. To perform the differential abundance analysis within each tertile between the baseline and 1-year timepoints, ASV counts and taxonomic information generated with QIIME2 were imported into the MicrobiomeAnalyst webtool [15], where the data filtering and normalization steps were performed. Differential abundance analyses were assessed with MetagenomeSeq within MicrobiomeAnalyst with the default parameters of the developer. On the other hand, the longitudinal analysis, to perform the differential abundance analysis between microbiota changes among tertiles, was assessed through a volatility analysis, by using the q2-longitudinal plugin to search for important features, and analyzed to establish statistical significance within the same plugin. Phylogenetic Investigation of Communities by Reconstruction of Unobserved States plugin (PICRUSt2) was used to predict metagenome function within QIIME2. MetaCyc pathways were normalized within QIIME2 and further analyzed with STAMP with Welch's t-test option.

Statistical Analysis

Statistical analysis was performed with IBM SPSS Statistics 25 (IBM, Armonk, NY, USA). Quantitative variables were expressed as mean ± standard deviation (SD) for normally distributed data and as median ± interquartile range (IQR) for non-normally distributed data and percentages for categorical variables. The population was stratified by tertiles of change in total physical activity-related energy expenditure like lifestyle after the 1-year intervention. The normal distribution of variables was assessed using the Kolmogorov–Smirnov test. The bivariate analysis was performed using paired Student's tests for continuous data or the Wilcoxon test for non-normally distributed data. Differences across groups were evaluated through one-way analysis of variance (ANOVA) for continuous data or Kruskal–Wallis's test for non-normally distributed data. Categorical data were analyzed using Pearson's chi-square test. Correlations were assessed by Spearman´s rank correlation. Values were statistically significant when $p < 0.05$. Regarding the microbiota analysis, the statistically significant threshold was established at $p \leq 0.05$ and FDR-corrected $q < 0.2$ to formulate the possible hypothesis.

RESULTS

Characteristics of the study population

Table 1 shows the information relative to the anthropometric and laboratory and blood pressure results of the study. In general, after the 1-year intervention, a significant decrease in weight and waist circumference was observed in all three groups, as well as, significant differences were observed in the glucose, triglycerides, HDL, and HbA1c in the T3 group after 1-year of intervention. We observed lower levels of PA in the T3 group *versus* T1 and T2 groups at baseline, as well as a greater percentage of total PA change after 1-year of intervention in T3 ($p < 0.001$). Although participants belonged to a Mediterranean country, the baseline Mediterranean adherence score was equal to or below the median Mediterranean adherence score [low (≤ 7), medium (8-10), and high (11-17)] in the three groups. This adherence augmented after 1-year of intervention, with significantly greater improvements in the T3 group *versus* T2 and T1 groups ($p = 0.005$). Concerning changes at 1-year in anthropometric variables, participants from the three groups decreased an average of -2.85 ± 4.24 kg of body weight, with a greater weight loss in T3 participants ($p = 0.005$). BMI, waist circumference, and hip circumference changes decreased in the three groups, but significant differences in changes were observed between T2 and T3 compared to T1 in hip circumference ($p = 0.002$). T3 decreased significantly their waist circumference and BMI to T1 participants ($p < 0.001$ and $p = 0.020$, respectively). Finally, T3 participants decreased their LDL-cholesterol *versus* T2 and T1 participants, although translated into changes showed only a trend towards statistical significance ($p = 0.051$).

Changes in gut microbiota within each group after 1-year of intervention

Gut microbiota populations changed within each group according to weighted UniFrac distances: T1 group ($p = 0.042$; Figure 1A), T2 group ($p = 0.009$; Figure 2A), and T3 group ($p = 0.046$; Figure 3A), although this trend was not observed in the unweighted version. On the other hand, no differences were observed according to alpha diversity assessments, using phylogenetic diversity

TABLE 1. Clinical and laboratory characteristics at baseline and 1-year of intervention according to study total physical activity tertile groups.

		T1 (n = 99)	T2 (n = 99)	T3 (n = 99)	*p-value* across tertiles &
Variables					
Age (years)		65.00 ± 5.02	64.45 ± 4.64	64.42 ± 5.50	0.740
Sex (male/female)		45/54	51/48	56/43	0.293
Weight (Kg), mean ± SD	Baseline	85.77 ± 12.21	88.55 ± 12.06	89.69 ± 12.67 [a]	0.072
	1-year	84.03 ± 12.41 [*]	86.20 ± 11.87 [*]	86.14 ± 12.87 [*]	0.435
	Change	-2.04 ± 3.75	-2.57 ± 4.48	-3.95 ± 4.51 [a, b]	0.005
Waist circumference (cm), mean ± SD	Baseline	107.70 ± 9.72	109.86 ± 9.34	110.12 ± 9.12 [a]	0.140
	1-year	106.25 ± 10.48 [*]	107.30 ± 9.78 [*]	106.11 ± 10.16 [*]	0.688
	Change	-1.34 ± 4.19	-2.27 ± 4.84	-3.60 ± 5.30 [a]	< 0.001
Hip circumference (cm), median (IQR)	Baseline	109.0 (103.9–115.3)	109.0 (103.5–114.5)	110.5 (104.0–116.0)	0.711
	1-year	108.0 (102.5–114.3) [*]	108.9 (103.0–114.5)	107.0 (102.0–113.0) [*]	0.333
	Change	-0.72 ± 4.01	-0.20 ± 4.53	-2.40 ± 4.19 [a, b]	0.002
Waist-Hip ratio, mean ± SD	Baseline	0.98 ± 0.07	1.00 ± 0.07	0.99 ± 0.07	0.159
	1-year	0.98 ± 0.07	0.98 ± 0.07 [*]	0.98 ± 0.07 [*]	0.628
	Change	-0.53 ± 4.39	-1.99 ± 4.49	-1.17 ± 4.82	0.055
BMI (Kg/m^2), median (IQR)	Baseline	32.3 (29.6–35.1)	32.8 (30.2–35.4)	32.7 (31.1–35.9)	0.205
	1-year	31.5 (29.5–34.7) [*]	32.1 (29.4–34.5)	31.7 (29.5–35.0) [*]	0.883
	Change	-1.99 ± 3.48	-2.50 ± 4.64	-3.68 ± 4.42 [a]	0.020
Glucose (mg/dL), median (IQR)	Baseline	103.0 (93.0–116.0)	101.0 (91.0–118.0)	104.0 (95.0–117.0)	0.561
	1-year	101.0 (94.0–114.0)	101.0 (91.0–119.0)	101.0 (91.0–113.0) [*]	0.841
	Change	-0.94 ± 13.35	0.83 ± 16.62	-2.06 ± 17.95	0.192
Triglycerides (mg/dL), median (IQR)	Baseline	162.0 (117.0–232.0)	151.0 (103.0–196.0)	152.0 (118.0–210.0)	0.345
	1-year	153.0 (109.0–203.0)	135.0 (103.7–177.5)	137.0 (109.0–184.0) [*]	0.323
	Change	2.34 ± 44.74	-2.20 ± 32.98	0.76 ± 68.39	0.441
Total cholesterol (mg/dL), median (IQR)	Baseline	197.0 (174.0–225.0)	199.0 (172.0–223.0)	197.0 (178.0–223.0)	0.760
	1-year	195.0 (174.0–223.0)	202.0 (167.7–228.0)	192.0 (175.0–219.0)	0.853
	Change	1.02 ± 17.92	0.66 ± 15.83	-0.98 ± 14.62	0.354
HDL (mg/dL), median (IQR)	Baseline	47.0 (40.0–52.0)	48.0 (42.0–57.0)	46.0 (41.0–55.0)	0.372
	1-year	49.0 (41.0–58.0) [*]	49.0 (42.0–59.0)	51.0 (44.0–58.0) [*]	0.601
	Change	5.68 ± 12.00	2.48 ± 18.97	8.69 ± 17.71	0.093
LDL (mg/dL), median (IQR)	Baseline	111.0 (97.0–130.0)	114.0 (91.7–140.2)	117.0 (102.0–138.0)	0.333
	1-year	113.0 (91.0–135.0)	118.5 (96.5–145.2)	113.0 (99.0–131.0)	0.488
	Change	3.23 ± 30.38	4.05 ± 21.45	-1.40 ± 22.86	0.051
HbA1c (%)	Baseline	6.07 ± 1.10	6.10 ± 0.85	6.02 ± 0.68	0.206
	1-year	5.95 ± 0.89	6.07 ± 1.11	5.91 ± 0.64 [*]	0.298
	Change	-2.23 ± 13.93	-1.40 ± 14.27	-1.38 ± 6.73	0.496
SBP (mm Hg), median (IQR)	Baseline	139.0 (130.0–149.7)	138.3 (128.0–146.3)	138.3 (128.3–149.3)	0.526
	1-year	136.3 (124.3–146.3) [*]	136.7 (125.7–146.7)	133.7 (125.3–146.0)	0.961
	Change	-2.98 ± 9.94	-1.27 ± 11.18	-1.90 ± 10.85	0.523
DBP (mm Hg), mean ± SD	Baseline	79.00 ± 9.94	80.11 ± 8.60	80.17 ± 10.78	0.642
	1-year	76.72 ± 9.18 [*]	78.13 ± 8.14 [*]	78.34 ± 10.72 [*]	0.440
	Change	-2.29 ± 10.24	-1.79 ± 11.13	-1.82 ± 9.90	0.930
17-point Mediterranean adherence score, median (IQR)	Baseline	8.0 (6.0–9.0)	8.0 (6.0–10.0)	8.0 (6.0–10.0)	0.785
	1-year	12.0 (10.0–14.0) [*]	13.0 (10.0–15.0) [*]	14.0 (11.0–16.0) [*, a]	0.002
	Change	3.93 ± 3.03	4.14 ± 3.63	5.27 ± 3.48 [a]	0.005
Total physical activity (METs-min/week), median (IQR)	Baseline	3338.0 (1766.9–5048.9)	2125.8 (1165.5–3356.6) [a]	1021.9 (524.4–1874.1) [a, b]	< 0.001
	1-year	1524.4 (671.3–2564.1) [*]	2937.0 (1342.6–4510.5) [*, a]	3416.3 (1958.0–5272.7) [*, a]	< 0.001
	Change	-44.83 ± 24.94	28.96 ± 23.33 [a]	273.64 ± 221.42 [a, b]	< 0.001

BMI, body mass index; DBP, diastolic blood pressure; HbA1c, glycated hemoglobin; HDL, high-density lipoprotein; IQR, interquartile range; LDL, low-density lipoprotein; METs, metabolic equivalent of tasks; SBP, systolic blood pressure; SD, standard deviation. Participants were divided by tertiles of 1-year change in total PA-related energy expenditure, between -98.77 and -10.24 for T1, between -10.25 and 69.10 for T2, and between 69.11 and 1099.99 for T3. * $p \leq 0.05$ baseline vs. 1-year of intervention value, according to paired Student's tests or Wilcoxon tests. & One-way ANOVA, Pearson's chi-square test or Kruskal–Wallis test used to calculate differences across tertiles; Pearson's chi-square test, Student's t-test or Mann–Whitney test used to calculate differences between tertiles; a $p \leq 0.05$ vs. T1; b $p \leq 0.05$ vs. T2.

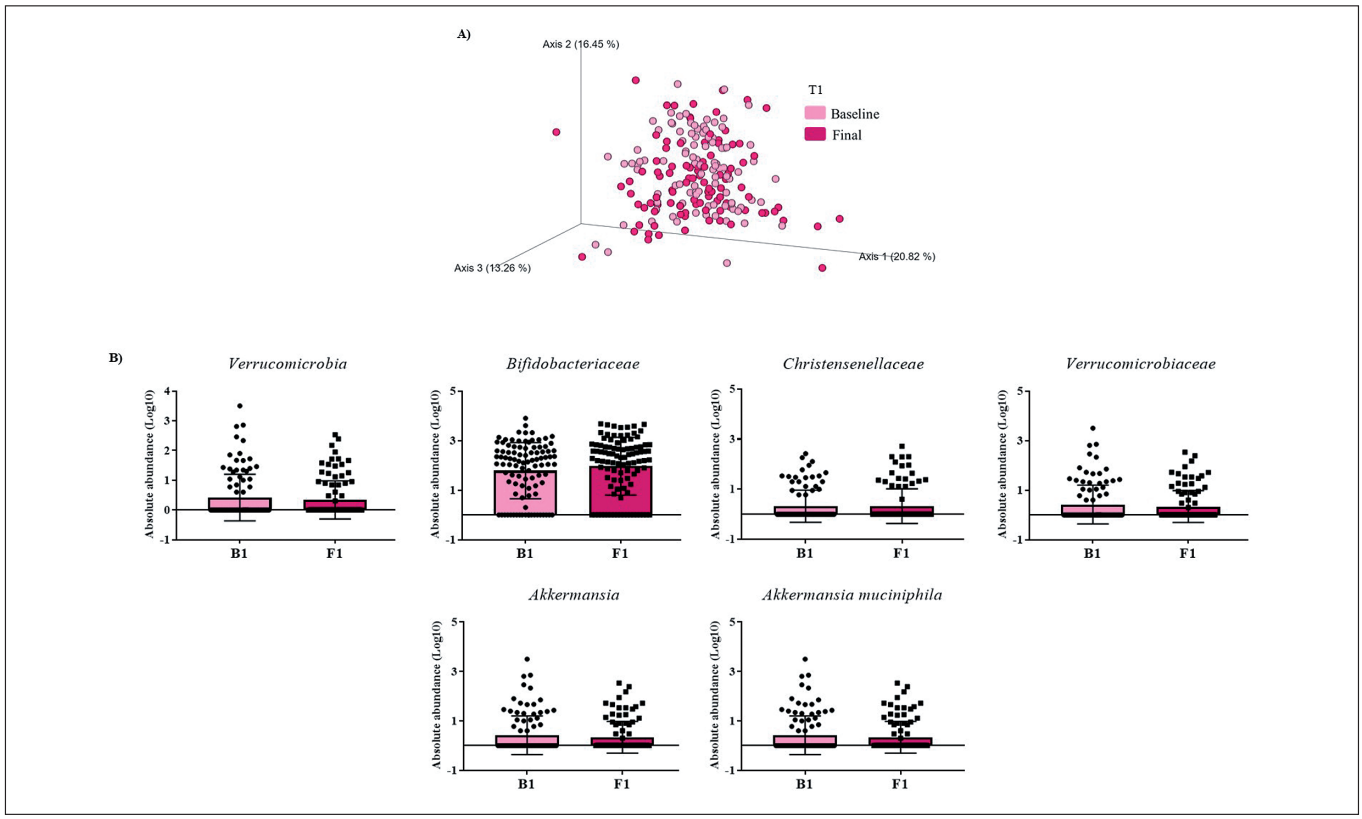


FIG. 1. Changes in gut microbiota within the T1 group. A) Significant changes in PCoA of weighted UniFrac distances (Baseline: grey diamonds; final point: black dots). B) Significant changes in the abundance of the interest bacteria evaluated with MetagenomeSeq and having a $p < 0.05$ and $q < 0.2$, at phylum, family, genus, and species levels.

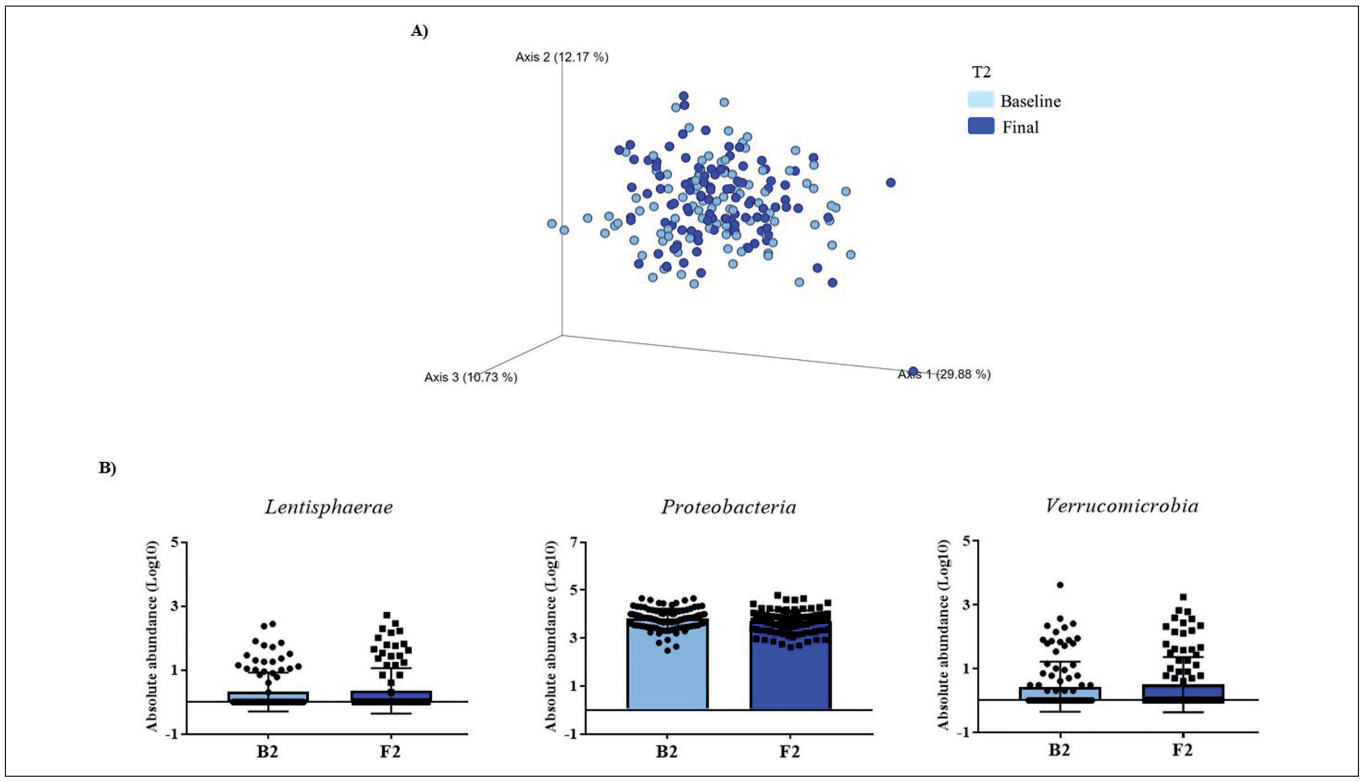


FIG. 2. Changes in gut microbiota within the T2 group. Clustering of fecal bacterial communities according to the different study groups by PCoA using weighted UniFrac distances. A) Significant changes in PCoA of weighted UniFrac distances (Baseline: grey dots; final point: black rings). B) Significant changes in the abundance of the interest bacteria evaluated with MetagenomeSeq and with a $p < 0.05$ and $q < 0.2$, at the phylum level.

(Faith_pd), richness community (Observed features), and homogeneity (Pielou-Evenness) (Supplementary Table 1).

The MetagenomeSeq analysis was used to evaluate the gut microbiota features changes comparing baseline and 1-year timepoint of the T1, T2, and T3 groups. The T1 group of participants was characterized by a decrease in the level of *Verrucomicrobia* ($p < 0.001$; $q = 0.004$), *Verrucomicrobiaceae* ($p < 0.001$; $q = 0.018$), *Akkermansia* ($p < 0.001$; $q = 0.019$), as well as its species *A. muciniphila* ($p = 0.003$; $q = 0.059$). While, *Christensenellaceae* ($p = 0.003$; $q = 0.044$) and *Bifidobacteriaceae* ($p = 0.020$; $q = 0.173$) were significantly expanded at 1-year time point (Figure 1B). Participants in the T2 group increased their levels of *Lentisphaerae* ($p < 0.001$; $q = 0.001$) and decreased *Verrucomicrobia* ($p = 0.0017$; $q = 0.005$) and *Proteobacteria* ($p = 0.035$; $q = 0.071$) (Figure 2B). Finally, the T3 participants increased their levels of *Lachnospira* ($p = 0.042$; $q = 0.203$), *Desulfovibrio* ($p = 0.008$; $q = 0.129$) and *Akkermansia* ($p = 0.025$; $q = 0.174$) at 1-year timepoint. On the other hand, the T3 group decreased their levels of *Anaerostipes* ($p < 0.001$; $q = 0.003$), *Blautia* ($p = 0.022$; $q = 0.174$), and *Collinsella* ($p = 0.030$; $q = 0.174$) through the time (Figure 3B).

Changes in gut microbiota between groups

To know the most relevant taxa according to the changes observed during the lifestyle intervention, a volatility analysis was performed. This volatility analysis, with an accuracy of the model at the genus level of $p < 0.1$, showed 30 important genera. Thus, these genera were subjected to a paired analysis between the three groups of study resulting in four genera significantly different ($p < 0.05$) and three genera tended to differ ($p < 0.1$) between the groups. *Bifidobacterium* abundance decreased in T3 group compared to T2 ($p = 0.04$; $q = 0.06$) and T1 ($p = 0.02$; $q = 0.06$). *Collinsella* and *Adlercreutzia* abundances decreased in the T3 group compared to T2 ($p = 0.03$; $q = 0.1$ and $p = 0.03$; $q = 0.09$, respectively). *Lachnospira* abundance increased in the T3 group compared to the T2 group ($p = 0.02$; $q = 0.08$). An unclassified genus of order *RF32* abundance increased in the T3 compared to T1 ($p = 0.04$; $q = 0.07$) and increased in the T2 group compared to T1 ($p = 0.007$; $q = 0.02$). *Sutterella* abundance was higher in the T3 compared to T2 (p = 0.06; q = 0.09) and T1 ($p = 0.01$; $q = 0.04$), and *Bilophila* abundance was higher in the T3 group compared to the T2 group ($p = 0.009$; $q = 0.01$) and T1 group ($p = 0.01$; $q = 0.01$). These results are summarized in Figure 4.

Correlation studies between changes in gut microbiota and clinical parameters

Correlation studies demonstrated that the changes in *Verrucomicrobia*, its family *Verrucomicrobiaceae* and its genus *Akkermansia,* were negatively associated with changes in waist circumference. *Christensenellaceae* and the genus *Sutterella* were negatively associated with changes in HbA1c. *Sutterella* was negatively associated with weight changes, as well. The genus *Lachnospira* was positively associated with changes in HDL and negatively with changes in LDL and the genus *Blautia* was positively associated with changes in SBP and DBP (Figure 5).

Differences in the Metabolic Profiles of Gut Microbiota

An ANOVA analysis showed that 42 pathways differed between groups in some way ($p < 0.05$, $q < 0.2$). These pathways mainly belonged to roles relative to Biosynthesis, Generation of Precursor Metabolites and Energy, and Degradation/Utilization/Assimilation. These pathways were further analyzed to study their changes between groups with a pairwise analysis (Figure 6, Supplementary Table 2). Although the heatmap clearly shows a different pattern between group T3 and T1 and T2 groups, only some pathways reached at least a statistical tendency when changes were compared. According to the Kruskal Wallis test, allantoin degradation to glyoxylate III (PWY-5705) and the superpathway of thiamine diphosphate biosynthesis II (PWY-6895) showed statistically different changes between groups ($p < 0.05$), whilst *D*-glucarate degradation I (GLUCARDEG-PWY), aromatic biogenic amine degradation (PWY-7431), pyruvate fermentation to acetone (PWY-6588), thiazole component of thiamine diphosphate biosynthesis II (PWY-6891), and aerobactin biosynthesis (AEROBACTINSYN-PWY) showed a tendency to differ between groups ($p < 0.1$).

DISCUSSION

In the current study, we observed metabolic benefits associated with an increase in PA in an older adult population. Moreover, changes in PA were associated with specific variations in the gut microbiota profile and its potential functionality accordingly, which could have influenced the improvement of the metabolic variables of the patients.

Recent research has demonstrated that exercise-related physiological remodeling might be extended to gut microbiota [16]. Through weighted UniFrac distances, our study has shown that the gut microbiota population changed differently with PA over a period of 1-year. Our results were in line with works in which α-diversity remained unchanged but the overall community composition (β-diversity) changed after PA intervention [17]. Additionally, others have reported that exercise might increase α-diversity [18], but despite these controversial results, PA has been proposed as a therapeutic approach for obesity and/or hypertension through the modulation of gut microbiota [19].

The differences found in the gut microbiota population indicated different shifts in the abundance of features more than a different profile. Indeed, the T1 group was characterized by an increase of *Bifidobacteriaceae* and *Christensenellaceae* families, which have been associated with leanness, and have been proposed as a marker of healthy aging and longevity [20], which could be the result of adherence to the Mediterranean lifestyle. The levels of the *Verrucomicrobia* phylum, as well as its family *Verrucomicrobiaceae* and its genus *Akkermansia*, were reduced in the T1 group, in the same manner as *Verrucomicrobia* phylum in the T2 group. A lower proportion

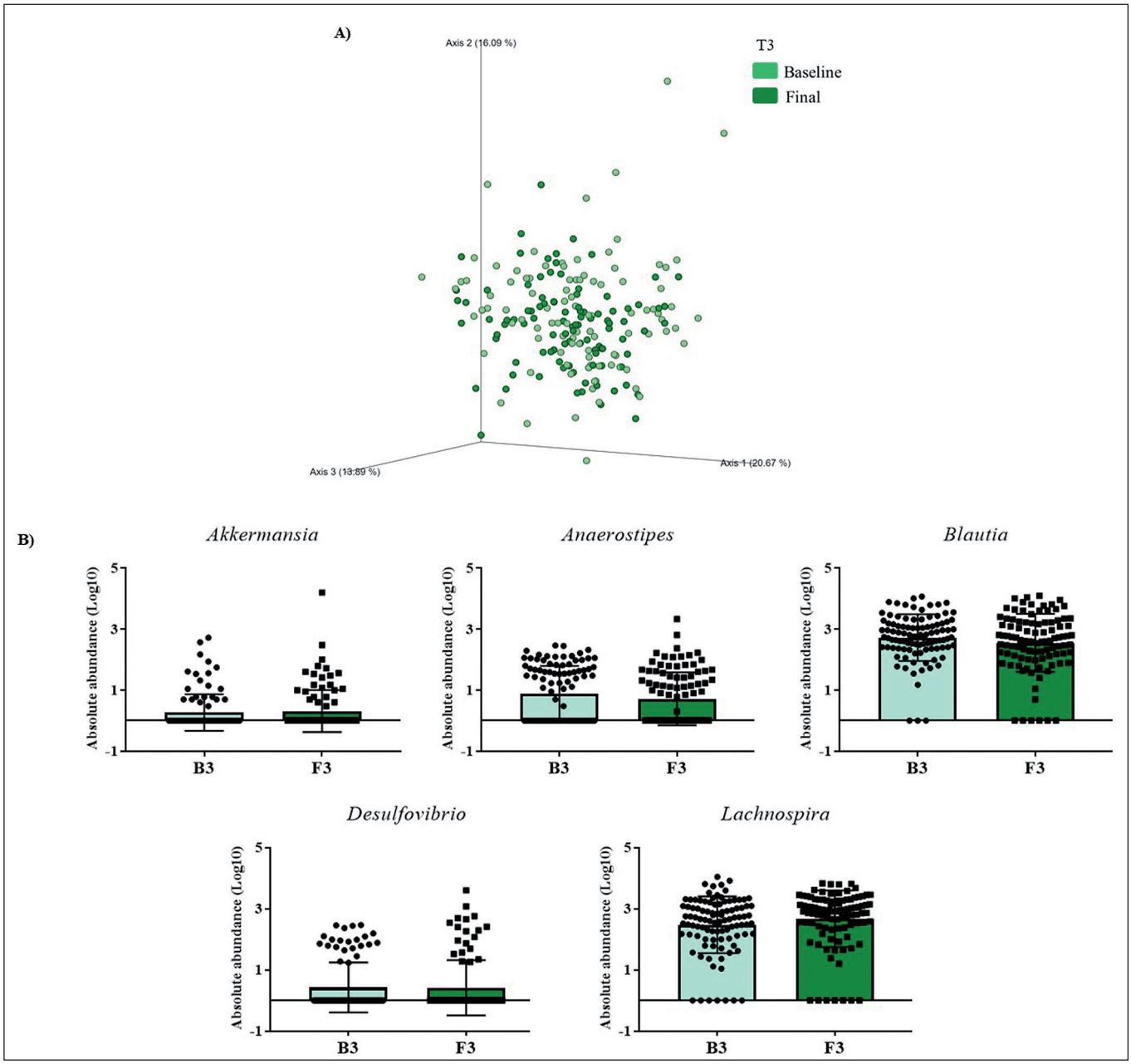


FIG. 3. Changes in gut microbiota within the T3 group. Clustering of fecal bacterial communities according to the different study groups by PCoA using weighted UniFrac distances. A) Significant changes in PCoA of weighted UniFrac distances (Baseline: grey cones; final point: black squares). B) Significant changes in the abundance of the interest bacteria evaluated with MetagenomeSeq and having a $p < 0.05$ and $q < 0.2$, at the genus level.

of *Verrucomicrobia* has been reported in subjects with obesity [21]. Nevertheless, the T3 group presented an increased level of *Akkermansia* after 1-year of intervention. Thus, PA could increase the levels of *Akkermansia* in accordance with other reports [22]. Moreover, we have observed that these changes in *Verrucomicrobia*-related features could be directly implicated in the metabolic improvement of the study subjects because were negatively associated with changes in waist circumference.

The T2 group displayed a reduction in levels of *Proteobacteria*. A raise in *Proteobacteria* has been reported in individuals with obesity and was related to inflammation [23]. Thus, even a small increase of PA, as it occurs in T2, could be related to a betterment in the inflammatory milieu. Additionally, we have detected an increased level of *Lentisphaerae* phylum in this group, but little is known about this minority phylum, although it has been related to *Verrucomicrobia* [24] in terms of health benefits.

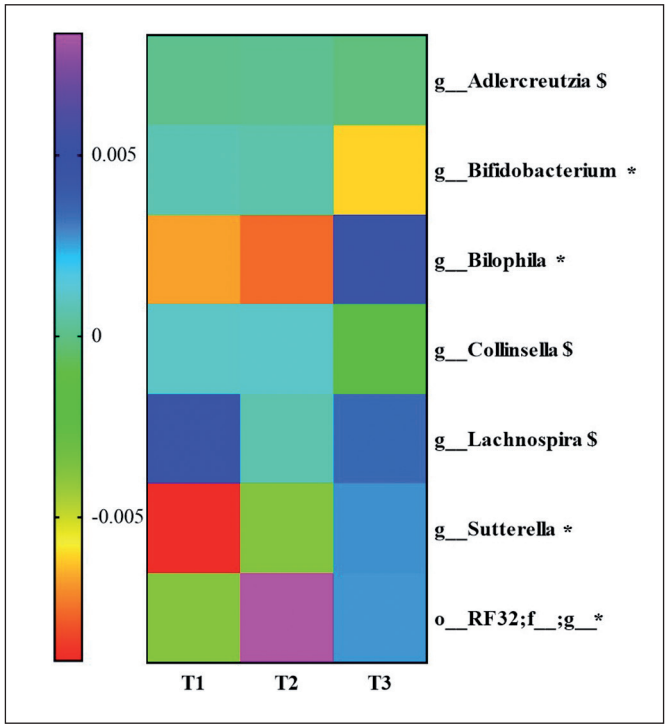


FIG. 4. Heatmap for genera that have shown statistical differences between the three physical activity tertile groups. Significantly differences *$p < 0.05$ and, $ $p < 0.1$.

The group with the highest increase in PA (T3) showed the greatest changes in its microbiota population. We detected an increase in the level of the genera *Lachnospira* and *Desulfovibrio* at 1-year of intervention. *Desulfovibrio* belongs to the sulfate-reducing bacteria (SRB), which produces hydrogen sulfide (H_2S), a key intestinal metabolite with diverse effects on host health. Thus, H_2S released by bacteria in the colon may also contribute to the control of arterial blood pressure [25] and, although the T3 group has not shown statistically significant differences in blood pressure, we observed a slight decrease after 1-year of PA. An increase in the abundance of *Bilophila* was also observed in the T3 group, a genus observed enriched in high-performing individuals [26]. Additionally, like the current study, a recent PREDIMED-Plus sub-study has shown that an increased abundance in *Lachnospira* and *Lachnospiraceae NK4A136* group were noticed in a frame of a Mediterranean lifestyle [27].

On the other hand, the genera *Collinsella* and *Blautia* decreased their levels in the T3 groups. In line with our study, Cancello R. *et al.* observed a decline in *Collinsella* levels after 15 days of the rehabilitation program and a short-term dietary intervention in elderly women with obesity [28]. Moreover, elevated levels of *Collinsella* have been reported to be associated with high levels of total and LDL cholesterol [29]. In agreement with our findings, the T3 group displayed lower levels of LDL and total cholesterol, although these changes were not significant. For its part, *Blautia* is a controversial bacterium in the context of obesity, as *Blautia* has been associated both directly and inversely with obesity [30]. Contrary to our results, others have reported an increase in *Blautia* levels with exercise training although in children [31]. These contradictory results about *Blautia* could be due to the great diversity among *Blautia* oligotypes, indicating that this genus comprises strains with a variety of metabolic capacities developed to a host and a host environment [32].

A decrease in the abundance of *Bifidobacterium* was detected in the T3 group. The intake of *Bifidobacterium* probiotics by athletes has been related to improving exercise physiological adaptation [33], so *Bifidobacterium* could be compromised in some manner with an increase in PA. In addition, an increased abundance of the *Sutterella* genus was observed in the T3 group, in accordance with another study that demonstrated that an unclassified taxon from the *Sutterella* genus had a key role in the transition from sedentary to active individuals [34]. Moreover, we observed a negative association between changes in the abundance of *Sutterella* with changes in weight and HbA1c. Studies have demonstrated that the abundance of *Sutterella* was negatively associated with obesity [35]. However, other findings pointed out *Sutterella* was positively associated with metabolic syndrome [36]. More in-depth studies are needed to understand the contradictory findings of *Blautia*, *Bifidobacterium,* and *Sutterella*.

Our functionality prediction analysis pointed out that the group which the greatest increase in PA (T3) showed an increase in vitamin metabolism and cofactors such as thiamine (vitamin B1). Some findings have shown that PA may increase the body's need for thiamine [37], and in this way, there are vitamin B1-producing bacteria with the complete vitamin B1 synthesis pathway, which includes pathways for the synthesis of thiazole and pyrimidine [38]. Indeed, the T3 group involves a higher degradation of various substrates as sources of energy and nutrients of sugars, including increased degradation of sugars such as D-glucarate and amines such as allantoin, which is supported by Yu D. *et al.* who observed in their healthy diet group the same metabolic changes [39]. Additionally, the T3 group significantly decreased its abundance of branched-chain amino acids (BCAAs) after the PA protocol. BCAAs are involved in muscle growth, muscle soreness, and exercise fatigue reductions, interesting features for those who increase their PA. These changes in metabolism according to the level of PA could agree with a study in which patients with prediabetes reported significant differences in the gut microbiome composition after a 12-week aerobic exercise intervention [40]. Moreover, the T3 group significantly decreased their abundance of short-chain fatty acids (SCFAs), and although the decrease of SCFAs could reveal contradictory findings, a study of Muralidharan *et al*. is in line with our findings, and they observed a decrease in predicted pathways related to SCFAs with a lifestyle intervention directed to weight loss [27]. These results further support that PA might mediate effects on human metabolism through changes in the gut microbiome.

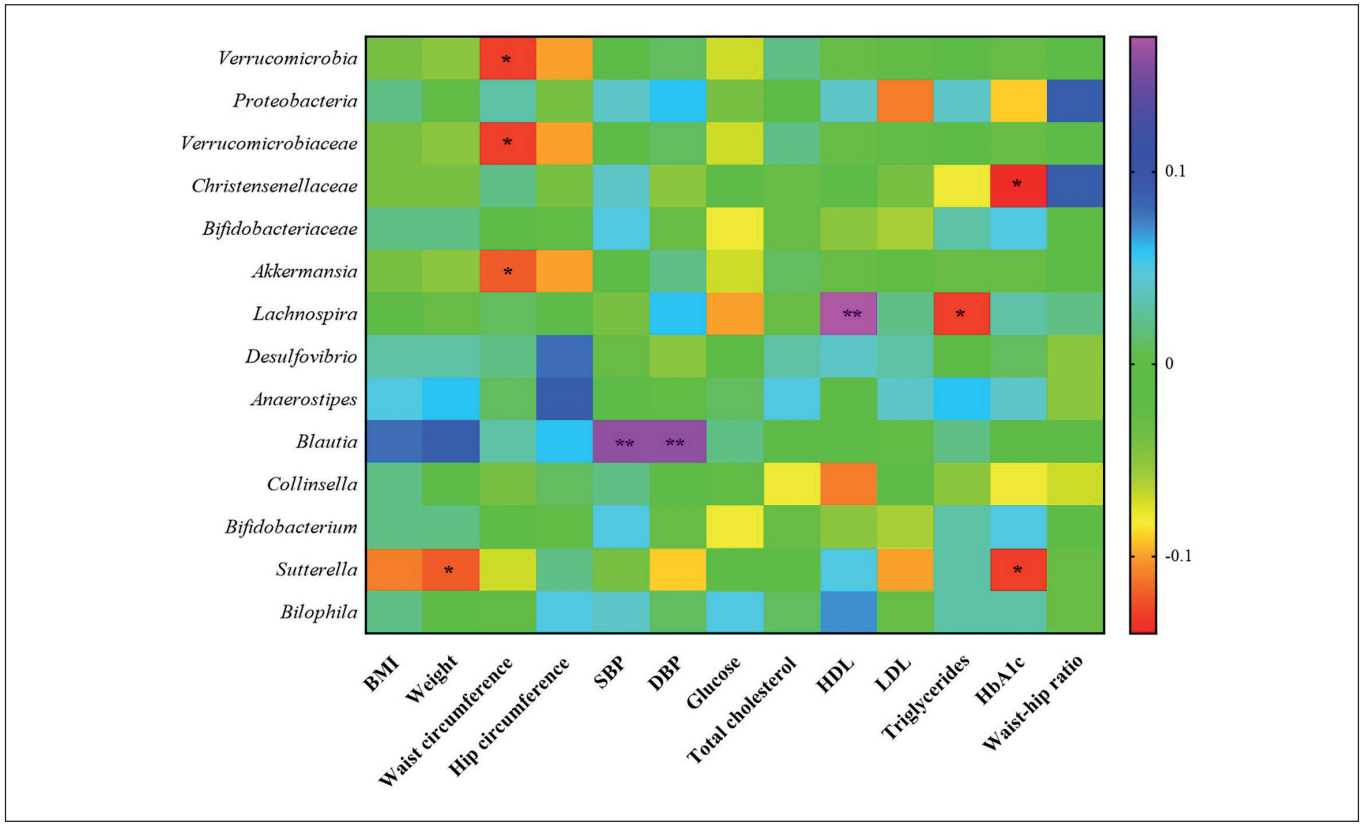


FIG. 5. Heatmap representing correlations in the total study population (n = 297) between changes in gut microbiota and clinical variables. Significantly differences *$p < 0.05$ and **$p < 0.01$.

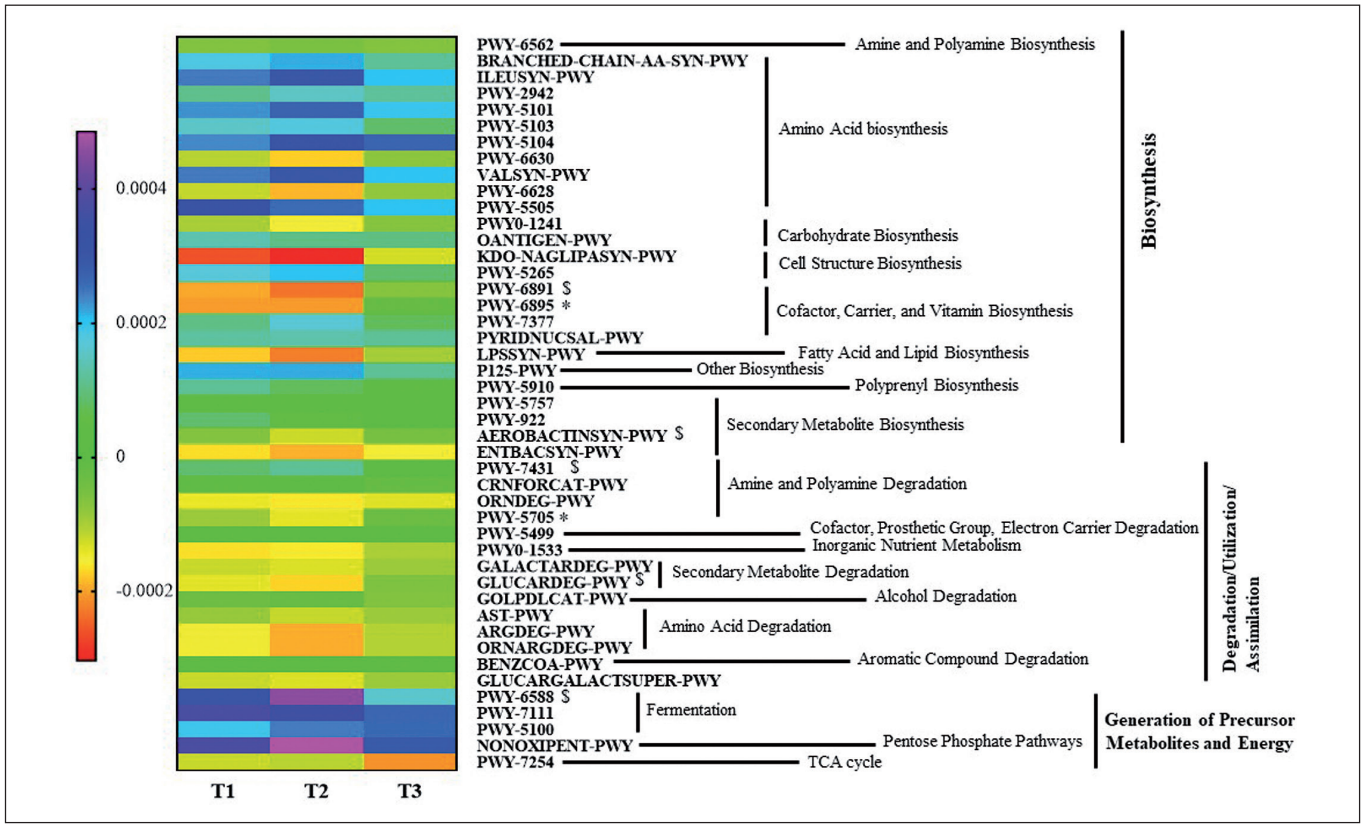


FIG. 6. Heatmap representing median values of significantly increasing or decreasing predicted metagenome pathways between the three groups. *Indicates significant differences between groups ($p < 0.05$) and, $ indicates $p < 0.1$ in multiple group tests with the Kruskal Wallis test.

The current study has multiple strengths like the fact of being built under a great populational study like PREDIMED-Plus with complete phenotyping of the volunteers. However, it is also subject to a series of limitations. First, the multifaceted intervention strategy whose outcome inference cannot be fully associated with a single component of the intervention. Second, the activity was calculated from a questionnaire self-administered, which could overestimate, or underestimate the values. Nevertheless, the use of a REGICOR questionnaire is a reliable and validated method that records information about leisure and occupational time and the four dimensions of PA including type of activity, frequency, duration, and intensity of PA, as well as sedentary behavior [11]. Third, body composition was assessed with waist circumference, weight, and height, having obtaining more information with other techniques, such as impedanciometry or Dual X-ray Absorptiometry. Fourth, due to the sub-study characteristic of the study, results are focused on changes in the variables during a well-followed-up intervention cohort to avoid baseline differences. Fifth, the aging of the participants needs from other similar studies to extrapolate these results to the whole population, as well as from additional omics analysis that permit more complete information. Lastly, 16S sequencing limits the taxonomy profiling to genus-level resolution, and consequently, it is not possible to determine the pathways associated with the observed relationships. Notwithstanding, 16S sequencing offers the advantage of analyzing a substantial number of samples, benefiting from established and well-curated databases. However, these results point out an implication of the gut microbiome in the improvements associated with an increase in PA that deserves to be further investigated with cohorts specially chosen for this hypothesis.

CONCLUSIONS

Taken together our results have demonstrated that changes in PA such as lifestyle and Mediterranean diet induces specific variations in the gut microbiota profile. Moreover, this study identifies that the modulation suffered by the gut microbiome populations and their metabolic capacities may contribute to the health of the aged individuals with overweight/obesity and metabolic syndrome.

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Conflict of interest

The authors declare no conflict of interest.

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Data sharing

According to the data regulations and ethical considerations, the datasets generated and analyzed during the study are not publicly available, because our participants only provided their consent to the original team of investigators to use their data, so this information might compromise their consent for the study. Nevertheless, collaboration for data analyses can be requested by sending a letter to the PREDIMED-Plus steering Committee (predimed_plus_scommittee@googlegroups.com). All members of the PREDIMED-Plus Steering Committee will be notified of the request for their consideration.

REFERENCES

1. Haskell WL, Lee IM, Pate RR, Powell KE, Blair SN, Franklin BA, Macera CA, Heath GW, Thompson PD, Bauman A. Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. Med Sci Sports Exerc. 2007 Aug; 39(8):1423–34.
2. Harvey JA, Chastin SFM, Skelton DA. Prevalence of sedentary behavior in older adults: a systematic review. Int J Environ Res Public Health. 2013 Dec; 10(12):6645–61.
3. Cárdenas Fuentes G, Bawaked RA, Martínez González MÁ, Corella D, Subirana Cachinero I, Salas-Salvadó J, Estruch R, Serra-Majem L, Ros E, Lapetra Peralta J, Fiol M, Rekondo J, Gómez-Gracia E, Tur Marí JA, Pinto Sala X, Babio N, Ortega C, Martínez JA, Schröder H. Association of physical activity with body mass index, waist circumference and incidence of obesity in older adults. Eur J Public Health. 2018 Oct; 28(5):944–50.
4. Salas-Salvadó J, Díaz-López A, Ruiz-Canela M, Basora J, Fitó M, Corella D, Serra-Majem L, Wärnberg J, Romaguera D, Estruch R, Vidal J, Alfredo Martínez J, Arós F, Vázquez C, Ros E, Vioque J, López-Miranda J, Bueno-Cavanillas A, Tur JA, Tinahones FJ, Martín V, Lapetra J, Pintó X, Daimiel L, Delgado-Rodríguez M, Matía P, Gómez-Gracia E, Díez-Espino J, Babio N, Castañer O, Sorlí J V., Fiol M, Zulet MÁ, Bulló M, Goday A, Martínez-González M. Effect of a Lifestyle Intervention Program With Energy-Restricted Mediterranean Diet and Exercise on Weight Loss and Cardiovascular Risk Factors: One-Year Results of the PREDIMED-Plus Trial. Diabetes Care [Internet]. 2019 May 1 [cited 2023 Jul 10]; 42(5):777–88. Available from: https://pubmed.ncbi.nlm.nih.gov/30389673/
5. Monda V, Villano I, Messina A, Valenzano A, Esposito T, Moscatelli F, Viggiano A, Cibelli G, Chieffi S, Monda M, Messina G. Exercise modifies the gut microbiota with positive health effects [Internet]. Vol. 2017, Oxidative Medicine and Cellular Longevity. Hindawi Limited; 2017 [cited 2021 Apr 16]. Available from: /pmc/articles/PMC5357536/
6. Dao MC, Everard A, Aron-Wisnewsky J, Sokolovska N, Prifti E, Verger EO, Kayser BD, Levenez F, Chilloux J, Hoyles L, Dumas ME, Rizkalla SW, Doré J, Cani PD, Clément K, Le Mouhaër S, Cotillard A, Kennedy SP, Pons N, Le Chatelier E, Almeida M, Quinquis B, Galleron N, Batto JM, Renault P, Zucker JD, Ehrlich SD, Blottière H, Leclerc M, Juste C, De Wouters T, Lepage P. Akkermansia muciniphila and improved metabolic health during a dietary intervention in obesity: relationship with gut microbiome richness and ecology. Gut. 2016 Mar 1; 65(3):426–36.
7. Aya V, Flórez A, Perez L, Ramírez JD. Association between physical activity and changes in intestinal microbiota composition: A systematic review. PLoS One [Internet]. 2021 Feb 1 [cited 2022 Feb 4]; 16(2):e0247039. Available from: https://journals.plos.org/plosone/article?id = 10.1371/journal.pone.0247039
8. Shimizu Y. Gut microbiota in common elderly diseases affecting activities of daily living. World J Gastroenterol. 2018 Nov; 24(42):4750–8.
9. Zhong X, Powell C, Phillips CM, Millar SR, Carson BP, Dowd KP, Perry IJ, Kearney PM, Harrington JM, O'Toole PW, Donnelly AE. The Influence of Different Physical Activity Behaviours on the Gut Microbiota of Older Irish Adults. J Nutr Health Aging. 2021;
10. Sayón-Orea C, Razquin C, Bulló M, Corella D, Fitó M, Romaguera D, Vioque J, Alonso-Gómez ÁM, Wärnberg J, Martínez JA, Serra-Majem L, Estruch R, Tinahones FJ, Lapetra J, Pintó X, Tur JA, López-Miranda J, Bueno-Cavanillas A, Delgado-Rodríguez M, Matía-Martín P, Daimiel L, Sánchez VM, Vidal J, Vázquez C, Ros E, Ruiz-Canela M, Sorlí J V., Castañer O, Fiol M, Navarrete-Muñoz EM, Arós F, Gómez-Gracia E, Zulet MA, Sánchez-Villegas A, Casas R, Bernal-López R, Santos-Lozano JM, Corbella E, Bouzas C, García-Arellano A, Basora J, Asensio EM, Schröder H, Moñino M, García De La Hera M, Tojal-Sierra L, Toledo E, Díaz-López A, Goday A, Salas-Salvadó J, Martínez-González MA. Effect of a Nutritional and Behavioral Intervention on Energy-Reduced Mediterranean Diet Adherence Among Patients With Metabolic Syndrome: Interim Analysis of the PREDIMED-Plus Randomized Clinical Trial. JAMA [Internet]. 2019 Oct 10 [cited 2022 Nov 25]; 322(15):1486. Available from: /pmc/articles/PMC6802271/
11. Molina L, Sarmiento M, Peñafiel J, Donaire D, Garcia-Aymerich J, Gomez M, Ble M, Ruiz S, Frances A, Schröder H, Marrugat J, Elosua R. Validation of the Regicor Short Physical Activity Questionnaire for the Adult Population. PLoS One. 2017 Jan; 12(1):e0168148.
12. Ainsworth BE, Haskell WL, Herrmann SD, Meckes N, Bassett DR, Tudor-Locke C, Greer JL, Vezina J, Whitt-Glover MC, Leon AS. 2011 Compendium of Physical Activities: a second update of codes and MET values. Med Sci Sports Exerc. 2011 Aug; 43(8):1575–81.
13. Rosique-Esteban N, Díaz-López A, Martínez-González MA, Corella D, Goday A, Martínez JA, Romaguera D, Vioque J, Arós F, Garcia-Rios A, Tinahones F, Estruch R, Fernández-García JC, Lapetra J, Serra-Majem L, Pinto X, Tur JA, Bueno-Cavanillas A, Vidal J, Delgado-Rodríguez M, Daimiel L, Vázquez C, Rubio MÁ, Ros E, Salas-Salvadó J. Leisure-time physical activity, sedentary behaviors, sleep, and cardiometabolic risk factors at baseline in the PREDIMED-PLUS intervention trial: A cross-sectional analysis. PLoS One. 2017 Mar 1; 12(3).
14. Bolyen E, Rideout JR, Dillon MR, Bokulich NA, Abnet CC, Al-Ghalith GA, Alexander H, Alm EJ, Arumugam M, Asnicar F, Bai Y, Bisanz JE, Bittinger K, Brejnrod A, Brislawn CJ, Brown CT, Callahan BJ, Caraballo-Rodríguez AM, Chase J, Cope EK, Da Silva R, Diener C, Dorrestein PC, Douglas GM, Durall DM, Duvallet C, Edwardson CF, Ernst M, Estaki M, Fouquier J, Gauglitz JM, Gibbons SM, Gibson DL, Gonzalez A, Gorlick K, Guo J, Hillmann B, Holmes S, Holste H, Huttenhower C, Huttley GA, Janssen S, Jarmusch AK, Jiang L, Kaehler BD, Kang K Bin, Keefe CR, Keim P, Kelley ST, Knights D, Koester I, Kosciolek T, Kreps J, Langille MGI, Lee J, Ley R, Liu YX, Loftfield E, Lozupone C, Maher M, Marotz C, Martin BD, McDonald D, McIver LJ, Melnik A V., Metcalf JL, Morgan SC, Morton JT, Naimey AT, Navas-Molina JA, Nothias LF, Orchanian SB, Pearson T, Peoples SL, Petras D, Preuss ML, Pruesse E, Rasmussen LB, Rivers A, Robeson MS, Rosenthal P, Segata N, Shaffer M, Shiffer A, Sinha R, Song SJ, Spear JR, Swafford AD, Thompson LR, Torres PJ, Trinh P, Tripathi A, Turnbaugh PJ, Ul-Hasan S, van der Hooft JJJ, Vargas F, Vázquez-Baeza Y, Vogtmann E, von Hippel M, Walters W, Wan Y, Wang M, Warren J, Weber KC, Williamson CHD, Willis AD, Xu ZZ, Zaneveld JR, Zhang Y, Zhu Q, Knight R, Caporaso JG. Reproducible, interactive, scalable and extensible microbiome data science using QIIME 2. Nat Biotechnol. 2019 Aug;37(8):852-857. doi: 10.1038/s41587-019-0209-9
15. Dhariwal A, Chong J, Habib S, King IL, Agellon LB, Xia J. MicrobiomeAnalyst: a web-based tool for comprehensive statistical, visual and meta-analysis of microbiome data. Nucleic Acids Res. 2017 Jul; 45(W1):W180–8.

16. Watson MD, Cross BL, Grosicki GJ. Evidence for the Contribution of Gut Microbiota to Age-Related Anabolic Resistance. Nutrients. 2021 Feb 1; 13(2):1–21.
17. Ortiz-Alvarez L, Xu H, Martinez-Tellez B. Influence of Exercise on the Human Gut Microbiota of Healthy Adults: A Systematic Review. Clin Transl Gastroenterol. 2020 Feb 1; 11(2):e00126.
18. Keohane DM, Woods T, O'Connor P, Underwood S, Cronin O, Whiston R, O'Sullivan O, Cotter P, Shanahan F, Molloy MGM. Four men in a boat: Ultra-endurance exercise alters the gut microbiome. J Sci Med Sport. 2019 Sep 1; 22(9):1059–64.
19. Petriz BA, Castro AP, Almeida JA, Gomes CPC, Fernandes GR, Kruger RH, Pereira RW, Franco OL. Exercise induction of gut microbiota modifications in obese, non-obese and hypertensive rats. BMC Genomics. 2014; 15(1):511.
20. Tavella T, Rampelli S, Guidarelli G, Bazzocchi A, Gasperini C, Pujos-Guillot E, Comte B, Barone M, Biagi E, Candela M, Nicoletti C, Kadi F, Battista G, Salvioli S, O'Toole PW, Franceschi C, Brigidi P, Turroni S, Santoro A. Elevated gut microbiome abundance of Christensenellaceae, Porphyromonadaceae and Rikenellaceae is associated with reduced visceral adipose tissue and healthier metabolic profile in Italian elderly. Gut Microbes. 2021; 13(1):1–19.
21. Garcia-Mantrana I, Selma-Royo M, Alcantara C, Collado MC. Shifts on gut microbiota associated to mediterranean diet adherence and specific dietary intakes on general adult population. Front Microbiol. 2018 May 7; 9(MAY).
22. Bressa C, Bailén-Andrino M, Pérez-Santiago J, González-Soltero R, Pérez M, Montalvo-Lominchar MG, Maté-Muñoz JL, Domínguez R, Moreno D, Larrosa M. Differences in gut microbiota profile between women with active lifestyle and sedentary women. Dasgupta S, editor. PLoS One. 2017 Feb 10; 12(2):e0171352.
23. Crovesy L, Masterson D, Rosado EL. Profile of the gut microbiota of adults with obesity: a systematic review. European Journal of Clinical Nutrition 2020 74:9. 2020 Mar 30; 74(9):1251–62.
24. Gupta RS, Bhandari V, Naushad HS. Molecular Signatures for the PVC Clade (Planctomycetes, Verrucomicrobia, Chlamydiae, and Lentisphaerae) of Bacteria Provide Insights into Their Evolutionary Relationships. Front Microbiol [Internet]. 2012 [cited 2023 Jul 10]; 3(SEP). Available from: https://pubmed.ncbi.nlm.nih.gov/23060863/
25. Shen X, Carlström M, Borniquel S, Jädert C, Kevil CG, Lundberg JO. Microbial regulation of host hydrogen sulfide bioavailability and metabolism. Free Radic Biol Med. 2013 Jul; 60:195–200.
26. Liang R, Zhang S, Peng X, Yang W, Xu Y, Wu P, Chen J, Cai Y, Zhou J. Characteristics of the gut microbiota in professional martial arts athletes: A comparison between different competition levels. PLoS One [Internet]. 2019 Dec 1 [cited 2023 Jul 10]; 14(12). Available from: https://pubmed.ncbi.nlm.nih.gov/31881037/
27. Muralidharan J, Moreno-Indias I, Bulló M, Lopez JV, Corella D, Castañer O, Vidal J, Atzeni A, Fernandez-García JC, Torres-Collado L, Fernández-Carrión R, Fito M, Olbeyra R, Gomez-Perez AM, Galiè S, Bernal-López MR, Martinez-Gonzalez MA, Salas-Salvadó J, Tinahones FJ. Effect on gut microbiota of a 1-y lifestyle intervention with Mediterranean diet compared with energy-reduced Mediterranean diet and physical activity promotion: PREDIMED-Plus Study. Am J Clin Nutr. 2021 May 21;
28. Cancello R, Turroni S, Rampelli S, Cattaldo S, Candela M, Cattani L, Mai S, Vietti R, Scacchi M, Brigidi P, Invitti C. Effect of Short-Term Dietary Intervention and Probiotic Mix Supplementation on the Gut Microbiota of Elderly Obese Women. Nutrients [Internet]. 2019 Dec 1 [cited 2023 Jul 10]; 11(12). Available from: https://pubmed.ncbi.nlm.nih.gov/31835452/
29. Gomez-Arango LF, Barrett HL, Wilkinson SA, Callaway LK, McIntyre HD, Morrison M, Dekker Nitert M. Low dietary fiber intake increases Collinsella abundance in the gut microbiota of overweight and obese pregnant women. Gut Microbes. 2018 May 4; 9(3):189–201.
30. Kasai C, Sugimoto K, Moritani I, Tanaka J, Oya Y, Inoue H, Tameda M, Shiraki K, Ito M, Takei Y, Takase K. Comparison of human gut microbiota in control subjects and patients with colorectal carcinoma in adenoma: Terminal restriction fragment length polymorphism and next-generation sequencing analyses. Oncol Rep. 2016 Jan 1; 35(1):325–33.
31. Quiroga R, Nistal E, Estébanez B, Porras D, Juárez-Fernández M, Martínez-Flórez S, García-Mediavilla MV, de Paz JA, González-Gallego J, Sánchez-Campos S, Cuevas MJ. Exercise training modulates the gut microbiota profile and impairs inflammatory signaling pathways in obese children. Exp Mol Med. 2020 Jul 1; 52(7):1048–61.
32. Eren AM, Sogin ML, Morrison HG, Vineis JH, Fisher JC, Newton RJ, McLellan SL. A single genus in the gut microbiome reflects host preference and specificity. ISME J [Internet]. 2015 Jan 11 [cited 2023 Jul 10]; 9(1):90–100. Available from: https://pubmed.ncbi.nlm.nih.gov/24936765/
33. Huang WC, Hsu YJ, Huang CC, Liu HC, Lee MC. Exercise Training Combined with Bifidobacterium Longum OLP-01 Supplementation Improves Exercise Physiological Adaption and Performance. Nutrients. 2020 Apr 1; 12(4).
34. Castellanos N, Diez GG, Antúnez-Almagro C, Bressa C, Bailén M, González-Soltero R, Pérez M, Larrosa M. Key bacteria in the gut microbiota network for the transition between sedentary and active lifestyle. Microorganisms. 2020 May 1; 8(5).
35. Palmas V, Pisanu S, Madau V, Casula E, Deledda A, Cusano R, Uva P, Vascellari S, Loviselli A, Manzin A, Velluzzi F. Gut microbiota markers associated with obesity and overweight in Italian adults. Sci Rep. 2021 Dec 1; 11(1).
36. Lim MY, You HJ, Yoon HS, Kwon B, Lee JY, Lee S, Song YM, Lee K, Sung J, Ko G. The effect of heritability and host genetics on the gut microbiota and metabolic syndrome. Gut. 2017 Jun 1; 66(6):1031–8.
37. Manore MM. Effect of physical activity on thiamine, riboflavin, and vitamin B-6 requirements. Am J Clin Nutr. 2000 Aug 1; 72(2):598S-606S.
38. Yoshii K, Hosomi K, Sawane K, Kunisawa J. Metabolism of dietary and microbial vitamin b family in the regulation of host immunity. Vol. 6, Frontiers in Nutrition. Frontiers Media S.A.; 2019. p. 48.
39. Yu D, Yang Y, Long J, Xu W, Cai Q, Wu J, Cai H, Zheng W, Shu XO. Long-term Diet Quality and Gut Microbiome Functionality: A Prospective, Shotgun Metagenomic Study among Urban Chinese Adults. Curr Dev Nutr. 2021 Apr 29; 5(4).
40. Liu Y, Wang Y, Ni Y, Cheung CKY, Lam KSL, Wang Y, Xia Z, Ye D, Guo J, Tse MA, Panagiotou G, Xu A. Gut Microbiome Fermentation Determines the Efficacy of Exercise for Diabetes Prevention. Cell Metab. 2020 Jan 7; 31(1):77-91.e5.

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SUPPLEMENTARY TABLE 1. Alpha diversity measurements in gut microbiota within each group T1, T2, and T3 after 1-year of intervention and, as well as, across the three groups.

	Faith_pd *p-value*	Observed features *p-value*	Pielou-Evenness *p-value*
T1 (n = 99)	0.981	0.722	0.319
T2 (n = 99)	0.701	0.780	0.574
T3 (n = 99)	0.675	0.720	0.055
Across three groups	0.438	0.758	0.122

SUPPLEMENTARY TABLE 2. List of the predicted pathways between three groups.

BioCyc Pathway ID	Pathway
PWY-6562	norspermidine biosynthesis
BRANCHED-CHAIN-AA-SYN-PWY	superpathway of branched chain amino acid biosynthesis
ILEUSYN-PWY	L-isoleucine biosynthesis I (from threonine)
PWY-2942	L-lysine biosynthesis III
PWY-5101	L-isoleucine biosynthesis II
PWY-5103	L-isoleucine biosynthesis III
PWY-5104	L-isoleucine biosynthesis IV
PWY-6630	superpathway of L-tyrosine biosynthesis
VALSYN-PWY	L-valine biosynthesis
PWY-6628	superpathway of L-phenylalanine biosynthesis
PWY-5505	L-glutamate and L-glutamine biosynthesis
PWY0-1241	ADP-L-*glycero*-β;-D-*manno*-heptose biosynthesis
OANTIGEN-PWY	*O*-antigen building blocks biosynthesis (*E. coli*)
KDO-NAGLIPASYN-PWY	superpathway of $(Kdo)_2$-lipid A biosynthesis
PWY-5265	peptidoglycan biosynthesis II (staphylococci)
PWY-6891	thiazole component of thiamine diphosphate biosynthesis II
PWY-6895	superpathway of thiamine diphosphate biosynthesis II
PWY-7377	cob(II)yrinate *a,c*-diamide biosynthesis I (early cobalt insertion)
PYRIDNUCSAL-PWY	NAD salvage pathway I (PNC VI cycle)
LPSSYN-PWY	superpathway of lipopolysaccharide biosynthesis
P125-PWY	superpathway of (*R, R*)-butanediol biosynthesis
PWY-5910	superpathway of geranylgeranyldiphosphate biosynthesis I (via mevalonate)
PWY-5757	fosfomycin biosynthesis
PWY-922	mevalonate pathway I (eukaryotes and bacteria)
AEROBACTINSYN-PWY	aerobactin biosynthesis
ENTBACSYN-PWY	enterobactin biosynthesis
PWY-7431	aromatic biogenic amine degradation (bacteria)
CRNFORCAT-PWY	creatinine degradation I
ORNDEG-PWY	superpathway of ornithine degradation
PWY-5705	allantoin degradation to glyoxylate III
PWY-5499	vitamin B_6 degradation

SUPPLEMENTARY TABLE 2. Continue.

PWY0-1533	methylphosphonate degradation I
GALACTARDEG-PWY	D-galactarate degradation I
GLUCARDEG-PWY	*D*-glucarate degradation I
GOLPDLCAT-PWY	superpathway of glycerol degradation to 1,3-propanediol
AST-PWY	L-arginine degradation II (AST pathway)
ARGDEG-PWY	superpathway of L-arginine, putrescine, and 4-aminobutanoate degradation
ORNARGDEG-PWY	superpathway of L-arginine and L-ornithine degradation
BENZCOA-PWY	anaerobic aromatic compound degradation (*Thauera aromatica*)
GLUCARGALACTSUPER-PWY	superpathway of D-glucarate and D-galactarate degradation
PWY-6588	pyruvate fermentation to acetone
PWY-7111	pyruvate fermentation to isobutanol (engineered)
PWY-5100	pyruvate fermentation to acetate and lactate II
NONOXIPENT-PWY	pentose phosphate pathway (non-oxidative branch) I
PWY-7254	TCA cycle VII (acetate-producers)

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The effect of physical exercise during competitions and in simulated conditions on hormonal-neurophysiological relationships in kickboxers

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ABSTRACT: K1-format kickboxing is a widely followed combat sport that requires intense physical exercise. However, research into the body's response to this type of combat is sparse. This study aims to assess the alterations in hormone levels and brain activity in elite kickboxers following an actual K1 bout and compare these changes with those observed in a control group engaged in a simulated fight exercise with a punchbag. The study included 100 male professional kickboxers, randomly divided into two groups: an experimental group (K1 fight) and a control group (simulated fight with a punchbag). Blood samples were obtained before and after exercise to evaluate testosterone (T) and cortisol concentrations (C). Concurrently, brain activity was recorded using quantitative electroencephalography (QEEG). After the activity in the experimental group mean testosterone level slightly, non-significantly decreased from 13.7 nmol/l to 12.4 nmol/l, while mean cortisol significantly ($p < 0.001$) increased from 313 to 570 nmol/l. In the control group after the exertion against a punchbag mean cortisol significantly ($p < 0.001$) increased from 334 to 452 nmol/l and testosterone increased non-significantly, from 15.1 to 16.3 nmol/l. In both groups, the testosterone/cortisol ratio (T/C ratio) showed significantly lower levels after the intervention ($p < 0.001$ and $p < 0.032$) in the experimental and control group respectively. The comparison of groups after exercise revealed significantly higher cortisol levels (experimental group $x = 570$ nmol/l; control group $x = 452$ nmol/l) and a significantly lower T/C ratio (experimental group $x = 2.7$; control group $x = 3.9$), ($p = 0.001$) in the experimental group. Significantly higher brain activity was found in selected leads after a bout (experimental group). Furthermore, in the experimental group, significant associations of weak to moderate strength were found between hormone fluctuations and selected areas of brain activity ($p < 0.05$). K1-format kickboxing induces a stress response, evident in the sharp changes in cortisol and testosterone levels. A notable observation was the inverse direction of changes in both hormones. Brain activity analysis indicated the potential influence of raised cortisol concentrations on specific brain areas. This study augments our understanding of the physiological responses during K1 kickboxing bouts and may inform the future evolution of this sport.

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INTRODUCTION

Kickboxing is a spectacular combat sport based on punches and kicks. The sport attracts many spectators who watch sports competitions and practitioners who actively participate in training and competitions at various skill levels [1, 2]. The athletes fight in a standing position and they perform punches and kicks using upper and lower limbs. They are allowed to use full power, in order to demonstrate an advantage over the opponent [3]. The bout can be settled by knockout, technical knockout (inability of the opponent to continue the fight), corner retirement, or judge's decision (advantage of technical points after the full standard time of the fight) [2]. Importantly, kickboxing requires the use of different motor skills and both aerobic and anaerobic capacity [4].

In training and competing in combat sports, understanding and optimizing adaptive potential is critical [5–7]. Central to the

adaptive mechanisms is the endocrine system, with numerous alterations induced by physical exercise. Endogenous testosterone (T) and cortisol (C) levels are frequently tested in elite athletes as hormonal changes are indicative of the body's response to physical or psychological stimuli [8, 9]. While cortisol facilitates catabolic processes, testosterone fosters anabolic ones. Their balance, reflected in T/C ratio, is crucial [10, 11] and has been studied in sports such as judo [12], wrestling [13], boxing [14], and taekwondo [15]. In kickboxing, differences in cortisol and testosterone concentrations have been found between competitive fighting and experimental forms of training [16]. No hormonal differences between winners and losers have been detected in kickboxing sparring simulations [17]. Slimani et al. reported that integrating mental training for kickboxers resulted in decreased cortisol levels mitigating stress [18].

The intrinsic competitive nature of kickboxing requires intense physical confrontations, making athletes susceptible to multiple injuries [19–21]. Especially concerning is the vulnerability of the head, a topic much discussed in boxing [22]. Post-fight mortality rates and cardiac arrests leading to debilitating and permanent injuries have been documented [23]. The K1 kickboxing format, characterized by its lenient regulations on strike force and the use of knee strikes [3], often witnesses fighters aiming to win the fight by knockout. This illustrates the aspect of the quality of blows delivered with full power. Furthermore, in quantitative terms, careful observation and scientific analysis reveal how a large proportion of strikes is performed directly to the head, or indirectly to the guard in K1 bouts, and qualitative inference has been made in other striking combat sports [24]. In 2007, Tanriverdi et al. established a link between amateur kickboxing and hypopituitarism [25]. It is also known that active and retired athletes alike have demonstrated significant correlations between cognitive functions and GH-IGF-I levels [26]. Follmer et al. emphasized that coaches and athletes need to learn how to recognize concussion symptoms and give first aid [27]. Recent findings suggested brain dysfunctions in K1 fighters that need to be further explored [25, 26]. Currently, electroencephalography (EEG) is popular and widely used in the medical community, providing physicians with important diagnostic information on brain function, with possible neurological disorders. Importantly, EEG is a very practical and inexpensive method of functional neuroimaging [28]. EEG is a qualitative method. On the other hand, the use of quantitative electroencephalography (QEEG), i.e. the analysis of individual brain waves and the ability to extract them, is of increasing interest to researchers in the field of sports [29]. Previous analyses in this area of research indicated that elite athletes had high amplitudes of beta 1 and beta 2 waves in the frontal lobe area during the period of detraining compared to normal values and non-athletes, which, according to the authors, could be related to the accumulation of emotions that negatively affect judgment and coordination [30]. Another study evaluating brain wave activity in kickboxers showed high intensity of sensorimotor rhythm (SMR), beta 1, and beta 2 waves. It was found that high activity of these waves can cause anxiety, stress, difficulty concentrating, and reduced levels of physical activity [31]. Global conclusions from these studies indicate that specific brain wave activity can have both negative and positive effects on brain function and indirectly on sports performance. In contrast, in a state of immediate combat readiness, before a sporting event, fighters exhibit elevated and diverse brain wave activity, associated with stress, arousal, and concentration [32]. Participating in this sport might lead to severe and irreversible neurological conditions.

K1 kickboxing offers opportunities to analyse the body's neuroendocrine and neurophysiological responses to stress, with athletes enduring rigorous physical strain, psychological exposure, and potentially serious injuries. Notwithstanding the burgeoning interest [6], literature surveys have shown a paucity of comprehensive studies integrating hormonal, neurophysiological, and neurocognitive analyses during K1 bouts. This research gap highlights the need for holistic diagnosis in this domain.

This study pursues two primary objectives:

1. To investigate hormonal and post-bout alterations in brain activity in K1 kickboxers (experimental group) compared to a control group participating in a punchbag session simulating fight conditions.
2. To evaluate relationships between hormonal profiles and brain activity.

The findings here can enhance our understanding of neuroendocrine dynamics during kickboxing, thus providing a foundation for therapeutic strategies and innovative corrective therapies.

In our study, based on previous scientific reports, we hypothesized that depending on the type of stimulus (real fight or punchbag), there would be variation in the levels of the hormone indices studied.

MATERIALS AND METHODS

Participants

The study involved 100 male professional kickboxers from Poland, all competing in the K1 format. The mean age (years), body height (cm), and body mass (kg) of participants in the research population were 26.06 ± 4.9 (range: 18–35), 178.5 ± 5.9 (range 165–189), and 77.3 ± 8.8 (range: 61.4–94.1) respectively. Inclusion criteria were as follows: a minimum of 5 years of training experience, absence of injuries, up-to-date medical examinations, no history of severe knockouts, a positive medical recommendation, and active participation in competitions. Exclusion criteria included having less than 5 years of training experience, conditions such as seizures or other neurological disorders, presence of injuries, lack of participation in competitions, history of severe knockouts, or a negative medical recommendation. The athletes were randomly divided into two groups: the control group (n = 50) and the experimental group (n = 50). The mean age (years), body height (cm), and body mass (kg) of participants in the experimental group

were 25.5 ± 4.6 (range: 18–33), 179.3 ± 6.1 (range 168–189), and 76.7 ± 10.0 (range: 61.4–94.1) respectively. The mean age (years), body height (cm), and body mas (kg) of participants in the control group were 26.6 ± 5.2 (range: 18–35), 177.7 ± 5.6 (range 165–187), and 77.9 ± 7.5 (range: 65.7–90.0) respectively. The sample size was determined using G*power (confidence level 95%, margin of error 5%). Each participant was assigned a unique identification number, and group placement was determined through a random number generator. All participants were informed in detail about the experimental procedure and provided written consent to participate in the experiment. The study was conducted according to the Declaration of Helsinki and approved by the Ethics Committee of the University of Rzeszów (protocol code 8/12/2021).

Methods

The athletes in the experimental group participated in simulated sparring in the ring, organized for this research project according to the K1 rules adopted by the World Association of Kickboxing Organizations (WAKO) [33]. The bout was divided into 3 rounds lasting 2 minutes each, with a one-minute break between rounds. The athletes were divided by weight categories. The bouts were supervised by a qualified and licensed judge. Twenty-five bouts were held over the full duration of standard fighting time. The study of both groups was conducted before noon. The control group athletes participated in a punchbag training session that simulated the conditions of a kickboxing match. The fatigue-focused session consisted of three 2-minute work periods (equivalent to K1 rounds) separated by a one-minute break between them. The participant stood in a fighting stance, directly in front of the punchbag at a fighting distance. During each period of work, following the command *Start*, the participant performed as many offensive combinations of K1 formula techniques as possible, performed individually or in series. The focus was on an intense effort. The command *Stop* marked the end of a given work period and a one-minute break after the first and second work periods. The simulation was developed on request. In order to confirm the relevance of the intervention, participants were measured for cardiovascular stress parameters (HR $\hat{x} = 182.67 \pm 5.9$), which indicated that it represented a test of very high-intensity exercise compared to a sports bout. The results obtained are similar to literature data indicating that in trained athletes, intense exercise based on hand-to-hand combat techniques results in an increase in the minute heart rate ranging from 165 to 185 beats per minute [34]. Blood samples (1.5 ml each) were collected from the antecubital vein of participants from both groups before the warm-up and 3 minutes after exercise. These procedures were performed by a qualified nurse. Serum concentrations of testosterone and cortisol were evaluated based on the electrochemiluminescence method, using a COBAS Integra 400 Plus analyser. Every batch of analysis included control sera to gauge the precision of the measurements. The within-series coefficient of variation (CV) for both hormones was 3.8%, and the between-series CV was 4.2%. On the basis of T and C concentration values, the anabolic-catabolic balance index was calculated (T/C * 100).

QEEG Analysis

The QEEG method was used to identify the profile of brain wave activity in the kickboxers before and after the experimental intervention and to diagnose the relationship with hormonal pattern. Quantitative electroencephalography (QEEG) offers a numerical spectral analysis of the EEG record. This process involves digitally coding the data, followed by a statistical analysis using the Fourier transform algorithm. Each examination, conducted individually, lasted roughly 10–15 minutes and comprised two phases: recording brainwave activity with eyes closed (3 min) and with eyes open (3 min). The amplitude and power of distinct frequencies were scrutinized. Based on established norms for adults, a general rule was that the lower the wave frequency was, the higher was its amplitude. Established standard values were delta waves under 20 μV, theta under 15 μV, alpha under 10 μV, and SMR, beta 1, and beta 2 in the range 4–10 μV. The EEG signal was processed using a Cz montage with the Cz electrode often employed as the primary reference. Quantification was performed using Elmiko DigiTrack software (version 15 PL, ELMIKO, Poland). Delta, theta, alpha, SMR, beta 1, and beta 2 waves were recorded at nine electrode points: frontal (FzF3F4), central (CzC3C4), and parietal (PzP3P4). The amplitude of QEEG rhythm met the medical standards specified for the DigiTrack device. A signal spectrum reflects its frequency-dependent pattern. The fast Fourier transform (FFT algorithm) was employed, yielding the function: $f(z) = A(z) + j*F(z)$. FFT analysis utilized parameters such as a minimum signal amplitude of 0.5 μV and a minimum temporal gap between individual peak values of 0.5 Hz. Analysis was performed with a computation buffer of 8.2 s (2048 assessment points, accuracy of 0.12 Hz). Consequently, an amplitude value set for each segment of the frequency spectrum was generated. The gap between individual values, measured in Hz, determined the computation resolution. For the FFT algorithm, this parameter depends on the signal sampling frequency and the computation buffer length: $r = fs/N$, where 'r' is the computation resolution, 'fs' is the signal sampling frequency, and 'N' denotes the computation buffer length. The FFT panel in DigiTrack displayed peak-to-peak amplitudes. Measurement epochs of several seconds were used to ensure reliable results. The duration of these epochs determined the frequency resolution of the Fourier transform: a 1-second epoch translated into a 1 Hz resolution (± 0.5 Hz), while a 4-second epoch yielded 0.25 Hz or ± 0.125 Hz resolution. Artefact removal from the EEG recording was performed both manually and automatically. For the experimental group, the initial test was executed before the warm-up, and the subsequent test immediately after the K1 kickboxing match. Each bout consisted of three 2-minute rounds interspersed with one-minute intervals. For the control group, the baseline measurement was performed before the warm-up, and the next one followed a simulated bout with a punchbag, structured identically to that in the experimental

group [30, 31, 35, 36]. The results of the QEEG for open eyes are presented in this study since only these values showed statistically significant correlations.

Statistical Analysis Methods

In the study's data analysis, basic statistical methods were employed, including the calculation of the arithmetic mean and standard deviation. Additionally, specialized statistical analyses were conducted, such as relative to variables and the differentiation in brain activity of the experimental group, diagnosed before and after intervention. A one-way analysis of variance (ANOVA) with repeated measures and a post-hoc Bonferroni test were used. For assessing the variation in hormonal indicators, before and after the intervention in the studied groups, a two-way analysis of variance with repeated measures (group * time) was utilized. Effect sizes for each time and group factor were determined, followed by the application of the post-hoc Bonferroni test for comparing variables between measurements and between groups using an interaction layout. Linear correlation coefficients were employed to evaluate the relationships between variables (brain activity vs. hormonal indicators). The inference thresholds for Pearson's correlation are as follows: 0.50–1.00 – strong correlation, 0.30–0.49 – moderate correlation, below 0.29 – low correlation [37]. All data analyses were conducted using STATISTICA software version 13.3. Statistical significance was established at a p-value of less than 0.05.

RESULTS

Table 1 presents the statistical characteristics of the studied hormonal indicators before and after the research intervention in both groups, along with the results of the two-factor analysis of variance. Intragroup comparison revealed a significant increase in post-exertion cortisol concentrations in both research groups. An opposite trend was observed regarding the T-to-C ratio. A significant decrease in the value of the anabolic-catabolic index (T/C*100) was observed in both research groups (Table 1). The post-exertion relative increase in cortisol concentration in the experimental group (by 82%) was over twice as high as that in the control group (by 35%). The value of the anabolic-catabolic index decreased by 2.2 points in the experimental group (1.1 points in the control group). No significant post-exertion changes in testosterone concentration were observed in either group, but there was a slight decrease in this hormone's level in the experimental group by 9.5% and an increase in the control group (by 7.9%).

Inter-group comparisons revealed no significant differences for testosterone, cortisol, and the anabolic-catabolic index (T/C*100) before exertion. Following the application of the intervention stimulus, statistically significant intergroup differences in the studied hormonal parameters were found. In the experimental group, the C level was higher (by 20.8%), and lower values for T (by 31.5%) and T/C*100 (by 44.4%) were noted compared to the corresponding parameters for the control group (Table 1).

Table 2 shows the nature of the co-occurrence between selected hormone parameters and parameters of brain electrical activity (QEEG), after the K1 bout in the experimental group. There was a significant negative correlation between alpha frequency (Fz) and T of moderate strength. A similar trend was noted between Beta 1 (P3) and C, with an inverse positive direction of correlation. Significant and weak positive correlations were found between alpha (P3), SMR (F3), beta 1 (F3), and C. Theta (C4) and alpha (Fz) showed a similar profile of correlations with T/C, with a different (negative) direction (see Table 2). In the experimental group, there was a moderate yet close to the lower limit of strong negative correlation between cortisol and testosterone levels after the K1 bout ($r = -0.47$; $p < 0.05$). No such correlations were found in the control group or the two study groups before exercise.

Table 3 displays the average values (for selected leads) of brain electrical activity before and after the research intervention in the experimental group, along with the results of the comparative analysis. The presented parameters played a significant role in the previously described significant relationships (Table 2). The comparison of means showed statistically significant differences for all variables, where their activity markedly increased. The exception was the alpha wave (lead Fz), whose amplitude increased slightly by 4.5%.

DISCUSSION

Cortisol and testosterone responses to exercise depending on its duration and intensity have been extensively described in the literature. Prolonged exercise, such as long-distance running [38–41] or triathlon competitions [42], often leads to a significant increase in cortisol levels and a decrease in testosterone levels. However, after shorter maximal exercise, testosterone levels do not decrease and they often increase, as do levels of luteinizing hormone (LH) [43, 44]. This suggests the stimulation of the hypothalamic-pituitary-gonadal (HPG) axis. Evaluation of post-exercise testosterone changes should focus not only on secretion but also on transient blood concentration. This nuance can obscure the testosterone changes induced by secretion, and researchers sometimes neglect this in their analyses. If the focus is solely on immediate post-exercise androgenic activity in the blood without considering the causes of changes in androgen concentration, the post-exercise haemoconcentration effect can be missed. This effect can rise to several percent directly after supramaximal exercise [45].

Although a single competitive effort in combat sports lasts several minutes, it intensely activates both the HPA (hypothalamic-pituitary-adrenal) and HPG (hypothalamic-pituitary-gonadal) axes, elevating both cortisol and testosterone levels. However, contrary to that rule, in our study, we observed a rise in cortisol only but not in the androgen level after a 3-round fight. The control group, performing exercise of similar duration and intensity with a punchbag, showed a smaller hormone increase, likely due to the absence or minimal psycho-emotional component of the post-exercise stress. Although

TABLE 1. Descriptive statistics and results of the two-factor analysis of variance for hormonal parameters in the control and experimental groups.

Variable	EXP		CON		Between groups	interaction Variable*time		
T (nmol/l)	Mean	SD	Mean	SD				
Pre	13.7	2.7	15.1	3.9	p = 0.309	p	Partial η^2	power
Post	12.4	2.4	16.3	5.0	**p < 0.001**			
Between examination	p = 0.456		p = 0.641			**< 0.017**	**0.029**	**0.666**
Time effect	p = 0.907 partial η^2 < 0.001 power = 0.052							
C (nmol/l)	EXP		CON		Between groups	interaction Variable*time		
	Mean	SD	Mean	SD				
Pre	312.9	95.1	334.2	82.4	p = 1.000	p	Partial η^2	power
Post	570.4	123.9	451.8	94.1	**p < 0.001**			
Between examinations	**p < 0.001**		**p < 0.001**			**< 0.001**	**0. 111**	**0.998**
Time effect	**p < 0.001 partial η^2 = 0.473 power = 1.000**							
T/C*100	EXP		CON		Between groups	interaction Variable*time		
	Mean	SD	Mean	SD				
Pre	4.9	2.2	5.0	2.8	p = 0.073	p	Partial η^2	power
Post	2.7	1.0	3.9	1.9	**p = 0.001**			
Between examinations	**p < 0.001**		**p = 0.032**					
Time effect	**p < 0.001. partial η^2 = 0.174 power = 0.999**					**< 0.015**	**0.030**	**0.683**

EXP – Experimental Group, Con – Control Group , T-Testosterone, C – Cortisol , SD – Standard Devotion, p – significance

TABLE 2. Correlations between testosterone levels, cortisol levels, the testosterone/cortisol ratio, and QEEG parameters after the fight in the experimental group.

Parameter	Testosterone, (nmol/l)		Cortisol, (nmol/l)		Testosterone/Cortisol	
	r	p	r	p	r	p
Theta 4 Hz-8 Hz (C4)	-0.19	0.180	0.23	0.102	-0.28*	**0.048**
Alpha 8 Hz-12 Hz (Fz)	-0.30**	**0.034**	0.15	0.303	-0.29*	**0.043**
Alpha 8 Hz-12 Hz (P3)	0.12	0.404	0.29*	**0.038**	-0.09	0.513
SMR 12 Hz-15 Hz (F3)	0.04	0.806	0.29*	**0.040**	-0.10	0.481
Beta1 15 Hz-20 Hz (F3)	0.15	0.310	0.29*	**0.039**	-0.05	0.715
Beta1 15 Hz-20 Hz (P3)	0.17	0.237	0.30**	**0.034**	-0.05	0.717

* – low correlation, ** – moderate correlation, C4 – right central electrode, Fz – central frontal electrode, P3 – left occipital electrode, F3 – left frontal electrode

TABLE 3. Results of One-way ANOVA and post-hoc Bonferroni test for selected QEEG electrodes (which demonstrated statistically significant correlations) before and after the intervention in the experimental group.

Brain waves parameters	Pre intervention	Post intervention	p-value	Partial η^2	power
Theta 4 Hz-8 Hz (C4)	6.64 ± 1.21	7.21 ± 1.26	**0.016**	**0.058**	**0.680**
Alpha 8 Hz-12 Hz (Fz)	7.26 ± 1.75	7.60 ± 1.76	0.333	0.009	0.161
Alpha 8 Hz-12 Hz (P3)	7.75 ± 2.54	9.35 ± 3.32	**0.014**	**0.060**	**0.696**
SMR 12 Hz-15 Hz (F3)	4.39 ± 0.73	5.94 ± 1.14	**< 0.001**	**0.396**	**1.000**
Beta1 15 Hz-20 Hz (F3)	5.50 ± 0.65	6.54 ± 1.24	**< 0.001**	**0.191**	**0.997**
Beta1 15 Hz-20 Hz (P3)	5.53 ± 0.72	6.46 ± 1.06	**< 0.001**	**0.256**	**0.999**

C4 – right central electrode, Fz – central frontal electrode, P3 – left occipital electrode, F3 – left frontal electrode

this group performed a simulated fight, they did not receive any blows. Other studies have also reported elevated cortisol levels following a real fight compared to contact-free exercise simulating a kickboxing bout [16]. The consistent cortisol levels between groups before the exercise suggest only minimal HPA axis activation before the fight, which was not as demanding as official competitions. Especially noteworthy is the observed interaction between the two hormones after the bout in the experimental group. A negative correlation was found between cortisol and testosterone levels, due to the inhibitory effect of elevated cortisol levels on the HPG axis in men. This phenomenon occurs either when cortisol levels are particularly high or for longer exposure durations, as corroborated by other studies [8, 38–42, 46]. In the post-exercise recovery period following two sequential exhaustive workouts, a significant negative correlation between testosterone and cortisol was also observed [43].

In evaluating the physiological and metabolic changes induced by cortisol, it is necessary to emphasize that most effects are attributed to the unbound cortisol fraction. This fraction, considered biologically active, diffuses from the circulation into target cells and comprises roughly 10–15% of the total hormone concentration. As total cortisol concentration increases, the unbound fraction does as well but not proportionally. A marked increase in free cortisol becomes evident when the total hormone concentration exceeds 500 nmol/l [44]. In our study, only 13 athletes from the control group and 30 from the experimental group had post-exercise levels above 500 nmol/l. Perhaps the interaction between the hormones and the shifts in brain electrical activity after a kickboxing match are more influenced by the elevated concentration of the biologically active fraction that permeates the blood-brain barrier than by the cumulative cortisol concentration. This theory is consistent with the observed positive post-bout correlations between cortisol and alpha 8–12 Hz (P3), beta1 15–20 Hz (F3), and beta1 15–20 Hz (P3) frequencies in the experimental group. These findings are similar to those described in a review article [45], suggesting the possibility that either endogenous or exogenous cortisol stimulates regions of the limbic system, including the amygdala, hippocampus, paraventricular nucleus, and prefrontal cortex, and that shifts in delta and beta wave amplitudes reflect the degree of stress induced by perceived threats [47, 48]. Brain activity, especially in the pituitary-hypothalamic area, can affect the regulation of sex hormones, including testosterone. The brain controls the secretion of hormones by the pituitary gland, which in turn controls the secretion of hormones by the testes in men, including testosterone [49]. Stress, poor nutrition, sleep deprivation, and other factors can affect the functioning of the endocrine system, testosterone levels, and thus the brain waves. A variety of meditation practices used by athletes before a fight, associated with alpha waves, can affect the body's hormonal balance, including levels of sex hormones such as testosterone. Exercises related to relaxation, meditation, and breathing techniques help athletes reduce stress and tension. In a state of relaxation, an increase in alpha waves in the brain can be observed [50].

Available research also suggests that reducing stress levels and stimulating alpha wave activity can affect overall hormonal balance, including levels of sex hormones such as testosterone. Reduced stress levels can help maintain hormonal balance. Sleep is a key part of recovery, including hormonal recovery. Theta waves are also associated with a certain stage of sleep. If sleep is disturbed, a person experiences fluctuations within this wave, followed by fluctuations in hormone levels. Sleep deprivation can lead to lower testosterone levels. There is a link between cortisol levels and brain wave activity, especially in terms of the body's response to stress [51]. During stressful situations, cortisol levels in the body increase. Cortisol plays an important role in the stress response, helping the body adapt to difficult situations. It affects many body functions, including brain function. Brain wave activity can change in response to stress. For example, in stressful situations, there may be an increase in beta wave frequencies, which is associated with a more alert state of mind. In general, there is a complex interaction between cortisol and brainwave activity, but this depends on many factors, including the type of stress, the duration of the stress response, and individual variability [52]. Research in this field is still ongoing, and understanding this interaction may contribute to a better understanding of the body's response to stress and its impact on brain function.

Addressing the influence of kickboxing on brain electrical activity mandates consideration of EEG study results linked to laboratory exercises devoid of head injury risk. Increases in alpha, theta, beta, and gamma wave amplitudes following strength training have been documented [53]. During progressively intense cycling on an ergometer, alpha, theta, and beta wave activity across various brain regions seemed to increase simultaneously [54]. Moreover, the extent of post-exercise EEG alterations depends on individual exercise preferences [55]. Another investigation revealed that after acclimatizing to exercise over a training period, the peak frequency of alpha waves rose only following exhaustive maximal exercise rather than moderate, stable-intensity exercise without emotional arousal [56]. A few studies have concentrated on brain electrical activity in relation to androgen status. It was reported that exogenous testosterone amplified affective stress responses, notably in dominant males [57]. Interpreting the negative correlation between alpha 8–12 Hz (Fz) and endogenous testosterone is difficult without the analysis of bout outcomes and psychological studies. This underlines the necessity for further more comprehensive kickboxing research that includes psychological assessment [58].

Limitations of the Study

The lack of research opportunities and activities regarding the diagnosis related to tournament fights means that the results of this study may be limited to a certain extent. However, in light of the inevitable limitations of our experimental design, we recruited a significant number of elite K1 athletes, the procedures were carried out according to a strict protocol, and the results are scientifically valid. To

capture the multifaceted clinical context, future research should consider making comparisons between other populations, such as athletes of other combat sports, non-athletes, and groups of female athletes.

CONCLUSIONS

1. Both study groups showed significant psychophysiological stress following the application of the experimental stimulus, resulting in strong activation of the HPA axis and noticeable changes in blood testosterone levels.
2. Post-intervention comparative analysis showed significantly higher cortisol levels and a significantly lower T/C ratio for the experimental group performing real bouts.
3. When confronted with an opponent (simulated sparring), there was a significantly negative correlation between cortisol and testosterone levels in the experimental group.
4. Simulated K1 sparring in the experimental group resulted in a significant increase in brainwave activity.
5. In the immediate recovery phase for the experimental group, there were statistically significant correlations between cortisol and selected indices of brain electrical activity. Such associations did not occur after equivalent non-contact exercise.

Practical Implications

The results of the study inspire further research on the relationship of a kickboxing bout with selected brain bioelectrical indices, hormonal activity, and hormonal-neurophysiological interactions in athletes. The results of these observations can also affect the programming of the training process and significantly affect the modification of regulations in combat sports, emphasizing the safety of participants and enhancing health protection measures.

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Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. Slimani M, Chaabene H, Miarka B, Franchini E, Chamari K, Cheour F. Kickboxing review: anthropometric, psychophysiological and activity profiles and injury epidemiology. Biol Sport. 2017; 34(2):185–196.
2. Rydzik Ł. Indices of technical and tactical training during kickboxing at different levels of competition in the K1 Formula. J Kinesiol Exerc Sci. 2022; 31(94):1–5.
3. Di Marino S. A Complete Guide to Kickboxing. New York: Enslow Publishing; 2018.
4. Senduran F, Mutlu S. The effects of Kick-Box training based group fitness on cardiovascular and neuromuscular function in male non-athletes. J Sci Med Sport. 2017; 20:33.
5. Andreato LV, Lara FJD, Andrade A, Branco BHM. Physical and Physiological Profiles of Brazilian Jiu-Jitsu Athletes: a Systematic Review. Sport Med. 2017; 13; 3(1):9.
6. Podrigalo LV, Shi K, Podrihalo OO, Volodchenko OA, Halashko OI. Main research areas in kickboxing investigations: an analysis of the scientific articles of the Web of Science Core Collection. Pedagog Phys Cult Sport. 2022; 26(4):244–259.
7. Ružbarský P, Němá K, Perič T, Ambroży T, Bąk R, Niewczas M, Rydzik Ł. Physical and physiological characteristics of kickboxers : a systematic review. Arch Budo. 2022; 18:111–120.
8. Tota Ł, Piotrowska A, Pałka T, Morawska M, Mikuľáková W, Mucha D, Żmuda-Pałka M, Pilch W. Muscle and intestinal damage in triathletes. Harnish C, editor. PLoS One. 2019; 18; 14(1):1–14.
9. Kuikman MA, Coates AM, Burr JF. Markers of Low Energy Availability in Overreached Athletes: A Systematic Review and Meta-analysis. Sport Med. 2022; 11; 52(12):2925–2941.
10. De Luccia TP. Use of the Testosterone/ Cortisol Ratio Variable in Sports. Open Sports Sci J. 2016; 23; 9(1):104–113.
11. Sollberger S, Ehlert U. How to use and interpret hormone ratios. Psychoneuroendocrinology. 2016; 63:385–397.
12. Marques L, Franchini E, Drago G, Aoki MS, Moreira A. Physiological and performance changes in national and international judo athletes during block periodization training. Biol Sport. 2017; 34(4):371–378.
13. Barbas I, Fatouros IG, Douroudos II, Chatzinikolaou A, Michailidis Y, Draganidis D, Jamurtas AZ, Nikolaidis MG, Parotsidis C, Theodorou AA, Katrabasas I, Margonis K, Papassotiriou I, Taxildaris K. Physiological and performance adaptations of elite Greco-Roman wrestlers during a one-day tournament. Eur J Appl Physiol. 2011; 111(7):1421–1436.
14. Kelestimur F, Tanriverdi F, Atmaca H, Unluhizarci K, Selcuklu A, Casanueva FF. Boxing as a sport activity associated with isolated GH deficiency. J Endocrinol Invest. 2004; 27(11):28–32.
15. Pilz-Burstein R, Ashkenazi Y, Yaakobovitz Y, Cohen Y, Zigel L, Nemet D, Shamash N, Eliakim A. Hormonal response to Taekwondo fighting simulation in elite adolescent athletes. Eur J Appl Physiol. 2010; 110(6):1283–1290.
16. Ouergui I, Houcine N, Marzouki H, Davis P, Zaouali M, Franchini E, Gmada N, Bouhlel E. Development of a Noncontact Kickboxing Circuit Training Protocol That Simulates Elite Male Kickboxing Competition. J Strength Cond Res. 2015; 29(12):3405–3411.
17. Ouergui I, Davis P, Houcine N, Marzouki H, Zaouali M, Franchini E, Gmada N, Bouhlel E. Hormonal Physiological, and Physical Performance During Simulated Kickboxing Combat: Differences Between Winners and Losers. Int J Sports Physiol Perform. 2016; 11(4):425–431.
18. Slimani M, Taylor L, Baker JS, Elleuch A, Ayedi FM, Chamari K, Chéour F. Effects of mental training on muscular force, hormonal and physiological changes in kickboxers. J Sports Med Phys Fitness. 2017; 57:(7–8).
19. Romaine LJ, Davis SE, Casebolt K, Harrison KA. Incidence of Injury in Kickboxing Participation. J Strength Cond Res. 2003; 17(3):580.
20. Zazryn TR. A 16 year study of injuries to professional kickboxers in the state of Victoria, Australia. Br J Sports Med. 2003; 37(5):448–51.
21. Lystad RP. Injuries to Professional and Amateur Kickboxing Contestants. Orthop J Sport Med. 2015; 3(11):1–5.
22. Lundberg GD. Boxing Should Be Banned in Civilized Countries. JAMA J Am Med Assoc. 1983; 249(2):250.
23. Battalia J, Aschenbrener C, Bennett D. Braininjury in boxing. Council on scientific affairs. J Am MedAssoc. 1983; 249:254–257.
24. Rydzik Ł, Wąsacz W, Ambroży T, Pałka T, Sobiło-Rydzik E, Kopańska M. Comparison

of Head Strike Incidence under K1 Rules of Kickboxing with and without Helmet Protection—A Pilot Study. Int J Environ Res Public Health. 2023; 20(6):4713.
25. Tanriverdi F, Unluhizarci K, Coksevim B, Selcuklu A, Casanueva FF, Kelestimur F. Kickboxing sport as a new cause of traumatic brain injury-mediated hypopituitarism. Clin Endocrinol (Oxf). 2007; 66(3):360–366.
26. Tanriverdi F, Suer C, Yapislar H, Kocyigit I, Selcuklu A, Unluhizarci K, Casanueva FF, Kelestimur F. Growth hormone deficiency due to sports-related head trauma is associated with impaired cognitive performance in amateur boxers and kickboxers as revealed by P300 auditory event-related potentials. Clin Endocrinol (Oxf). 2013; 78(5):730–737.
27. Follmer B, Varga AA, Zehr EP. Understanding concussion knowledge and behavior among mixed martial arts, boxing, kickboxing, and Muay Thai athletes and coaches. Phys Sportsmed. 2020; 48(4):417–423.
28. Shoeibi A, Rezaei M, Ghassemi N, Namadchian Z, Zare A, Gorriz JM. Automatic Diagnosis of Schizophrenia in EEG Signals Using Functional Connectivity Features and CNN-LSTM Model. In: Ferrández Vicente JM, Álvarez-Sánchez JR, De La Paz López F, Adeli H, eds. Artificial Intelligence in Neuroscience: Affective Analysis and Health Applications. 2022:63–73.
29. Rydzik Ł, Wąsacz W, Ambroży T, Javdaneh N, Brydak K, Kopańska M. The Use of Neurofeedback in Sports Training: Systematic Review. Brain Sci. 2023; 13(4):1–18.
30. Rydzik Ł, Ambroży T, Pałka T, Wąsacz W, Spieszny M, Perliński J, Król P, Kopańska M. Preliminary Development of a Brainwave Model for K1 Kickboxers Using Quantitative Electroencephalography (QEEG) with Open Eyes. Int J Mol Sci. 2023; 24(10):1–17.
31. Rydzik Ł, Pałka T, Sobiło-Rydzik E, Tota Ł, Ambroży D, Ambroży T, Ruzbarsky P, Czarny W, Kopańska M. An Attempt to Develop a Model of Brain Waves Using Quantitative Electroencephalography with Closed Eyes in K1 Kickboxing Athletes—Initial Concept. Sensors. 2023; 23(8):1–14.
32. Rydzik Ł, Wąsacz W, Ambroży T, Kasicki K, Ratkowski W, Kopańska M. Kickboxing on Theta and Beta-2 waves: unravelling the mind's secrets through QEEG analysis. Arch Budo Sci Martial Arts Extrem Sport. 2023:19.
33. World Association of Kickboxing Organizations. WAKO K1-Rules. WAKO; 2020:4–10
34. Rydzik Ł. Determination of the real training load based on monitoring of K1 kickboxing bouts. J Kinesiol Exerc Sci. 2022; 32(99):1–8.
35. Kopańska M, Kuduk B, Łagowska A, Mytych W, Muchacka R, Banaś-Ząbczyk A. Quantitative electroencephalography interpretation of human brain activity after COVID-19 before and after Sudarshan Kriya Yoga. Front Hum Neurosci. 2022:16.
36. Nieuwenhuis S, Forstmann BU, Wagenmakers E-J. Erroneous analyses of interactions in neuroscience: a problem of significance. Nat Neurosci. 2011; 14(9):1105–1107.
37. Cohen J. Statistical Power Analysis for the Behavioral Sciences Second Edition. Routledge; 2013.
38. Kupchak BR, Kraemer WJ, Hoffman MD, Phinney SD, Volek JS. The Impact of an Ultramarathon on Hormonal and Biochemical Parameters in Men. Wilderness Environ Med. 2014; 25(3):278–288.
39. Tong TK, Baker JS, Henriquez FL, Shi Q, Zhang H, Kong Z, Nie J. A Combined Approach for Health Assessment in Adolescent Endurance Runners. Healthcare. 2021; 9(2):163.
40. Karkoulias K, Habeos I, Charokopos N, Tsiamita M, Mazarakis A, Pouli A, Spiropoulos K. Hormonal responses to marathon running in non-elite athletes. Eur J Intern Med. 2008; 19(8):598–601.
41. Li C-Y. Salivary Immuno Factors, Cortisol and Testosterone Responses in Athletes of a Competitive 5,000 m Race. Chin J Physiol. 2015; 58(4):263–269.
42. Vaamonde D, García-Manso JM, Algar-Santacruz C, Abbasi A, Sarmiento S, Valverde-Esteve T. Behaviour of salivary testosterone and cortisol in men during an Ironman Triathlon. Eur J Sport Sci. 2022; 22(9):1335–1342.
43. Brownlee KK, Moore AW, Hackney AC. Relationship between circulating cortisol and testosterone: influence of physical exercise. J Sports Sci Med. 2005; 4(1):76–83.
44. Paccotti P, Minetto M, Terzolo M, Ventura M, Ganzit GP, Borrione P, Termine A, Angeli A. Effects of High-Intensity Isokinetic Exercise on Salivary Cortisol in Athletes with Different Training Schedules: Relationships to Serum Cortisol and Lactate. Int J Sports Med. 2005; 26(9):747–755.
45. Harrewijn A, Vidal-Ribas P, Clore-Gronenborn K, Jackson SM, Pisano S, Pine DS, Stringaris A. Associations between brain activity and endogenous and exogenous cortisol – A systematic review. Psychoneuroendocrinology. 2020; 120:1–53.
46. Vaamonde D, Da Silva M, Poblador M, Lancho J. Reproductive Profile of Physically Active Men After Exhaustive Endurance Exercise. Int J Sports Med. 2006; 27(9):680–689.
47. Poppelaars ES, Klackl J, Pletzer B, Jonas E. Delta-beta cross-frequency coupling as an index of stress regulation during social-evaluative threat. Biol Psychol. 2021; 160:1–10.
48. Poppelaars ES, Harrewijn A, Westenberg PM, van der Molen MJW. Frontal delta-beta cross-frequency coupling in high and low social anxiety: An index of stress regulation? Cogn Affect Behav Neurosci. 2018; 18(4):764–777.
49. Głombik K, Detka J, Budziszewska B. Hormonal Regulation of Oxidative Phosphorylation in the Brain in Health and Disease. Cells. 2021; 10(11):1–28.
50. Ciocca G, Limoncin E, Carosa E, Di Sante S, Gravina GL, Mollaioli D, Gianfrilli D, Lenzi A, Jannini EA. Is Testosterone a Food for the Brain? Sex Med Rev. 2016; 4(1):15–25.
51. Kopańska M, Ochojska D, Muchacka R, Dejnowicz-Velitchkov A, Banaś-Ząbczyk A, Szczygielski J. Comparison of QEEG Findings before and after Onset of Post-COVID-19 Brain Fog Symptoms. Sensors. 2022; 22(17):1–12.
52. Sroykham W, Wongsawat Y. Effects of brain activity, morning salivary cortisol, and emotion regulation on cognitive impairment in elderly people. Medicine (Baltimore). 2019; 98(26):1–8.
53. Engchuan P, Wongsuphasawat K, Sittiprapaporn P. Brain electrical activity during bench press weight training exercise. Asian J Med Sci. 2019; 10(5):80–85.
54. Bailey SP, Hall EE, Folger SE, Miller PC. Changes in EEG during graded exercise on a recumbent cycle ergometer. J Sports Sci Med. 2008; 7(4):505–511.
55. Schneider S, Brümmer V, Abel T, Askew CD, Strüder HK. Changes in brain cortical activity measured by EEG are related to individual exercise preferences. Physiol Behav. 2009; 98(4):447–452.
56. Gutmann B, Mierau A, Hülsdünker T, Hildebrand C, Przyklenk A, Hollmann W, Strüder HK. Effects of Physical Exercise on Individual Resting State EEG Alpha Peak Frequency. Neural Plast. 2015; 2015:1–6.
57. Knight EL, Christian CB, Morales PJ, Harbaugh WT, Mayr U, Mehta PH. Exogenous testosterone enhances cortisol and affective responses to social-evaluative stress in dominant men. Psychoneuroendocrinology. 2017; 85:151–157.
58. Miličić D, Brajković L, Maček JL, Andrić A, Ardalić Ž, Buratović T, Marčinko D. Type a personality, stress, anxiety and health locus of control in patients with acute myocardial infarction. Psychiatr Danub. 2016; 28(4):409–414.

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Effects of plyometric-based structured game active breaks on fundamental movement skills, muscular fitness, self-perception, and actual behaviour in primary school students

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ABSTRACT: This study examined the effects of plyometric-based structured game active breaks on fundamental movement skills (FMS), muscular fitness, student self-perception, and teacher's rating of actual behaviour in Grade 3 and 4 students. Primary school children aged 8–10 years old, from four classes, were cluster-randomly assigned to an intervention group (IG) ($n = 54$) or a control group (CG) ($n = 48$). The IG participated in structured plyometric-based game active breaks for 7–10 minutes daily, for six consecutive weeks. The CG resumed their regular daily school routine. FMS were assessed with the Canadian Agility Movement Skills Assessment test, and muscular fitness with the standing long jump (SLJ), countermovement jump (CMJ), and seated medicine ball chest throw tests. The Self-Perception Profile for Children and the Teacher's Rating Scale of Child's Actual Behaviour assessed student self-perception and teacher's perception of student actual behaviour, respectively. 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, $\eta p^2 = 0.05$). No difference ($p > 0.05$) was found in other variables. Integrating plyometric-based structured game active breaks into primary school settings evidenced improvement in FMS, muscular fitness, student self-perception, and teacher's rating of student actual behaviour.

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INTRODUCTION

Schools are continually seeking strategies to improve student learning and enhance wellbeing. A contemporary strategy gaining attention is short physical activity breaks integrated into the lesson, primarily aiming to improve cognition, executive functions, and learning outcomes [1]. Typically, physical activity breaks, or active breaks, consist of 5–10 minutes of physical activity and are integrated into classroom time after 40–60 minutes of learning [1]. Previous studies have demonstrated that embedding an active break into the school day can also increase children's cognitive performance [2], and physical activity levels [1]. However, there has been little examination of the effect on student fundamental movement skills (FMS), muscular fitness, student self-perception (i.e., global self-worth, scholastic, athletic and social competence) and student actual behaviour [1].

Over the last 10 years, schools implementing active breaks have tended to use the Finnish model, characterised by unstructured physical activity or play, contributing to healthier children and improved classroom learning [3]. Unstructured breaks have been suggested to result in positive changes in the critical region of the brain's executive control centre, the prefrontal cortex, which is responsible for problem-solving, decision-making, planning, and regulating emotions, and may result in improved student behaviour and engagement [4]. However, as noted in the meta-analysis by Infantes-Paniagua et al. [1], one challenging aspect of unstructured activity breaks is ensuring that all students are active and moving sufficiently to benefit from the intended outcomes.

As knowledge regarding child development and learning has grown, the need to shape more effective educational practices within the

set learning time has also increased. By successfully integrating insights from sports science, neurosciences, psychology, sociology, and learning sciences, more effective holistic approaches are likely to emerge in education. Therefore, a deeply integrated approach to classroom practices (i.e., active breaks) with multifaced benefits needs further examination. For example, there appears to be no studies examining active breaks that have been designed with the additional purpose of improving students' psychomotor domain of learning. This area warrants further investigation, considering that executive function seems especially sensitive to coordinative complex movements [5]. Moreover, FMS proficiency is associated with scholastic competence, social acceptance, global self-worth and athletic competence [6, 7]. This association is significant since positive self-perceived competence is associated with resilience, enhanced motivation, and reduced anxiety [8]. Therefore, research is needed to examine a multi-purpose approach to active breaks that may result in a broader range of benefits for students, potentially improving FMS and related aspects of student perceived competence, hence a more effective use of active break time within the school setting.

Plyometric exercises are broadly used in sports training to improve physical performance by enhancing the use of the stretch-shortening cycle, in which a lengthening movement (eccentric) is quickly followed by a shortening movement (concentric) and to optimise related neuro-mechanical mechanisms [9]. In primary-aged students, it has been demonstrated that short-term plyometric training regimens can improve motor coordination, FMS, and muscular fitness [10, 11]. Embedding plyometric exercises into structured games during active breaks could be an innovative approach that may lead to multifaceted benefits for students.

Using a structured game approach to active breaks rather than unstructured physical activity, could also provide students with an improvement in self-perception by promoting both physical and psychological advantages [12, 13]. Due to the social nature of structured collaborative games, participation provides opportunities for social interaction and companionship, and may have more significant benefits for social and mental wellbeing than unstructured play [12, 13]. Therefore, through interaction with peers during structured plyometric-based active breaks, children may be more likely to experience physical, psychological, social benefits, and improved classroom behaviour conduct outcomes [1].

Therefore, the aim of this study was to determine the effects of plyometric-based structured game active breaks on FMS, muscular fitness, student self-perception, and actual behaviour in Grade 3 and 4 students. It was hypothesised that plyometric-based structured game active breaks would improve FMS competence, muscular fitness parameters, student self-perception, and student's actual behaviour.

MATERIALS AND METHODS

Participants

The sample comprised of 102 primary school children, 55 females and 47 males, aged 8 to 10 years old, from two Grade 3 and two Grade 4 classes at a primary school, who volunteered for this study. Inclusion criteria were: students aged 8 to 10 years, in Grades 3 or 4 and without musculoskeletal injuries. Using G*Power software (Heinrich-Heine-Universität, Düsseldorf, Germany) with P value and power fixed at 0.05 and 90%, respectively, with medium effect size, a sample size of 44 students per group was required to detect any interaction effect. After the study protocol received approval from the Ethics Committee of the University of Notre Dame Australia, and prior to familiarisation sessions and any data collection sessions, all teachers, students and their parents or guardians received a written explanation of all study procedures, were offered the opportunity to attend information sessions, and allowed to ask questions of the research team. Subsequently, teachers, students and their parents agreed to participate in the study with informed signed consent. Parents/guardians with their child completed a physical activity readiness questionnaire to ensure they were physically healthy to participate in this study. The parents/guardians also completed the Children's Leisure Activities Study Survey (Class) parental proxy questionnaire according to their child's physical activities during a typical week [14] (Table 1). All participants in the study were informed that they could withdraw from the study at any time without penalty. All study procedures conformed to the 2013 Declaration of Helsinki guidelines.

TABLE 1. Characteristics of the two groups

Characteristics	IG (n = 54)	CG (n = 48)	*p-value*
Gender (girls/ boys)	55.6/ 44.4	52.1/ 47.9	0.73
Age (years)	8.96 ± 0.69	9.13 ± 0.64	0.23
Height (cm)	138.26 ± 6.69	138.15 ± 6.04	0.93
Weight (kg)	33.94 ± 6.50	34.41 ± 8.62	0.76
BMI (kg/m^2)	17.67 ± 2.62	17.89 ± 3.71	0.73
Physical activity level (h/wk)	10.90 ± 4.93	11.42 ± 6.37	0.16

Notes: Data are reported as mean ± SD or percentage, and level of significance (p-value) of the comparison between groups. P-values were calculated using an unpaired t-test. Abbreviations: IG: intervention group; CG: control group; BMI: body mass index; h/wk: hours per week. *: Statistically significant with $p < 0.05$ comparison between groups.

Experimental design

A cluster-randomised controlled trial was conducted using four natural classes in a primary school. The four classes were assigned randomly to the following study groups: intervention group (IG) (n = 54) or control group (CG) (n = 48). The participants' general characteristics are outlined in Table 1. The exclusion criteria for data were: not attending 85% of the plyometric-based structured game breaks, or missing more than three game breaks consecutively.

Procedures

All procedures were performed during the final school term for the year (October, November, and December 2022). Prior to the commencement of the research study, students were familiarised on the assessment protocols over the duration of a school day. At the end of the familiarisation sessions, all participants were instructed to refrain from strenuous physical activity or sport the day before testing. Pre- and post-test measurements were conducted at the same time of day for each class to control for potential diurnal variation in test results by completing post-tests within one hour of the pre-tests. The students completed the tests in the same student sequence and test order on the first and second day in the pre- and post-testing weeks using identical equipment, positioning, and technique. To eliminate the effects of the environment and weather conditions (e.g., direct sunlight, wind, temperature) on performance, the pre and post-tests on the first day of testing were performed in the school hall and then on the second day in an undercover shielded area. The research assistants were trained and familiar with the tests they administered; they were also blinded to the groups to which students belonged. The physical assessment tests were conducted after a general warm-up of jogging, running, lower-body callisthenics, and whole-body dynamic stretches. For each test described in the following sections, all participants had a brief familiarisation warm-up before executing the tests.

Anthropometric measurements

Anthropometric measurements were obtained using a mobile stadiometer (SECA 217, Hamburg, Germany) and an electronic scale (SECA 803, Hamburg, Germany) during pre- and post-test sessions following the International Society for the Advancement of Kinanthropometry (ISAK) guidelines. The body height (± 0.1 cm) was measured with the participant standing barefoot using a stadiometer. Body mass (± 0.1 kg) was measured using the electronic scale, with the participants standing barefoot, with feet together. Body mass index (BMI) was calculated as weight [kg]/ (height [m])^2.

Canadian agility and movement skill assessment

The Canadian Agility Movement Skill Assessment, a valid and reliable measure to evaluate children's FMS competence [15], was implemented following the protocol described by Longmuir et al. [16]. The test requires the students to complete a prescribed movement course involving a sequence of movement skills: two-foot jumping, sliding, catching, throwing at a target, skipping, one-foot hopping, and kicking a soccer ball through cones. A skill score based on a criterion-references assessment is determined, and the overall time to complete the movement course is recorded. The overall raw score was quantified as a sum of the skill and time criteria scores. The students were given two practice trials followed by two timed and scored attempts. All attempts were recorded and the best score was used for analysis.

Standing long jump test

The standing long jump test (SLJ) is a reliable and valid measure [17], and was used to assess maximum horizontal jump distance according to the previously described protocol [17]. The jump distance was measured using two parallel 10-metre fibreglass metric tapes 40 centimetres apart, from the marked starting line to where the heel contacted the ground on landing. The test was performed three times after an initial trial jump, separated by one-minute rest. All jumps were recorded and the furthest jump result was used for analysis.

Countermovement jump

A countermovement jump (CMJ) was used to assess lower-body muscular power: as the test is reliable and valid [17]. The student's maximum CMJ height was measured using a Vertec (Yardstick, Swift Performance Equipment, Australia) and according to the previously described protocol [18]. Students had four attempts, the first being a practice and then the subsequent three attempts recorded. The CMJ height was calculated by subtracting the standing reach height from the jump height, and then the best maximum jump height was used for subsequent analysis.

Seated medicine ball chest throw

The seated medicine ball chest throw test, a reliable and valid measure of upper body muscular power in children [19], was used to assess upper body muscular power according to the described protocol of Faigenbaum et al. [20]. The test was performed using a 20 cm diameter 1 kg medicine ball powdered with magnesium carbonate, two 10-metre fibreglass metric tapes one metre apart, affixed with clear tape to a black rubber floor mat. The test was performed three times after an initial trial chest throw, separated by one-minute rest, with all test throws recorded and the furthest throw distance used for analysis.

Self-perception profile for children questionnaire

The Self-Perception Profile for Children (SPPC) questionnaire was administered to students to evaluate changes in student perceived competence [21]. The SPPC is a validated and reliable psychometric measure in children [22]. The questionnaire consists of six questions per the following subscales: athletic competence, social competence, scholastic competence, and global self-worth. Each question is answered on a four-point scale, with higher scores being a more positive self-perception. The questionnaire was administered to students in the classroom environment by a trained research assistant,

with the teacher present, according to the protocol described by Harter [21].

Teacher's rating scale of child's actual behaviour questionnaire

The Teacher's Rating Scale of Child's Actual Behaviour questionnaire [21], was used to assess changes in each student's domain of behaviour conduct and athletic, social and scholastic competence based on teacher observations. The questionnaire has good internal reliability, internal consistency, test–retest reliability and construct and convergent validity [22]. The questionnaire contained twelve items scored on a four-point scale. Teachers were directed to complete the questionnaire for each student according to the protocol of Harter [21] and rate the student's actual behaviour in each domain.

Intervention program

The six-week intervention consisted of plyometric-based structured game active breaks in the middle of a two-hour learning block in the class's daily routine (see Table 2). Based on previous research, the plyometric-based games were specifically designed for primary school children [23, 24]. The intervention was performed each school day on school premises for seven to ten minutes. At the start of each game break, the classroom teacher, who had received training in delivering the games, demonstrated the proper game technique and reviewed procedures. The intervention included ten games that utilised plyometric exercises (jumping, skipping, hopping, medicine ball throw downs, rapid passing) using body weight and medicine balls (2 kg), with students playing the games in small groups of five to six. The six-week program was divided into two phases, each consisting of three weeks, with the second phase being of higher intensity by using more complex movements such as single-leg hops instead of two-legged jumps to maximise adaptations [25]. A fidelity checklist and logbook were used each day to monitor implementation for adherence and quality. The fidelity checklist and logbook included key aspects of the intervention, such as teacher delivery of the scheduled game, student participation, start and finish times and any occurrence of injuries. The lead researcher and an independent observer directly observed 96% of the implemented plyometric-based structured game active breaks for treatment integrity, demonstrating 100% adherence.

TABLE 2. Overview of the plyometric-based structured games

Name	Overview	Sets
1. Kangaroo Ninja Warrior Relay	• Jump 10 m with MB. • Five double-handed MB throwdowns. • Skip 10 m to starting position with MB.	4
2. Skip and Pick Up Bean Bags	• Skip 10 m, pick up the bean bag, and turn around. • Skip to starting position.	5
3. Throw Down and Travel Around the Globe	• Three double-handed throwdowns of the MB. • Then passed rapidly.	6
4. Bean Bag Pickup	• Four two-legged rapid jumps in and out of hoops, pick up one bean bag and then turn around. • Four two-legged rapid jumps back to starting position.	5
5. Basketball Hot Seat	• In a circle formation, catch the basketball and rapidly pass it back to the person in the circle's centre. Each student has a turn in the center.	4
6. Ultimate Ninja Warrior Relay	• One-legged hopping along a 10 m distance with MB. • Five single-handed MB throwdowns. • Skip 10 m back to starting position with MB.	4
7. Sticky Knees Relay	• Jump with a latex ball between the knees for 4 m, then turn around. • Jump back with the latex ball between the knees back to starting position.	4
8. Single Hand Throw Down and Travel Around the Globe	• With the group in a circle formation, perform three single-handed throwdowns with MB. • Then rapidly pass to the next student.	6
9. Single Leg Bean Bag Pickup	• Four single leg hops in and out of hoops, pick up one bean bag and then turn around. • Four single leg hops back to starting position.	5
10. Basketball Hopping Hot Seat	• In a circle formation, hop on the spot, catch the basketball, and rapidly pass back to the person in the circle's center. Each student has a turn in the center. • Continual hopping on either leg.	4

Note: The shaded area denotes the second phase of the program with more complex movements. All jumps were performed horizontally. MB: 2-kilogram medicine ball.

TABLE 3. Baseline data and differences between groups

Characteristics	IG (n = 54)	CG (n = 48)	*p-value*
Canadian agility movement skill assessment (score)	19.22 ± 3.90	19.00 ± 4.15	0.39
CMJ (cm)	27.39 ± 5.49	27.94 ± 5.72	0.31
Seated medicine ball chest throw (m)	2.77 ± 0.50	2.73 ± 0.46	0.33
SLJ (m)	1.35 ± 0.20	1.34 ± 0.24	0.71
Self-perception of athletic competence (score)	18.41 ± 3.96	18.63 ± 4.12	0.39
Self-perception of global self-worth (score)	19.28 ± 3.39	19.23 ± 3.54	0.47
Self-perception of scholastic competence (score)	17.19 ± 3.34	16.42 ± 4.56	0.17
Self-perception of social competence (score)	16.98 ± 3.60	17.10 ± 4.28	0.44
Teacher rating of athletic competence (score)	9.28 ± 2.26	8.71 ± 2.68	0.19
Teacher rating of behavioural conduct (score)	11.04 ± 2.02	10.83 ± 2.36	0.68
Teacher rating of scholastic competence (score)	9.13 ± 2.72	8.98 ± 3.33	0.23
Teacher rating of social competence (score)	8.02 ± 2.41	9.15 ± 2.96	0.14

Note: Data are reported as mean ± SD, and level of significance (p-value) of the comparison between groups. P-values were calculated using an unpaired t-test. Abbreviations: IG: intervention group; CG: control group; CMJ: countermovement jump; SLJ: standing long jump. *: Statistically significant with $p < 0.05$ comparison between groups.

TABLE 4. Changes in selected physical indicators from pre- to post-test

Group	Pre-test	Post-test	Δ%	ANOVA (group × time)	Bonferroni post-hoc (time) p-values (ES: *d*)
Fundamental Movement Skills					
Canadian agility movement skill assessment (score)					
IG	19.22 ± 3.90	21.74* ± 3.59	**13.11**	**$F_{(1,100)} = 14.09$, $p < 0.001$, $\eta p^2 = 0.12$**	**< 0.001** (0.81)
CG	19.00 ± 4.15	19.44 ± 3.76	1.02		0.28 (0.18)
Muscular Fitness					
CMJ (cm)					
IG	27.39 ± 5.49	29.33 ± 5.71	**7.08**	$F_{(1,100)} = 1.90$, $p = 0.17$, $\eta p^2 = 0.02$	**< 0.001** (0.35)
CG	27.94 ± 5.72	28.89 ± 6.95	3.40		0.07 (0.16)
Seated medicine ball chest throw (m)					
IG	2.77 ± 0.50	2.90* ± 0.52	**4.69**	**$F_{(1,100)} = 9.70$, $p = 0.002$, $\eta p^2 = 0.08$**	**< 0.001** (0.25)
CG	2.73 ± 0.46	2.72 ± 0.47	-1.00		0.90 (0.008)
SLJ (m)					
IG	1.35 ± 0.20	1.44* ± 0.21	**6.67**	**$F_{(1,100)} = 19.58$, $p < 0.001$, $\eta p^2 = 0.16$**	**< 0.001**(0.41)
CG	1.34 ± 0.24	1.35 ± 0.26	0.07		0.35 (0.04)

Note: Values are presented as mean ± SD and percentage of variation from baseline to follow-up (Δ%); F values, level of significance (*p*-value), and effect sizes as eta partial squared (ηp^2) following two-way repeated measures ANOVA; post-hoc multiple comparison analyses with Bonferroni adjustment; Cohen's *d* (*d*) in brackets of the within groups comparison are also displayed. *: Statistically significant difference between intervention and control group in post-intervention values. Numbers in bold represent statistically significant differences ($p < 0.05$). IG: intervention group (plyometric-based structured game active break group); CG: control group; CMJ: countermovement jump; SLJ: standing long jump.

TABLE 5. Change in self-perception and child's actual behaviour from pre- to post-test

Group	Pre-test	Post-test	Δ%	ANOVA (group × time)	Bonferroni post-hoc (time) p-values (ES: *d*)
Student Self-Perception					
Athletic competence (score)					
IG	18.41 ± 3.96	18.85 ± 3.77	2.39	$F_{(1,100)} = 1.26$,	0.34 (0.12)
CG	18.63 ± 4.12	18.31 ± 4.46	1.02	$p = 0.264$, $\eta p^2 = 0.01$	0.53 (0.07)
Global self-worth (score)					
IG	19.28 ± 3.39	20.21 ± 3.24	**4.82**	$F_{(1,100)} = 0.06$,	**0.049** (0.28)
CG	19.23 ± 3.54	20.25 ± 3.60	**5.30**	$p = 0.81$, $\eta p^2 = 0.001$	**0.03** (0.29)
Scholastic competence (score)					
IG	17.19 ± 3.34	18.44* ± 3.41	**7.27**	**$F_{(1,100)} = 11.30$,**	**< 0.001** (0.37)
CG	16.42 ± 4.56	16.06 ± 4.46	-2.24	**$p < 0.001$, $\eta p^2 = 0.10$**	0.31 (0.08)
Social competence (score)					
IG	16.98 ± 3.60	18.56* ± 3.04	**9.31**	**$F_{(1,100)} = 11.30$,**	**< 0.001** (0.47)
CG	17.10 ± 4.28	17.04 ± 4.31	-1.00	**$p < 0.001$, $\eta p^2 = 0.10$**	0.86 (0.015)
Teacher's Rating Scale of Child's Actual Behaviour					
Athletic competence (score)					
IG	9.28 ± 2.26	10.10 ± 1.99	8.84	$F_{(1,100)} = 1.66$,	0.20 (0.38)
CG	8.71 ± 2.68	9.15 ± 2.63	5.10	$p = 0.201$, $\eta p^2 = 0.016$	0.21 (0.17)
Behavioural conduct (score)					
IG	11.04 ± 2.02	11.26 ± 1.63	1.99	$F_{(1,100)} = 0.003$,	0.18 (0.11)
CG	10.83 ± 2.36	11.04 ± 1.97	1.93	$p = 0.954$, $\eta p^2 = 0.00$	0.24 (0.09)
Scholastic competence (score)					
IG	9.13 ± 2.72	9.48 ± 2.51	3.83	$F_{(1,100)} = 1.22$,	0.07 (0.12)
CG	8.98 ± 3.33	9.02 ± 3.13	0.04	$p = 0.272$, $\eta p^2 = 0.01$	0.84 (0.07)
Social competence (score)					
IG	8.02 ± 2.41	8.72* ± 2.43	**8.73**	**$F_{(1,100)} = 4.715$,**	**< 0.001** (0.29)
CG	9.15 ± 2.96	9.27 ± 2.91	1.31	**$p < 0.05$, $\eta p^2 = 0.05$**	0.52 (0.04)

Note: Values are presented as mean ± SD and percentage of variation from baseline to follow-up (Δ%); F values, level of significance (*p*-value), and effect sizes as eta partial squared (ηp^2) following two-way repeated measures ANOVA; post-hoc multiple comparison analyses with Bonferroni adjustment and Cohen's *d* (*d*) in brackets of the within groups comparison are also displayed. *: Statistically significant difference between intervention and control group in post-intervention values. Numbers in bold represent statistically significant differences ($p < 0.05$). IG: intervention group (plyometric-based structured game active break group); CG: control group.

Statistical Analysis

All statistical analyses were performed using the IBM SPSS Statistics for Windows software (Version 28.1; IBM Corp., Armonk, NY). Descriptive data were calculated for all variables. The normality of variables was tested using the Shapiro-Wilk test procedure. Descriptive variables from both groups and baseline data were compared using an unpaired t-test. The reliability of each test involving trials was assessed by calculating the intra-class correlation coefficient (ICC) [26]. A two-way ANOVA with repeated measures was used to determine the effects of the group (IG and CG) and time (baseline and post-intervention) as the between-and within-subject factors in the dependent variables. Effect size (ES) was evaluated with eta partial squared (ηp^2). According to Hopkins guidelines, the effect size (eta-squared; η^2) was established as follows: 0.01 – small, 0.06 – medium, and 0.14 – large [27]. To control for Type 1 errors, a Bonferroni post-hoc test was conducted to identify where significant differences occurred and to determine the within-group changes. Within effect was assessed using Cohen's *d* 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) [27].

RESULTS

There were no significant between-group differences ($p > 0.05$) in the descriptive variables and baseline data (see Tables 1 and 3). The ICC of all physical assessment tests ranged between 0.813 and 0.983 ($p < 0.001$). For six tests, statistically significant improvements ($p < 0.05$) were observed in the intervention group compared to the control group. The pre- and post-test outcomes for both groups and the statistical analysis results are displayed in Tables 4 and 5.

DISCUSSION

This study aimed to evaluate the changes in FMS competence, muscular fitness, self-perceived competence, and teacher rating of student actual behaviour resulting from the effects of engaging in a daily active break consisting of plyometric-based structured games nested in the middle of a 2-hour block of curriculum time in primary school children. The results indicate that the IG group significantly improved on the Canadian Agility Movement Skill Assessment, SLJ, seated medicine ball chest throw, self-perceived social and scholastic competence, and teacher rating of social competence compared to the CG that continued with the regular daily school routine. There was no significant difference between the groups for CMJ, self-perceived athletic competence and global self-worth, teacher rating of student athletic competence; student behaviour conduct; and scholastic competence. No injuries occurred throughout the study, and observations suggest that plyometric-based structured games led by general classroom teachers are a safe approach for Grades 3 and 4 students. As such, the results of the current study are novel and provide evidence of a multitude of benefits for students performing plyometric-based structured game active breaks, in contrast to the limited cognitive outcomes currently advocated for active breaks.

Student FMS proficiency is an important prelude to children's engagement in physical activity and sports [28]. In the current study, FMS was improved by 13.1% (medium ES) in the IG after six weeks of structured plyometric-based breaks. The results of the current study are consistent with those of Sortwell et al. [11], which showed that plyometric circuit of exercises within the primary school setting positively affects FMS competence (12.91%; ES = 0.60, large) in children aged 7–8 years. The current results could be expected, given that the structured games included plyometric exercises that have been shown to enhance FMS in primary-aged students [10, 23], and improve motor performance in young athletes [9]. Furthermore, the plyometric horizontal jumps used in the current study have also been suggested to be an efficient method for enhancing multi-vector performance for sport, hence the potential transference to the improved performance in the Canadian Agility Movement Skills Assessment test [29]. Even though in the current study the plyometric-based structured games were performed for only 7 to 10 minutes, the weekly frequency of the games was high (i.e., daily) and produced similar FMS enhancements to other studies that have engaged young school children in plyometric training [10, 23]. The improvement in FMS is most likely due to muscle adaptation driven by the plyometric exercises, resulting in possible neural and structural enhancements [9]. Given that FMS competence is generally undeveloped in children [28], embedding plyometrics-based structured games into school active breaks appears to be an efficient and effective method to improve FMS in children.

Our results indicate that the plyometric-based structured game active break intervention effectively improved muscular fitness, as the SLJ significantly increased by 6.7% (large ES), and the seated medicine ball chest throw increased significantly by 4.7% (medium ES). These improvements align with the results of previous studies involving primary school-aged children [10, 23, 24]. Even though the IG improved CMJ by 7.1%, this did not reach a significant difference between the groups. This is most likely due to the affinity between the type of jumps (i.e., horizontal) used in the games and the SLJ test [29]. Improvements in the SLJ and seated medicine ball chest throw may also be more related to biomechanical parameters such as maximal isometric voluntary force, changes in the stiffness of various elastic components of the muscle-tendon complex, musculoskeletal contractile properties, and rate of force development in the muscles in the children [30]. These findings have significant practical relevance for primary school students, since muscular fitness is associated with health and skills-related fitness components that support daily living, participation in physical activities and sports, and improvements in adiposity and cardiovascular disease risk factors [31].

The current study lends credence to previous research that reports on interventions emphasising the development of motor skills (i.e., FMS) and being associated with a boost in perceived scholastic competence [32]. Evidence suggests that structured exercise within the school setting can improve dimensions of cognitive function, including cognitive planning and reaction time in students [33]. Moreover, an extensive body of research indicates that fitness exercise can improve the scholastic performance of children via molecular, cellular, and behavioural brain mechanisms [34]. Therefore, it is plausible that students' perceived scholastic competence might have improved following the enhancement of FMS competence, resulting from perceptual-motor behaviours facilitating readiness to learn, thus, scholastic performance [35]. Furthermore, research in preschool children has found a strong relationship between complex fitness components such as hopping on one leg (as used in the current study) and cognitive attention [32], reinforcing the benefit of using plyometrics within active breaks. Despite the student improvement in self-perception in the scholastic competence domain, only minimal non-significant improvements (3.8%) in teacher perception of students scholastically were found.

Significantly improved student self-perceived social competence and teacher-rating of student social competence indicates the potential for plyometric-based structured game active breaks to contribute to enhanced student social competence and interpersonal skills. These findings are similar to the work by Kao [36], which engaged students in activities that enhance movement skills, and

psychomotor development through structured sports and games that can promote teamwork, sharing, which led to enhanced interpersonal relationships with peers. Furthermore, using a structured game approach to active breaks helps negate students experiencing negative self-perception as a result of social exclusion, which can occur in unstructured play and physical activity [37]. Therefore, the delivery of plyometric-based structured game active breaks rather than only free-play breaks may be a more effective strategy to facilitate inclusion and build student self-confidence [38]. Previous literature also supports this finding emphasising the benefits of using fitness activities and movement experiences in schools that are structured [39]. The outcomes of the current study corroborate the notion that forming student relationships through plyometric-based structured game active breaks may effectively improve social competence.

The intervention induced no significant differences in student athletic competence, global self-worth and teacher perception of student athletic competence and behaviour conduct. The absence of a between-group effect for measures of athletic competence in the current study is in accordance with the results of longitudinal studies, indicating that perceived athletic competence in children is relatively constant over time [40]. The minimal change in the general classroom teacher's rating of student athletic competence may also be due to the teacher being absent in the physical education lessons to view the translation into sports, since a specialist physical education teacher leads the lessons. While research indicates that high levels of athletic competence are positively associated with greater global self-worth [41], these relationships can be mediated to a substantial extent by BMI and cardiovascular fitness [42]. Similar to studies that have used classroom-based physical activity, participation did not result in a chronic effect on student behaviour conduct [43, 44]. Future studies should investigate the relationship between structured active breaks and the acute effect on student behaviour conduct and explore the effects of changing the current intervention parameters, such as increasing the duration from six weeks and altering the movement intensity, and assessing the effect on athletic competence, global self-worth, and behaviour conduct.

In the current study, we acknowledge some potential limitations. Firstly, we involved only students in Grades 3 and 4. Future studies should confirm its replicability in younger and older students. Furthermore, the research study was short-term, and the results do not provide insight into long-term changes or adaptations.

CONCLUSIONS

This is the first study that has investigated the effects of using plyometric-based structured games during primary school active breaks on FMS, muscular fitness, student self-perception and actual behaviour. The results of this study demonstrate the efficacy of using plyometric-based structured games during daily active breaks in the primary school setting and suggest that within six weeks, positive changes are produced in FMS, measures of muscular fitness (SLJ and seated medicine ball chest throw) and student social and scholastic competence. Overall, this study illuminates diverse student benefits derived from plyometric-based structured activities during primary school active breaks, surpassing the commonly emphasised academic-related cognitive outcomes and contributing to existing knowledge of active breaks by providing a new innovative approach that teachers can deliver. The evidence presented in this study may also help school practitioners design active break activities that help the student reset their focus for continual learning of the set curriculum and achieve psychomotor and psychological benefits that support the student's holistic development.

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Conflict of interest declaration

The authors declared no conflict of interest regarding the publication of this manuscript.

REFERENCES

1. Infantes-Paniagua Á, Silva AF, Ramirez-Campillo R, Sarmento H, González-Fernández FT, González-Víllora S, Clemente FM. Active School Breaks and Students' Attention: A Systematic Review with Meta-Analysis. Brain Sci. 2021; 11(6):675.
2. Peiris D, Duan Y, Vandelanotte C, Liang W, Yang M, Baker JS. Effects of In-Classroom Physical Activity Breaks on Children's Academic Performance, Cognition, Health Behaviours and Health Outcomes: A Systematic Review and Meta-Analysis of Randomised Controlled Trials. Int J Environ Res Public Health. 2022; 19(15):9479.
3. Rhea DJ, Rivchun AP. The LiiNK Project®: Effects of Multiple Recesses and Character Curriculum on Classroom Behaviors and Listening Skills in Grades K–2 Children. Front Educ. 2018; 3:9.
4. Graham JD, Bremer E, Fenesi B, Cairney J. Examining the Acute Effects of Classroom-Based Physical Activity Breaks on Executive Functioning in 11- to 14-Year-Old Children: Single and Additive Moderation Effects of Physical Fitness. Front Pediatr. 2021; 9:688251.
5. Fathirezaie Z, Matos S, Khodadadeh E, Clemente FM, Badicu G, Silva AF, Zamani Sani SH, Nahravani S. The Relationship between Executive Functions and Gross Motor Skills in Rural Children Aged 8–10 Years. Healthcare (Basel). 2022; 10(4):616.
6. Barnett LM, Morgan PJ, van Beurden E, Beard JR. Perceived sports competence mediates the relationship between childhood motor skill proficiency and adolescent physical activity and fitness: a longitudinal assessment. Int J Behav Nutr Phys Act. 2008; 5(1):40.
7. Piek JP, Baynam GB, Barrett NC. The relationship between fine and gross motor ability, self-perceptions and self-worth in children and adolescents. Hum Mov Sci. 2006; 25(1):65–75.
8. Craven RG, Marsh HW. The centrality of the self-concept construct for psychological wellbeing and unlocking human potential: Implications for child and educational psychologists. Educ Child Psych. 2008; 25:104–18.

9. Radnor JM, Oliver JL, Waugh CM, Myer GD, Moore IS, Lloyd RS. The Influence of Growth and Maturation on Stretch-Shortening Cycle Function in Youth. Sports Medicine. 2018; 48(1):57–71.
10. Nobre GG, de Almeida MB, Nobre IG, Dos Santos FK, Brinco RA, Arruda-Lima TR, de-Vasconcelos KL, de-Lima JG, Borba-Neto ME, Damasceno-Rodrigues EM, Santos-Silva SM, Leandro CG, Moura-Dos-Santos MA. Twelve-weeks of plyometric training improves motor performance of 7–10 year old overweight/obese boys: a randomized controlled intervention. J Strength Cond Res. 2016; 31(8):2091–2099.
11. Sortwell A, Newton M, Marinho D, Ferraz R, Perlman D. The Effects of an Eight Week Plyometric-based Program on Motor Performance Skills and Muscular Power in 7–8-Year-Old Primary School Students. Intl J Kinesiol Sports Sci. 2021; 9:1–12.
12. Street G, James R, Cutt H. The relationship between organised physical recreation and mental health. Health Promot J Austr. 2007; 18(3):236–9.
13. Eime RM, Harvey JT, Brown WJ, Payne WR. Does sports club participation contribute to health-related quality of life. Med Sci Sports Exerc. 2010; 42(5):1022–8.
14. Telford A, Salmon J, Jolley D, Crawford D. Reliability and Validity of Physical Activity Questionnaires for Children: The Children's Leisure Activities Study Survey (CLASS). Pediatr Exerc Sci. 2004; 16(1):64–78.
15. Menescardi C, Villarrasa-Sapiña I, Lander N, Estevan I. Canadian Agility Movement Skill Assessment (CAMSA) in a Spanish Context: Evidences of Reliability and Validity. Meas Phys Educ Exerc Sci. 2022; 26(3):245–255.
16. Longmuir PE, Boyer C, Lloyd M, Borghese MM, Knight E, Saunders TJ, Boiarskaia E, Zhu W, Tremblay MS. Canadian Agility and Movement Skill Assessment (CAMSA): Validity, objectivity, and reliability evidence for children 8–12 years of age. J Sport Health Sci. 2017; 6(2):231–40.
17. Fernandez-Santos JR, Ruiz JR, Cohen DD, Gonzalez-Montesinos JL, Castro-Piñero J. Reliability and Validity of Tests to Assess Lower-Body Muscular Power in Children. J Strength Cond Res. 2015; 29(8):2277–85.
18. Kurihara T, Terada M, Numasawa S, Kusagawa Y, Maeo S, Kanehisa H, Isaka T. Effects of age and sex on association between toe muscular strength and vertical jump performance in adolescent populations. PLoS One. 2021; 16(12):e0262100.
19. Davis KL, Kang M, Boswell BB, DuBose KD, Altman SR, Binkley HM. Validity and reliability of the medicine ball throw for kindergarten children. J Strength Cond Res. 2008; 22(6):1958–63.
20. Faigenbaum AD, McFarland JE, Keiper FB, Tevlin W, Ratamess NA, Kang J, Hoffman JR. Effects of a short-term plyometric and resistance training program on fitness performance in boys age 12 to 15 years. J Sports Sci Med. 2007; 6(4):519–25.
21. Harter S. Self-perception profile for adolescents: Manual and questionnaires. Denver, CO: Univeristy of Denver, Department of Psychology. 2012:31–45.
22. Muris P, Meesters C, Fijen P. The self-perception profile for children: Further evidence for its factor structure, reliability, and validity. Pers Individ Differ. 2003; 35(8):1791–802.
23. Trajković N, Madić D, Andrašić S, Milanović Z, Radanović D. Effects of Medicine Ball Training on Physical Fitness in Primary School Children. FU Phys Ed Sport. 2017; 15:185–93.
24. Faigenbaum A, Farrell A, Radler T, Zbojovsky D, Chu D, Ratamess N, Kang J, Hoffman J. A Novel Program of Short Bouts of Moderate and High Intensity Exercise Improves Physical Fitness in Elementary School Children. J Teach Phys Educ. 2009; 66:37–44.
25. Sankey S, Jones P, Bampouras T. Effects of two plyometric training programmes of different intensity on vertical jump performance in High School athletes. Serb. J. Sports Sci. 2008; 2:123–30.
26. Liljequist D, Elfving B, Skavberg Roaldsen K. Intraclass correlation – A discussion and demonstration of basic features. PLoS One. 2019; 14(7):e0219854.
27. 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.
28. Barnett LM, Stodden D, Cohen KE, Smith JJ, Lubans DR, Lenoir M, Iivonen S, Miller A, Laukkanen A, Dudley D, Lander N, Brown H, Morgan P. Fundamental Movement Skills: An Important Focus. J Teach Phys Educ. 2016; 35(3):219–25.
29. Moran J, Ramirez-Campillo R, Liew B, Chaabene H, Behm DG, García-Hermoso A, Izquierdo M, Granacher U. Effects of Vertically and Horizontally Orientated Plyometric Training on Physical Performance: A Meta-analytical Comparison. Sports Med. 2021; 51(1):65–79.
30. Ramírez-delaCruz M, Bravo-Sánchez A, Esteban-García P, Jiménez F, Abián-Vicén J. Effects of Plyometric Training on Lower Body Muscle Architecture, Tendon Structure, Stiffness and Physical Performance: A Systematic Review and Meta-analysis. Sports Med Open. 2022; 8(1):40.
31. Smith JJ, Eather N, Morgan PJ, Plotnikoff RC, Faigenbaum AD, Lubans DR. The health benefits of muscular fitness for children and adolescents: a systematic review and meta-analysis. Sports Med. 2014; 44(9):1209–23.
32. Wick K, Kriemler S, Granacher U. Associations between measures of physical fitness and cognitive performance in preschool children. BMC Sports Sci Med Rehabil. 2022; 14(1):80.
33. Subramanian SK, Sharma VK, Arunachalam V, Radhakrishnan K, Ramamurthy S. Effect of Structured and Unstructured Physical Activity Training on Cognitive Functions in Adolescents – A Randomized Control Trial. J Clin Diagn Res. 2015; 9(11):Cc04–9.
34. Sember V, Jurak G, Kovač M, Morrison SA, Starc G. Children's Physical Activity, Academic Performance, and Cognitive Functioning: A Systematic Review and Meta-Analysis. Front Public Health. 2020; 8:307.
35. Son S-H, Meisels SJ. The Relationship of Young Children's Motor Skills to Later Reading and Math Achievement. Merrill-Palmer Q. 2006; 52(4):755–78.
36. Kao C-C. Development of Team Cohesion and Sustained Collaboration Skills with the Sport Education Model. Sustainability. 2019; 11(8):2348.
37. Lynn Mulvey K, Boswell C, Zheng J. Causes and Consequences of Social Exclusion and Peer Rejection Among Children and Adolescents. Rep Emot Behav Disord Youth. 2017; 17(3):71–5.
38. Andermo S, Hallgren M, Nguyen TT, Jonsson S, Petersen S, Friberg M, Romqvist A, Stubbs B, Elinder LS. School-related physical activity interventions and mental health among children: a systematic review and meta-analysis. Sports Med Open. 2020; 6(1):25.
39. Mavilidi MF, Ruiter M, Schmidt M, Okely AD, Loyens S, Chandler P, Paas F. A Narrative Review of School-Based Physical Activity for Enhancing Cognition and Learning: The Importance of Relevancy and Integration. Front Psychol. 2018; 9:2079.
40. Noordstar J, Net J, Jak S, Helders P, Jongmans M. Global Self-Esteem, Perceived Athletic Competence, and Physical Activity in Children: A Longitudinal Cohort Study. Psychol Sport Exerc. 2016; 22:83–89.
41. Bardid F, De Meester A, Tallir I, Cardon G, Lenoir M, Haerens L. Configurations of actual and perceived motor competence among children: Associations with motivation for sports and global self-worth. Hum Mov Sci. 2016; 50:1–9.

42. Monacis D, Trecroci A, Invernizzi PL, Colella D. Can Enjoyment and Physical Self-Perception Mediate the Relationship between BMI and Levels of Physical Activity? Preliminary Results from the Regional Observatory of Motor Development in Italy. Int J Environ Res Public Health. 2022; 19(19):12567.
43. Katz DL, Cushman D, Reynolds J, Njike V, Treu JA, Walker J, Smith E, Katz C. Putting physical activity where it fits in the school day: preliminary results of the ABC (Activity Bursts in the Classroom) for fitness program. Prev Chronic Dis. 2010; 7(4):A82.
44. Hunter L, Abbott R, Macdonald D, Ziviani J, Cuskelly M. Active kids active minds: a physical activity intervention to promote learning? Asia Pac. J. Health Sport Phys. Educ. 2014; 5(2):117–31.

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Sodium bicarbonate and beta-alanine supplementation: Is combining both better than either alone? A systematic review and meta-analysis

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ABSTRACT: This systematic review and meta-analysis aimed to determine the effect of combined beta-alanine (BA) and sodium bicarbonate (SB) supplementation on exercise capacity and performance. Four databases (PubMed, SPORTDiscus, Web Of Science and MEDLINE) were searched using relevant terms for studies involving healthy (*e.g.* no chronic diseases or conditions) male or female adults of any training status (athletes, physically active and non-athletes) and that investigated BA and SB in isolation and combination at any dose on an exercise outcome. Ten studies, totalling 243 individuals, met the criteria with 12 outcomes for each nutritional supplement. No ergogenic effect was detected in this meta-analysis for BA (SMD = 0.18, 95% CI: -0.06; 0.43, p = 0.13, tau^2 = 0, tau = 0, I^2 = 0.0%) or SB (SMD = 0.17, 95% CI: -0.08; 0.41, p = 0.16, tau^2 = 0, tau = 0, I^2 = 0.0%) in isolation. However, there was a beneficial effect for the combination of BA and SB (SMD = 0.32, 95% CI: 0.07; 0.57, p = 0.02, tau^2 = 0, tau = 0, I^2 = 0.0%). Meta-regression identified no differences between supplementing with BA or SB separately (F = 0.58; p = 0.57). Combining BA and SB improved exercise performance, however, there was no benefit in taking these supplements individually.

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INTRODUCTION

High-intensity exercise relies on substantial energy supply from anaerobic metabolism [1], with a concomitant increase in hydrogen ions (H^+) due, at least in part, to imbalance in the strong ion difference [2]. Accumulation of H^+ can negatively impact exercise performance due to the reduction in muscle pH, namely muscle acidosis. A low muscle pH has been shown to affect muscle contractability by inhibiting glycolytic enzymes [3], increasing competition with calcium ions from the sarcoplasmic reticulum [4] and interfering with actin and myosin cross-bridge formation [5]. These lead to the muscle being unable to generate or maintain force which results in fatigue. The body has several physiological mechanisms, namely intracellular and extracellular buffering systems [6], that work to best maintain pH homeostasis during exercise, and these can be manipulated nutritionally to enhance their relative contributions.

Beta-alanine combines with L-histidine to create the dipeptide carnosine in muscle, which acts as an intracellular buffer against H^+ accumulation [7]. Supplementation of beta-alanine at doses of 3.2 to 6.4 g/day for 4–12 weeks has consistently been shown to increase muscle carnosine content, with increases expected in all individuals [8]. Thus, beta-alanine supplementation is an appropriate method to enhance the intracellular buffering capacity of our muscles. The bicarbonate buffering system is the most important system for maintaining pH homeostasis in the blood. Sodium bicarbonate supplementation can increase the concentration of circulating bicarbonate [9], with 0.3 g/kg body mass (BM) the most commonly employed dose in the literature [10]. Increased circulating bicarbonate increases the pH of the blood and also increases the transport of H^+ out of the exercising muscle [11], thereby indirectly contributing to the buffering capacity of the muscle. Enhancing these buffering systems via supplementation can support an athlete to maintain an elevated level of exercise performance.

Sodium bicarbonate and beta-alanine are both considered to be effective ergogenic supplements, a growing volume of reviews and meta-analytic evidence supporting their roles in improving athletic

performance and capacity [10; 12; 13; 14; 15; 16; 17; 18; 19]. Improvements with beta-alanine or sodium bicarbonate have been shown in various exercise modalities, including rowing [20; 21; 22; 23], swimming [16; 24; 25], cycling [26; 27; 28; 29], running [30; 31], team sports [32; 33] and combat sports [34; 35; 36]. These intracellular and extracellular buffering systems work simultaneously to maintain the homeostatic pH of the muscle, meaning that co-ingestion of beta-alanine and sodium bicarbonate may lead to additional improvements in exercise performance compared to taking either supplement in isolation. However, evidence for additional effects is unclear, with some studies showing strong additive effects of co-supplementation [37], others showing potential further benefits [38; 39], while others showed no additional benefit when beta-alanine and sodium bicarbonate were combined [40; 41]. A meta-analysis showed that adding sodium bicarbonate to beta-alanine led to greater performance gains than beta-alanine alone [14], but no comparison was made to sodium bicarbonate alone, hindering conclusions. Since recreational and trained athletes will likely consume a combination of different supplements in order to maximise performance [42], further exploration of the combined effects of ergogenic aids would provide a more thorough and practical understanding of how these substances interact to affect performance.

To date, there has been no systematic review and meta-analysis investigating the effect of the co-ingestion of beta-alanine or sodium bicarbonate. Therefore, the aim of this paper was to perform a systematic review of the current evidence and meta-analyse the data to determine if there is an additive benefit of co-supplementation of beta-alanine and sodium bicarbonate on exercise performance and capacity above either supplement alone.

MATERIALS AND METHODS

Study Eligibility

This systematic review with meta-analyses followed the PRISMA-P statement [43] protocols and the research framed using PICOS (Population, Intervention, Comparator, Outcomes, Study Design) [44]. The PRISMA checklist can be found as a Supplementary File. Only peer-reviewed experimental studies were included; unpublished documents, review studies, conference abstracts, theses, and book chapters were excluded. Study inclusion criteria were based on the PICOS framework, (i) population, (ii) intervention, (iii) comparisons, (iv) outcomes, and (v) study design. Inclusion criteria were as follows: i) studies involving healthy adults only (*e.g.*, no chronic diseases or conditions) of both sexes and any training status (athletes, physically active and non-athletes); ii) intervention session with sodium bicarbonate and beta-alanine in both isolation and combination at any dose; iii) comparison to a placebo; iv) exercise capacity or performance-related outcome(s); v) study trials with any experimental design. The exclusion criteria comprised: i) studies that recruited participants with any illness or physical restriction; ii) studies that did not measure exercise capacity or performance; iii) studies with blended supplements including substances other than beta-alanine and sodium bicarbonate.

Search Strategy

An online search of the literature was conducted in May 2021 and repeated again in February 2023 using the following databases: PubMed, SPORTDiscus, Web Of Science and MEDLINE. The Boolean operators and key words were, "(beta alanine OR beta-alanine OR β-alanine) AND (sodium bicarbonate) AND (exercise OR sport OR performance)". No year restriction was adopted. Search results were uploaded to an online platform (Rayyan software, Qatar Computing Research Institute, Qatar) [45] to perform the screening process.

Following the removal of duplicates, two reviewers (TCB and AGS) independently assessed the eligibility of the title and abstract of all the results provided by the search based on the inclusion and exclusion criteria. The separate selection of papers was then compared, with no conflicts. The next stage consisted of obtaining and evaluating the entire remaining articles against the inclusion/exclusion criteria. Where there were any conflicts about suitability, a decision was made following discussion with a third reviewer (BS). The search and screening strategy is depicted in Figure 1.

Data Extraction

The total number of articles were randomly halved and assigned to two authors (TCB and AGS) who each extracted data from their assigned studies, before each cross-checking the other's extracted data to avoid any errors. The following data was extracted from each selected studies: author and year of publication, population characteristics (sex, age, training status), experimental design, supplementation protocols (dose, timing), exercise protocol and exercise related outcome data. All the extracted data was organized in standardized Microsoft Excel spreadsheets. A single exercise outcome measure was extracted from each exercise protocol to ensure consistency in data analysis and avoid data repetition based on a hierarchy of a previous meta-analysis with beta-alanine supplementation and exercise [14]. The outcome data hierarchy was as follows: (i) total work; (ii) mean output throughout the test (i.e., mean power output; mean velocity; mean jump height); and (iii) time to completion (performance test)/time to exhaustion (capacity test). When data was available in the form of a figure, means and standard deviations were extracted with the *digitize* package in the Rstudio Software (Rstudio 1.4.1103, PBC, USA).

Four types of study designs were identified and are demonstrated in Figure 1. The four types included the following: 1) two parallel groups for beta-alanine with 1 baseline measure and a crossover between a placebo and a sodium bicarbonate condition; 2) four parallel groups (PLA/PLA, BA/PLA, PLA/SB, BA/SB) with individual baseline measures; 3) a crossover (PLA/BA) without baseline measures, but with a final crossover trial between PLA and SB and 4) a single group receiving beta-alanine with baseline and post trials with both PLA and SB.

Analysis

Obtained means and standard deviations (SDs) were transformed into standardized mean differences (SMDs, Hedge's *g*). The way in which

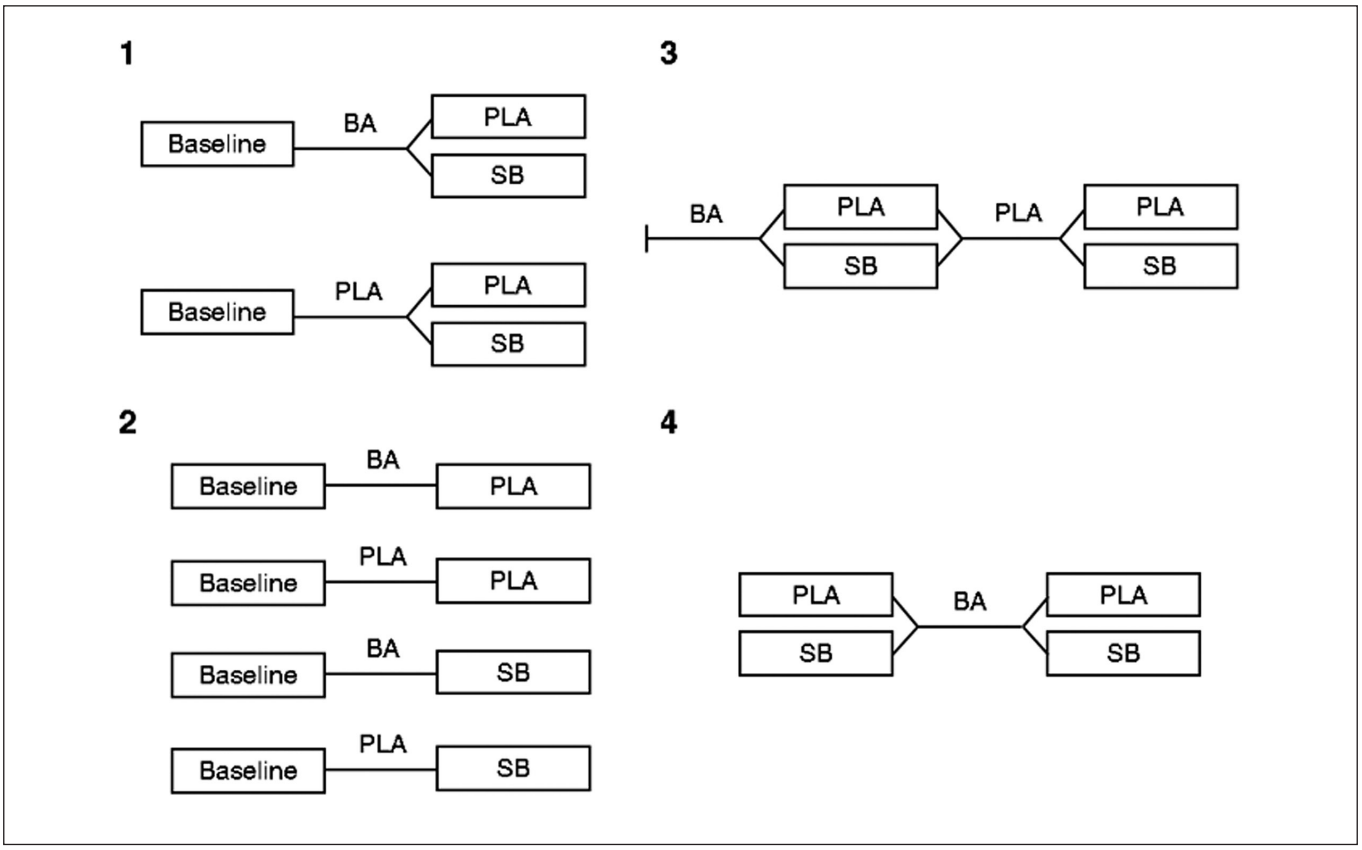


FIG. 1. Visual representation of each of the 4 study designs encountered. BA = Beta-alanine, SB = Sodium bicarbonate, PLA = Placebo.

the SMDs were calculated varied according to the study design. For pre-post design studies (designs 1 and 2) [1; 3; 4; 6; 7; 8; 9; 10], SMDs were calculated as per the d_{ppc2} effect size and variance $\sigma^2_{(dppc2)}$ described in Morris [46]. Since we did not have access to full datasets, and therefore could not calculate the correlation component of the variance estimate $\sigma^2_{(dppc2)}$, the suggested value of 0.7 was utilized. For pooled SD calculations, only baseline SD values were inputted.

Whenever studies utilized a cross-over model (study designs 3 and 4), SMDs and standard errors (SEs) were calculated utilizing simple pairwise group comparisons between means and standard deviations from experimental vs. placebo conditions (*esc_mean_sd* function from the *esc* package). A correlation of 0.7 was also inputted for these comparisons. Pooled SDs were calculated utilizing only the SDs of placebo conditions, since variances are expected to always be homogenous. In cases which a repeated measures design was utilized [25], SMDs were calculated individually for each measure and then combined as described by [47]. A correlation of 0.7 was also used for the combination calculus.

A three-level meta-analysis was then performed (*metagen* function from the *meta* package) with all the SMDs derived from separate studies with the restricted maximum-likelihood estimator (REML) for the obtention of variance estimates tau and tau-squared. This model was chosen due to its capacity to consider a within-study variance component, which accounts for the existence of more than one exercise outcome per study, which was the case, since comparisons were made between outcomes of single studies (BA/PLA vs. BA/SB, etc.). Random effects estimates were adjusted with the Hartung-Knapp method [48]. Confidence intervals for these estimates were calculated with the Profile-likelihood method for three-level meta-analyses [49]. A meta-regression was performed with supplement type as fixed factor with three levels (BA, SB or BA+SB) to investigate whether there are additional effects of supplementing BA and SB together and to compare the effects of both supplements separately.

Potential bias was assessed through a subjective evaluation of a funnel plot and, if any asymmetry was evident, specific tests were performed (Egger's test for small-study bias). All analyses were performed with the Rstudio Software (Rstudio 1.4.1103, PBC, USA). Statistical significance was previously set at $p < 0.05$.

RESULTS

Search strategy

The initial search identified 179 articles and after duplicates were removed reduced to 119 (Figure 2). Following title and abstract screening, this number was reduced to 13 which were screened in

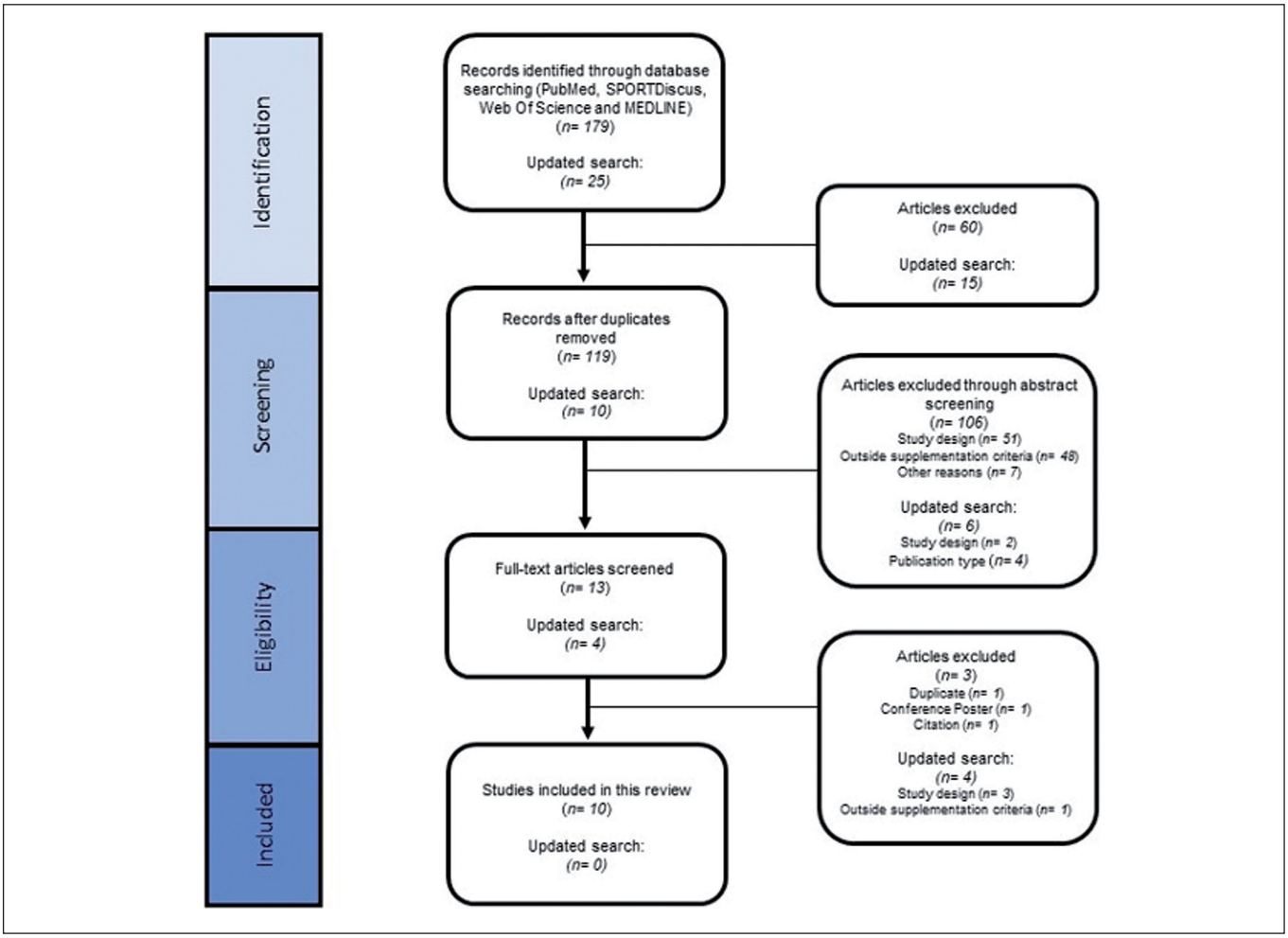


FIG. 2. Flowchart of the search strategy and study selection.

their entirety. A total of 10 articles of these 13 articles were included in this review after full text screening. The later update identified 25 additional studies which was reduced to 10 after removal of duplicates, and down to 4 for full-text screening. No additional studies were included into this review after the second screening.

Descriptives

The full analysis included 10 studies [25; 37-41; 50-53] with 12 outcomes for each supplement intervention in total, comprehending 243 individuals. Only 1 out of the 10 studies included females. Participant age ranged from 18–45 years between studies. Studies were performed across four different regions: United Kingdom (3), Australia (3), Brazil (3) and Finland (1). Exercise modalities comprised cycling (5 outcomes), rowing (1 outcome), swimming (4 outcomes) and intermittent running (2 outcomes). Eight of the outcomes were obtained from trained participants and 4 from untrained. In six of the outcomes, beta-alanine was supplemented for ≤ 4 weeks and > 4 in the remainder. Most of the exercise tests employed (n = 11) had a duration between 30 s to 10 minutes, and only 1 had a duration < 30 s, meaning most had a strong anaerobic component [1].

Meta-analysis

A forest plot summarizing the results of this study is represented in Figure 3. No effect was detected in this meta-analysis for BA (SMD = 0.18, 95% CI: -0.06; 0.43, p = 0.13, tau^2 = 0, tau = 0, I^2 = 0.0%) or SB (SMD = 0.17, 95% CI: -0.08; 0.41, p = 0.16, tau^2 = 0, tau = 0, I^2 = 0.0%) separately. However, an effect was seen for the combination of both SB and BA (SMD = 0.32, 95% CI: 0.07; 0.57, p = 0.02, tau^2 = 0, tau = 0, I^2 = 0.0%). A meta-regression did not identify any significant differences between supplementing with both BA or SB separately, or the combination of BA and SB (F = 0.58; p = 0.57). No asymmetry could be detected on the funnel plot derived from this meta-analysis, thus, publication and small-study bias were discarded (Figure 4).

DISCUSSION

The results of this meta-analysis showed that supplementing with beta-alanine and sodium bicarbonate together lead to benefits in exercise performance compared to a placebo, while there was no benefit in taking each of these supplements individually. These meta-analytic data confirm previous findings on co-supplementation [14], but contradict others regarding their individual efficacy [10; 12; 14].

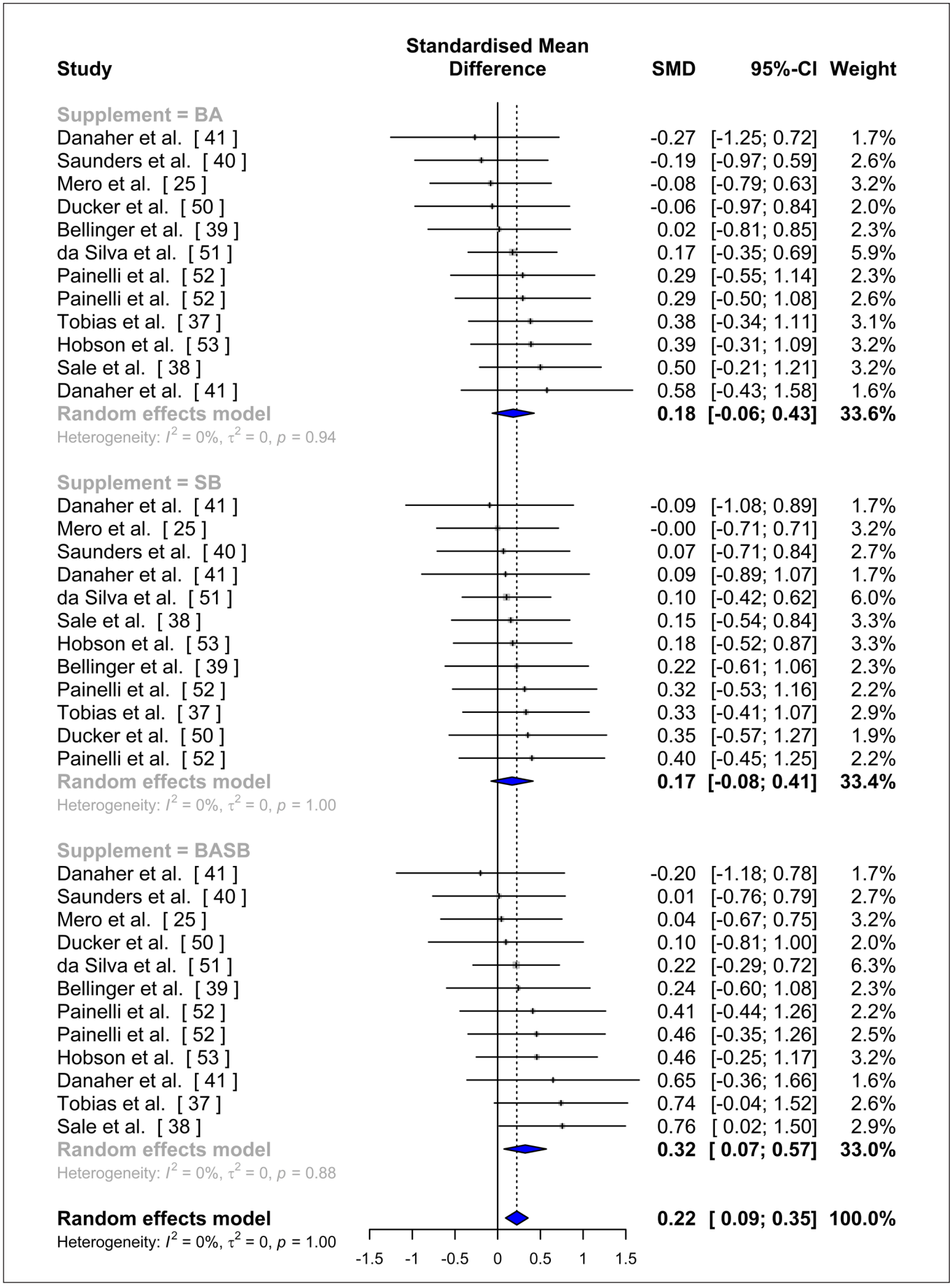


FIG. 3. Forest plot of the effect of beta-alanine (BA) alone, sodium bicarbonate (SB) alone, and beta-alanine and sodium bicarbonate (BASB) in combination.

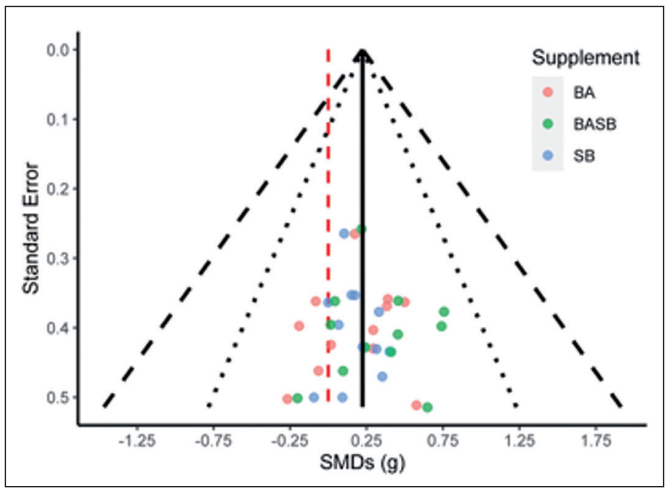


FIG. 4. Funnel plot representing effect sizes and their variances according to supplement intervention. The solid black line represents the mean SMD; the dashed red line indicates an SMD of zero. The inner and outer dashed lines represent 95% and 99% confidence intervals. SMDs = Standardised mean ifferences, BA = Beta-alanine, SB = Sodium bicarbonate, BASB = Beta-alanine and sodium bicarbonate.

Beta-alanine and sodium bicarbonate are considered effective ergogenic aids and are considered one of only five supplements that are worthwhile for performance as per the International Olympic Committee's position stand [54]. Furthermore, numerous meta-analyses have shown that both beta-alanine [13; 14] and sodium bicarbonate [10; 12; 18] can improve exercise performance. These meta-analyses were built upon a substantial literature demonstrating the performance-enhancing capacity of beta-alanine and sodium bicarbonate for rowing [20; 21; 22; 23], swimming [16; 24; 25], cycling [26; 27; 28; 29], running [30; 31], team sports [32; 33] and combat sports [34; 35; 36]. Thus, these current results appear in direct contrast to previous work, but may be explained by the low number of studies and outcomes included here. The previous largest beta-alanine meta-analysis was based upon 70 outcomes from 40 studies [14], while the most recent sodium bicarbonate meta-analysis was based upon 192 outcomes from 158 studies [10]. Twelve outcomes from ten studies were included in the current analysis; since only small effects are expected from nutritional supplements, the current analysis was likely underpowered. Indeed, the mean effect statistic for beta-alanine (SMD = 0.18) and sodium bicarbonate (SMD = 0.17) are very similar to previous positive meta-analyses (SMD = 0.18 for beta-alanine, [14]; SMD = 0.19 for sodium bicarbonate, [10]), although confidence intervals were wider from imprecision due to low sample sizes and study numbers. Thus, the lack of a significant effect of each supplement in isolation is likely due, in part, to the low number of studies included and low samples sizes within each study.

The combination of beta-alanine and sodium bicarbonate did lead to a small overall benefit on exercise outcomes. These data confirm a previous meta-analysis that showed that the addition of sodium bicarbonate to beta-alanine provided greater improvements than beta-alanine alone [14]. Several experimental studies also showed improved performance compared to baseline or a placebo when co-supplementing beta-alanine and sodium bicarbonate. Painelli et al. [24] showed a +2.13% performance improvement in 200 m swimming, Bellinger et al. [39] showed a +3.3% improvement in 4 min cycling performance, while both Sale et al. [38] and Danaher et al. [41] showed improvements of +16% in exercise capacity during a high-intensity cycling capacity test performed to exhaustion. Several individual studies did not report statistically significant additive effects of combined combination (i.e., compared to beta-alanine or sodium bicarbonate alone), though this might be due to studies with low samples sizes which were not sufficiently powered to detect small additive differences, if any exist. For example, Sale et al. [38] did not show any significant differences between combined supplementation (+16.2%) and beta-alanine (+12.1%) or sodium bicarbonate (+6.5%) alone. By pooling these data here via meta-analysis, it has been shown that the combination of these two supplements may be worthwhile for athletic populations since this generated the greatest improvements. This is supported by studies reporting further benefits of co-supplementation on repeated upper-body Wingate [37] and 2000 m rowing [20] performance. This is good news for athletes since data suggest they frequently engage in concurrent use of several supplements [55; 56]. The current data suggest that if these two products are beta-alanine and sodium bicarbonate, performance benefits are likely to occur.

In this meta-analysis we did not include analysis of changes in muscle carnosine content. Only one included study measured changes in muscle carnosine [41]. Although there may be some individual variation in the extent of these changes [57], all studies used recommended dosing strategies of between 3.2 and 6.4 $g \cdot day^{-1}$ and meta-analytical data suggest that all individuals increase muscle carnosine content with chronic beta-alanine supplementation [8] and that these doses lead to improved exercise performance [14]. Thus, this is unlikely to have substantially influenced the results. The current study did not determine the changes in blood bicarbonate concentration following sodium bicarbonate supplementation. Nine studies employed an acute dose as per recommendations (0.3 $g \cdot kg^{-1}$ BM) between 1 and 3 h prior to exercise, which will likely have sufficiently increased blood buffering capacity to elicit performance improvements [58]. Only one study used chronic dosing for sodium bicarbonate [37]. Meta-analytic data suggest that acute and chronic supplementation may be equally effective for exercise performance [10], nonetheless, it is possible that using a supplementation strategy in which exercise was initiated following attainment of peak blood bicarbonate values, performance improvements may have been optimised [59].

Practical implications

The combination of beta-alanine and sodium bicarbonate was shown to be an effective strategy to improve high-intensity exercise performance, and competitive athletes may wish to engage in supplementation to enhance performance during training and competition. Based upon the current data and current recommendations [10; 14; 54], athletes should ingest beta-alanine chronically, taking 6.4 g per day, for a minimum of 4 weeks before expecting performance improvements. To avoid uncomfortable side-effects, this should preferably be staggered over 4 individual 1.6 g doses separated by 3–4 h [60]. Sodium bicarbonate should be ingested at a dose of 0.3 $g \cdot kg^{-1}$ BM between 1 and 3 h prior to initiating exercise [58]. If possible, supplementation should occur in gastroresistant capsules and alongside a carbohydrate-rich meal to minimise any potential side-effects associated with sodium bicarbonate [61; 62].

CONCLUSIONS

The results of this meta-analysis showed that supplementing with beta-alanine and sodium bicarbonate together leads to benefits in exercise performance compared to a placebo, although there was no apparent benefit in taking each of these supplements individually.

Conflict of interest

André Guedes da Silva (2019/22249-7), Gabriel Barreto (2020/12036-3) and Bryan Saunders (2021/06836-0) acknowledge the receipt of personal research grants from São Paulo Research Foundation (FAPESP). Bryan Saunders has also previously received financial support from Natural Alternatives International (NAI), a company that produces beta-alanine, to undertake research. NAI has also provided supplements free of charge for experimental investigations and supported open access page charges for numerous publications involving Bryan Saunders. Bryan Saunders has also received remuneration for blog posts and GRAS relating to beta-alanine supplementation and carnosine, and financial support to attend the International Congress on Carnosine and Anserine 2017 in Kentucky, USA. Bryan Saunders has also received sodium bicarbonate supplements free of charge from Umara® (Sweden) and Farmácia Analítica (Brazil) for experimental investigations. These companies have not had any input (financial, intellectual, or otherwise) into the current article. The other authors declare that they have no conflicts of interest relevant to the content of this review.

REFERENCES

1. Gastin PB. Energy system interaction and relative contribution during maximal exercise. Sports Med. 2001;31(10):725-41. doi: 10.2165/00007256-200131100-00003.
2. Kowalchuk JM, Heigenhauser GJ, Lindinger MI, Sutton JR, Jones NL. Factors influencing hydrogen ion concentration in muscle after intense exercise. J Appl Physiol. 1988;65(5):2080-9. doi: 10.1152/jappl.1988.65.5.2080.
3. Spriet LL, Söderlund K, Bergström M, Hultman E. Skeletal muscle glycogenolysis, glycolysis, and pH during electrical stimulation in men. J Appl Physiol (1985). 1987;62(2):616-21. doi: 10.1152/jappl.1987.62.2.616.
4. Calbet JAL, Martín-Rodríguez S, Martin-Rincon M, Morales-Alamo D. An integrative approach to the regulation of mitochondrial respiration during exercise: Focus on high-intensity exercise. Redox Biol. 2020;35:101478. doi: 10.1016/j.redox.2020.101478.
5. Woodward M, Debold EP. Acidosis and Phosphate Directly Reduce Myosin's Force-Generating Capacity Through Distinct Molecular Mechanisms. Front Physiol. 2018;9:862. doi: 10.3389/fphys.2018.00862. PubMed PMID: 30042692; PubMed Central PMCID: PMC6048269.
6. Lancha Junior AH, Painelli Vde S, Saunders B, Artioli GG. Nutritional Strategies to Modulate Intracellular and Extracellular Buffering Capacity During High-Intensity Exercise. Sports Med. 2015;45 Suppl 1:S71-81. doi: 10.1007/s40279-015-0397-5.
7. Harris RC, Tallon MJ, Dunnett M, Boobis L, Coakley J, Kim HJ, et al. The absorption of orally supplied beta-alanine and its effect on muscle carnosine synthesis in human vastus lateralis. Amino Acids. 2006;30(3):279-89. doi: 10.1007/s00726-006-0299-9.
8. Rezende NS, Swinton P, De Oliveira LF, Da Silva RF, Da Silva VE, Nemezio K, et al. The Muscle Carnosine Response to Beta-Alanine Supplementation: A Systematic Review with Bayesian Individual and Aggregate Data E-Max Model and Meta-Analysis. Front Nutr. 2020;11:913. doi: 10.3389/fphys.2020.00913.
9. McNaughton LR. Bicarbonate ingestion: Effects of dosage on 60 s cycle ergometry. J Sport Sci. 1992;10(5):415-23. doi: 10.1080/02640419208729940.
10. de Oliveira LF, Dolan E, Swinton PA, Durkalec-Michalski K, Artioli GG, McNaughton LR, et al. Extracellular Buffering Supplements to Improve Exercise Capacity and Performance: A Comprehensive Systematic Review and Meta-analysis. Sports Med. 2022;52(3):505-26. doi: 10.1007/s40279-021-01575-x.
11. Mainwood GW, Worsley-Brown P. The effects of extracellular pH and buffer concentration on the efflux of lactate from frog sartorius muscle. J Physiol. 1975;250(1):1-22.
12. Carr AJ, Hopkins WG, Gore CJ. Effects of acute alkalosis and acidosis on performance: a meta-analysis. Sports Med. 2011;41(10):801-14. doi: 10.2165/11591440-000000000-00000.
13. Hobson RM, Saunders B, Ball G, Harris R, Sale C. Effects of β-alanine supplementation on exercise performance: a meta-analysis. Amino Acids. 2012;43(1):25-37.
14. Saunders B, Elliott-Sale K, Artioli GG, Swinton PA, Dolan E, Roschel H, et al. Times New Roman-alanine supplementation to improve exercise capacity and performance: a systematic review and meta-analysis. Br J Sports Med. 2017;51(8):658-69. doi: 10.1136/bjsports-2016-096396.
15. Saunders B, Oliveira LF, Dolan E, Durkalec-Michalski K, McNaughton L, Artioli GG, et al. Sodium bicarbonate supplementation and the female athlete: A brief commentary with small scale systematic review and meta-analysis. Eur J Sport Sci. 2021:1-10. doi: 10.1080/17461391.2021.1880649.
16. Grgic J, Mikulic P. Ergogenic Effects of Sodium Bicarbonate Supplementation on Middle-, But Not Short-Distance Swimming Tests: A Meta-Analysis. J Diet Suppl. 2021:1-12. doi: 10.1080/19390211.2021.1942381.
17. Grgic J, Pedisic Z, Saunders B, Artioli GG,

Schoenfeld BJ, McKenna MJ, et al. International Society of Sports Nutrition position stand: sodium bicarbonate and exercise performance. J Int Soc Sport Nutr. 2021;18(1):61. doi: 10.1186/s12970-021-00458-w.
18. Peart DJ, Siegler JC, Vince RV. Practical recommendations for coaches and athletes: a meta-analysis of sodium bicarbonate use for athletic performance. J Strength Cond Res. 2012;26(7):1975-83. doi: 10.1519/JSC.0b013e3182576f3d.
19. Heibel AB, Perim PHL, Oliveira LF, McNaughton LR, Saunders B. Time to Optimize Supplementation: Modifying Factors Influencing the Individual Responses to Extracellular Buffering Agents. Front Nutr. 2018;5:35. doi: 10.3389/fnut.2018.00035.
20. Hobson RM, Harris RC, Martin D, Smith P, Macklin B, Gualano B, et al. Effect of beta-alanine, with and without sodium bicarbonate, on 2000-m rowing performance. Int J Sport Nutr Exerc Metab. 2013;23(5):480-7. doi: 10.1123/ijsnem.23.5.480.
21. Baguet A, Bourgois J, Vanhee L, Achten E, Derave W. Important role of muscle carnosine in rowing performance. J Appl Physiol (1985). 2010;109(4):1096-101. doi: 10.1152/japplphysiol.00141.2010.
22. Ducker KJ, Dawson B, Wallman KE. Effect of beta-alanine supplementation on 2000-m rowing-ergometer performance. Int J Sport Nutr Exerc Metab. 2013;23(4):336-43. doi: 10.1123/ijsnem.23.4.336.
23. Hobson RM, Harris RC, Martin D, Smith P, Macklin B, Elliott-Sale KJ, et al. Effect of sodium bicarbonate supplementation on 2000-m rowing performance. Int J Sports Physiol Perform. 2014;9(1):139-44. doi: 10.1123/ijspp.2013-0086.
24. Painelli Vde S, Roschel H, Jesus F, Sale C, Harris RC, Solis MY, et al. The ergogenic effect of beta-alanine combined with sodium bicarbonate on high-intensity swimming performance. Appl Physiol Nutr Metab. 2013;38(5):525-32. doi: 10.1139/apnm-2012-0286.
25. Mero AA, Hirvonen P, Saarela J, Hulmi JJ, Hoffman JR, Stout JR. Effect of sodium bicarbonate and beta-alanine supplementation on maximal sprint swimming. J Int Soc Sports Nutr. 2013;10(1):52. doi: 10.1186/1550-2783-10-52.
26. Bellinger PM, Minahan CL. The effect of beta-alanine supplementation on cycling time trials of different length. Eur J Sport Sci. 2016;16(7):829-36. doi: 10.1080/17461391.2015.1120782.
27. Saunders B, Sale C, Harris RC, Sunderland C. Sodium bicarbonate and high-intensity-cycling capacity: variability in responses. Int J Sports Physiol Perform. 2014;9(4):627-32. doi: 10.1123/ijspp.2013-0295.
28. Gough LA, Deb SK, Sparks SA, McNaughton LR. Sodium bicarbonate improves 4 km time trial cycling performance when individualised to time to peak blood bicarbonate in trained male cyclists. J Sports Sci. 2018;36(15):1705-12. doi: 10.1080/02640414.2017.1410875.
29. Gurton WH, Gough LA, Sparks SA, Faghy MA, Reed KE. Sodium Bicarbonate Ingestion Improves Time-to-Exhaustion Cycling Performance and Alters Estimated Energy System Contribution: A Dose-Response Investigation. Front Nutr. 2020;7:154. doi: 10.3389/fnut.2020.00154.
30. Ducker KJ, Dawson B, Wallman KE. Effect of beta-alanine supplementation on 800-m running performance. Int J Sport Nutr Exerc Metab. 2013;23(6):554-61.
31. Goldfinch J, Mc Naughton L, Davies P. Induced metabolic alkalosis and its effects on 400-m racing time. Eur J Appl Physiol Occup Physiol. 1988;57(1):45-8. doi: 10.1007/BF00691236.
32. Saunders B, Sunderland C, Harris RC, Sale C. **β**-alanine supplementation improves YoYo intermittent recovery test performance. J Int Soc Sport Nutr. 2012;9(1):39. doi: 10.1186/1550-2783-9-39.
33. Krustrup P, Ermidis G, Mohr M. Sodium bicarbonate intake improves high-intensity intermittent exercise performance in trained young men. J Int Soc Sport Nutr. 2015;12(1):25. doi: 10.1186/s12970-015-0087-6.
34. Siegler JC, Hirscher K. Sodium bicarbonate ingestion and boxing performance. J Strength Cond Res. 2010;24(1):103-8. doi: 10.1519/JSC.0b013e3181a392b2.
35. de Andrade Kratz C, de Salles Painelli V, de Andrade Nemezio KM, da Silva RP, Franchini E, Zagatto AM, et al. Beta-alanine supplementation enhances judo-related performance in highly-trained athletes. J Sci Med Sport. 2017;20(4):403-8. doi: 10.1016/j.jsams.2016.08.014.
36. Lopes-Silva JP, Da Silva Santos JF, Artioli GG, Loturco I, Abbiss C, Franchini E. Sodium bicarbonate ingestion increases glycolytic contribution and improves performance during simulated taekwondo combat. Eur J Sport Sci. 2018;18(3):431-40. doi: 10.1080/17461391.2018.1424942.
37. Tobias G, Benatti FB, Painelli VS, Roschel H, Gualano B, Sale C, et al. Additive effects of beta-alanine and sodium bicarbonate on upper-body intermittent performance. Amino Acids. 2013;45(2):309-17. doi: 10.1007/s00726-013-1495-z.
38. Sale C, Saunders B, Hudson S, Wise JA, Harris RC, Sunderland CD. Effect of beta-Alanine Plus Sodium Bicarbonate on High-Intensity Cycling Capacity. Med Sci Sports Exerc. 2011;43(10):1972-8. doi: 10.1249/MSS.0b013e3182188501.
39. Bellinger PM, Howe ST, Shing CM, Fell JW. Effect of combined β-alanine and sodium bicarbonate supplementation on cycling performance. Med Sci Sports Exerc. 2012;44(8):1545-51. doi: 10.1249/MSS.0b013e31824cc08d..
40. Saunders B, Sale C, Harris RC, Sunderland C. Effect of sodium bicarbonate and Beta-alanine on repeated sprints during intermittent exercise performed in hypoxia. Int J Sport Nutr Exerc Metab. 2014;24(2):196-205. doi: 10.1123/ijsnem.2013-0102.
41. Danaher J, Gerber T, Wellard RM, Stathis CG. The effect of β-alanine and NaHCO3 co-ingestion on buffering capacity and exercise performance with high-intensity exercise in healthy males. Eur J Appl Physiol. 2014;114(8):1715-24. doi: 10.1007/s00421-014-2895-9.
42. Burke LM. Practical Issues in Evidence-Based Use of Performance Supplements: Supplement Interactions, Repeated Use and Individual Responses. Sports Med. 2017;47(Suppl 1):79-100. doi: 10.1007/s40279-017-0687-1.
43. Moher D, Shamseer L, Clarke M, Ghersi D, Liberati A, Petticrew M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev. 2015;4:1. doi: 10.1186/2046-4053-4-1.
44. Amir-Behghadami M, Janati A. Population, Intervention, Comparison, Outcomes and Study (PICOS) design as a framework to formulate eligibility criteria in systematic reviews. Emerg Med J. 2020;37(6):387-. doi: 10.1136/emermed-2020-209567.
45. Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A. Rayyan-a web and mobile app for systematic reviews. Systematic reviews. 2016;5(1):210. doi: 10.1186/s13643-016-0384-4.
46. Morris SB, DeShon RP. Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. Psychol Methods. 2002;7(1):105-25. doi: 10.1037/1082-989x.7.1.105.
47. Borenstein M, Cooper H, Hedges L, Valentine J. The Handbook of Research Synthesis and Meta-Analysis. Effect sizes for continuous data. The Russell Sage Foundation; 2009. p.221-235.
48. IntHout J, Ioannidis JP, Borm GF. The Hartung-Knapp-Sidik-Jonkman method for random effects meta-analysis is straightforward and considerably outperforms the standard DerSimonian-Laird method. BMC Med Res Methodol. 2014;14:25. doi: 10.1186/1471-2288-14-25.
49. Van den Noortgate W, Lopez-Lopez JA, Marin-Martinez F, Sanchez-Meca J.

Three-level meta-analysis of dependent effect sizes. Behav Res Methods. 2013;45(2):576-94. doi: 10.3758/s13428-012-0261-6.
50. Ducker KJ, Dawson B, Wallman KE. Effect of Beta alanine and sodium bicarbonate supplementation on repeated-sprint performance. J Strength Cond Res. 2013;27(12):3450-60. doi: 10.1519/JSC.0b013e31828fd310.
51. da Silva RP, de Oliveira LF, Saunders B, de Andrade Kratz C, de Salles Painelli V, da Eira Silva V, et al. Effects of β-alanine and sodium bicarbonate supplementation on the estimated energy system contribution during high-intensity intermittent exercise. Amino Acids. 2019;51(1):83-96. doi: 10.1007/s00726-018-2643-2.
52. Painelli VS, Roschel H, Jesus F, Sale C, Harris RC, Solis MY, et al. The ergogenic effect of beta-alanine combined with sodium bicarbonate on high-intensity swimming performance. Appl Physiol Nutr Metab. 2013;38(5):525-32. doi: 10.1139/apnm-2012-0286.
53. Hobson RM, Harris RC, Martin D, Smith P, Macklin B, Gualano B, et al. Effect of beta-alanine, with and without sodium bicarbonate, on 2000-m rowing performance. Int J Sport Nutr Exerc Metab. 2013;23(5):480-7.
54. Maughan RJ, Burke LM, Dvorak J, Larson-Meyer DE, Peeling P, Phillips SM, et al. IOC Consensus Statement: Dietary Supplements and the High-Performance Athlete. Int J Sport Nutr Exerc Metab. 2018;28(2):104-25. doi: 10.1123/ijsnem.2018-0020.
55. Shaw G, Slater G, Burke LM. Supplement Use of Elite Australian Swimmers. Int J Sport Nutr Exerc Metab. 2016;26(3):249-58. doi: 10.1123/ijsnem.2015-0182.
56. Erdman KA, Fung TS, Doyle-Baker PK, Verhoef MJ, Reimer RA. Dietary supplementation of high-performance Canadian athletes by age and gender. Clin J Sport Med. 2007;17(6):458-64. doi: 10.1097/JSM.0b013e31815aed33.
57. Saunders B, Painelli VS, LF DEO, V DAES, RP DAS, Riani L, et al. Twenty-four Weeks of beta-Alanine Supplementation on Carnosine Content, Related Genes, and Exercise. Med Sci Sports Exerc. 2017;49(5):896-906. doi: 10.1249/MSS.0000000000001173. PubMed
58. de Oliveira LF, Saunders B, Yamaguchi G, Swinton P, Artioli GG. Is Individualization of Sodium Bicarbonate Ingestion Based on Time to Peak Necessary? Med Sci Sports Exerc. 2020;52(8):1801-8. doi: 10.1249/MSS.0000000000002313.
59. Boegman S, Stellingwerff T, Shaw G, Clarke N, Graham K, Cross R, et al. The Impact of Individualizing Sodium Bicarbonate Supplementation Strategies on World-Class Rowing Performance. Front Nutr. 2020;7:138. doi: 10.3389/fnut.2020.00138.
60. Decombaz J, Beaumont M, Vuichoud J, Bouisset F, Stellingwerff T. Effect of slow-release beta-alanine tablets on absorption kinetics and paresthesia. Amino Acids. 2012;43(1):67-76. doi: 10.1007/s00726-011-1169-7.
61. Carr AJ, Slater GJ, Gore CJ, Dawson B, Burke LM. Effect of sodium bicarbonate on [HCO3-], pH, and gastrointestinal symptoms. Int J Sport Nutr Exerc Metab. 2011;21(3):189-94.
62. Hilton NP, Leach NK, Hilton MM, Sparks SA, McNaughton LR. Enteric-coated sodium bicarbonate supplementation improves high-intensity cycling performance in trained cyclists. Eur J Appl Physiol. 2020;120(7):1563-73. doi: 10.1007/s00421-020-04387-5.

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Effects of different ischemic pressures on bar velocity during the bench press exercise: A randomized crossover trial

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ABSTRACT: The main objective of this study was to evaluate the effects of different ischemic pressures applied during rest intervals on bar velocity during the bench press exercise. 10 resistance-trained males (age = 23.2 ± 2.7 years; body mass = 83.9 ± 9 kg; body height = 181 ± 5.2 cm; bench press 1 repetition maximum (1RM) = 125 ± 16.4 kg; training experience = 5.4 ± 3.4 years) participated in the study. During 4 experimental sessions, following a randomized crossover design, the subjects performed 5 sets of 3 repetitions of the bench press exercise with a load of 60% 1RM under conditions: with ischemia (50% or 80% of arterial occlusion pressure), with SHAM ischemia (20 mmHg) and without ischemia (control condition). For the ischemic conditions cuffs were applied before each set for 6.5 min and released 30 s before the start of the set as reperfusion (6.5 min ischemia + 0.5 min reperfusion). In the control condition, ischemia was not applied. The two-way repeated measures ANOVA showed no significant condition × set interaction for mean bar velocity (MV; $p = 0.17$) and peak bar velocity (PV; $p = 0.66$). There was also no main effect of condition for MV ($p = 0.58$) and PV ($p = 0.61$). The results indicate that ischemic or SHAM treatment (6.5 minutes ischemia or SHAM + 30 s reperfusion) does not affect mean and peak bar velocity during the bench press exercise regardless of the applied pressure.

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INTRODUCTION

Ischemia, also referred to as occlusion or blood flow restriction has been shown to be a training method with the objective of inducing not only chronic adaptations (strength development and muscle hypertrophy), but also acute responses (power output and strength-endurance) [1–4]. Through the application of external compression, most often with the use of pneumatic cuffs the blood flow is partially or fully blocked for designated duration, causing local hypoxia within the muscle tissue. The level of external compression is commonly expressed by % of arterial occlusion pressure (AOP), which is the amount of pressure required to cease the blood flow to a limb, and allows for more precise and individual determination of desired pressure compared to fixed values (e.g. 200 mmHg; [5]). During the resistance training cuffs are typically applied continuously throughout the sets and rest intervals (continuous ischemia [4]), however also other methods have been established, including intermittent ischemia (applied during an exercise [6]), pre-conditioning (ischemia applied before an exercise [7]) and post-conditioning (ischemia applied after the cessation of an exercise [8]).

However, recently a new method of applying ischemia during resistance training has been established. The ischemic intra-conditioning (ischemia applied during the rest periods between exercise) is an innovative but also very attainable, practical, and easy to apply technique [9–13]. In comparison to other methods, it is beneficial on account of its impact on perceptual responses (decreased discomfort). Furthermore, ischemia is applied only during rest intervals, thus possible negative impact associated with frequent use of blood flow restriction (deleterious impact on muscle tissue and attenuated muscle growth directly underneath the cuff) is minimized [13, 14]. However, currently its effect on cardiovascular responses remains unknown, as there is no available data related to this matter. Additionally, the movement structure remains unchanged due to the absence of the cuffs during exercise [15, 16]. Okita et al. [11] reported, that ischemia applied only during the rest intervals may induce a sufficient level of metabolic stress for muscular adaptations. Currently, there are only few studies available related to ischemic intra-conditioning during resistance exercise, yet its results seem

encouraging. However, there are several factors requiring clarification, which may impact the effectiveness of this method [1, 12, 17]. Wilk et al. [1] reported acute increases in power output and bar velocity during the bench press exercise with ischemia used during rest intervals [5 sets; 3 repetitions; 60% of one repetition maximum (1RM), 5 minutes ischemia; 80% AOP]. Importantly, such increases were recorded only in sets 3–5, suggesting that the use of ischemia during rest intervals may delay the symptoms of fatigue during successive sets. Interestingly, a similar phenomenon occurred when ischemic intra-conditioning was used on the lower limbs. Trybulski et al. [12] showed that the ischemia used during the rest intervals between sets (Keiser squat; 5 sets; 2 repetitions; 60% 1RM; 4.5 minutes ischemia; 30 s reperfusion; 60% AOP) caused the significantly lower decline in power output in sets 3–5 compared to the control condition. Therefore, those results suggest that ischemic intra-conditioning may counteract increasing fatigue in regard to upper- and lower-body power performance. Importantly, according to Trybulski et al. [12] not only the duration of ischemia, but also the time of reperfusion, referred to as restoration of perfusion and concomitant reoxygenation after previous restriction of blood flow [18] may be of importance in assessing effectiveness of ischemic intra-conditioning. Further, in a different study, Jarosz et al. [17] reported that ischemia (3 minutes rest interval with ~2.5 minutes ischemia and ~30 s cuff inflation and deflation period; 80% AOP), applied during rest intervals between sets increased peak bar velocity at loads 20% 1RM and 50% 1RM during 8 sets of 2 repetitions (10% increase in subsequent set form 20 to 90%1RM) of the bench press exercise. However, increases in bar velocity were not recorded at other loads, suggesting that acute effects of ischemia during rest intervals can be related to the external load used. Surprisingly, Jarosz et al. [17] reported no such increases at the load of 60% 1RM, which is in contrary to the study by Wilk et al. [1].

The available literature regarding ischemic intra-conditioning during resistance exercise is clearly contradictory, furthermore the abundance of modalities impacting the effectiveness of ischemia constitutes a valid necessity for further studies. Given the available research regarding ischemic intra-conditioning during resistance exercise, it has been shown that this method of applying blood flow restriction is effective, however various factors impacting on its efficacy may be differentiated. Furthermore, it is still uncertain which of these modalities are crucial regarding acute changes in power output. Therefore, the aim of this study was to assess the acute effects of different ischemia pressures used during rest intervals between sets of the bench press exercise on bar velocity changes. Given that the bench press is one of the most frequently used upper-body exercises, and it was previously used in research regarding this matter it was selected in this study [1, 19, 20]. To the best of our knowledge there was no other study analyzing the acute effects of different cuff pressures used during intra-conditioning ischemia. It has been shown that when the cuff pressure is set to 60% AOP or 80% AOP, ischemic intra-conditioning has a positive impact on bar velocity and power output [1, 12, 17]. However, previous research did not investigate the impact of cuff pressures < 80% AOP. Furthermore, given that it has been previously recommended that research regarding ischemia should include SHAM or placebo group [7], cuff pressure values of 50% AOP, 80% AOP and 20 mmHg (SHAM ischemia) have been selected. We hypothesized such outcome would occur only when the higher pressures were applied (50% AOP, 80% AOP).

MATERIALS AND METHODS

Experimental Approach to the Problem

The experiment was carried out according to a randomized crossover design. All subjects participated in 4 different testing protocols (2 ischemia conditions, 1 SHAM ischemia condition (SHAM) and 1 control condition) performed in counterbalanced order, arranged 4 to 7 days as washout period. The experiment was preceded by 2 familiarization sessions two weeks before the main testing sessions and 1RM strength test performed one week before the main testing sessions. During each experimental sessions the participants performed 5 sets of 3 repetitions of the bench press exercise with a load of 60%1RM [1]. In order to analyze the impact of cuff pressure on bar velocity during ischemic conditions 2 different values of cuff pressure were applied: ~50%AOP, ~80%AOP, however for the SHAM condition 20 mmHg pressure was used. Ischemia was not used during the control condition. The rest intervals between sets lasted 7 minutes and ischemia or SHAM were applied for 6.5 minutes (6.5 minutes ischemia or SHAM + 30 s reperfusion), excluding control condition. The peak and mean bar velocity were measured using a linear position transducer. All testing sessions were performed in the XXXXX. The experimental procedure did not change at any stage of the experiment.

Subjects

Ten healthy resistance-trained males (age = 23.2 ± 2.7 years; body mass = 83.9 ± 9 kg; body height = 181 ± 5.2 cm; bench press 1RM = 125 ± 16.4 kg; training experience = 5.4 ± 3.4 years) volunteered for the study. The inclusion criteria were: a) free from neuromuscular and musculoskeletal disorders, b) at least 2 years of resistance training experience, c) bench press 1RM performance of at least 120% body mass (verified during 1RM strength test), d) free of cardiovascular disease, including arterial hypertension, atrial fibrillation, thrombosis, myocardial insufficiency (self-declaration). Before providing their written informed consent, the participants were briefed about the potential risks of the study, moreover they were allowed to withdraw from the study at any time. They were also instructed to maintain their dietary and sleep habits throughout the course of the experiment. The randomization was performed with an online generator (randomization.org). Each participant received a number and sequence of the sessions. The participants were not informed about the expected outcomes of the experiment. The study protocol was approved by the Bioethics Committee for Scientific Research, at the Academy of Physical Education in Katowice, Poland (2/2019), and all procedures were in accordance with the ethical standards of the Declaration of Helsinki, 1983.

Procedures

Familiarization Session

Two weeks before the main experiment the subjects performed two familiarization sessions, arranged 2 to 4 days apart. During the familiarization sessions, after performing a standardized warm-up consistent with the subject's normal training habits each subject performed 5 sets of 3 repetitions of the bench press exercise with a load of 60% of their estimated 1RM with ischemia (50% AOP during the first session, and 80% AOP during the second session) used before the first set and during the rest intervals between sets [1]. The familiarization sessions were performed in order to minimize possible learning effects during the main testing sessions.

1RM Strength Test

One-week before the main experiment the free-weight bench press 1RM test was carried out. After arrival, the subjects cycled on a cycle-ergometer for 5 minutes, at an exercise intensity that induced a heart rate of~130 bpm, followed by a general upper-body warm-up as described elsewhere [21]. Then, the study participants performed 15, 10, 5, 3 bench press repetitions using 20, 40, 60 and 80% of their estimated 1RM, respectively. Then the load was increased by 2.5 to 10 kg for each subsequent attempt [22]. This process was repeated until failure (within a maximum of five attempts). The rest interval between successful trials was 5 minutes. Hand placement on the barbell, as well as movement tempo during the 1RM test were volitional. Testing was performed using an Olympic barbell (20 kg, 2.8 cm diameter, 1.92 m length) (Eleiko International, Halmstad, Sweden).

Experimental Sessions

The experimental procedure was designed similarly to that previously described in a different study regarding ischemic intra-conditioning [1], in order to allow for a comparison of the results. During each experimental session subjects performed 5 sets of 3 repetitions of the bench press exercise with a load of 60% 1RM with maximal possible velocity in the eccentric and concentric phase of the movement, moreover a 7-minutes rest interval between sets was used. For the control condition ischemia was not applied, however during other experimental sessions ischemia or SHAM was applied before the first set and during every rest interval between sets. Under ischemic conditions the cuff pressure was set to ~50%AOP or ~80%AOP, however in SHAM to 20 mmHg. A linear position transducer (Tendo Power Analyzer, Tendo Sport Machines, Trencin, Slovakia) was utilized to measure peak and mean bar velocity. It has been shown that for the measurement of bar velocity changes during the free-weight bench press exercise at 60% 1RM linear position transducers show good reliability; intra-class correlation co-efficient (ICC) 0.81, standard error of measurement percentage (SEM%) 5.1% for peak bar velocity and ICC 0.83, SEM% 5,8% for mean bar velocity [23, 24]. Peak bar velocity was obtained from the best repetition performed in each set. Mean bar velocity was obtained as the mean of 3 repetitions performed in each set. Tendo Power Analyzer unit cord was attached to the end of the barbell via Velcro. The device was placed in a manner that allowed for the most perpendicular trajectory of the cord. The same experienced investigator was responsible for accuracy of each measurement performed with the Tendo Power Analyzer unit during the course of the study.

Ischemic procedure

For the ischemic and SHAM conditions pressure cuffs were applied bilaterally as high as possible in the close proximity to axillary fossa. This study utilized Fit Cuffs (Fit Cuffs ApS, Denmark), which are 7-cm wide. For ischemic (~50%AOP, ~80%AOP) and SHAM (20 mmHg) conditions, before each set ischemia or SHAM were applied for 6.5 minutes and released 30 s before the beginning of a set (6.5 minutes ischemia + 30 seconds reperfusion). In order to determine AOP of each participant (~50% or ~80% AOP conditions) after the completion of general warm-up and a 5-minute rest interval the value of full arterial occlusion pressure (100% AOP) was determined (subjects remained in a seated position). A handheld Edan SD3 Doppler with an OLED screen and a 2 mHz probe made by Edan Instruments (Shenzhen, China) was utilized [1, 17]. The measurement was conducted on the radial artery, twice on each limb and the measurements were 5 min apart in the subject [3]. In case the obtained differences were within 20 mmHg, the mean of the two measurements was used to set the cuff pressure for the exercise protocol [1]. During ischemic conditions cuff pressure was set to ~50% AOP (78 ± 9 mmHg) or ~80% AOP (125 ± 13 mmHg), and during the SHAM condition to 20 mm Hg.

Statistical Analysis

All statistical analyzes were performed using Statistica 9.1. Results are presented as means and standard deviations. The Shapiro-Wilk test was used to verify Gaussian distribution, homogeneity, and sphericity of the sample data variances, respectively. Differences between the conditions were examined using two-way repeated measures ANOVA [4 conditions (ischemia at 80% AOP vs. ischemia at 50% AOP vs. vs. SHAM vs. control) × 5 sets of bench press]. Effect sizes (ES) for main effects and interactions were determined by partial eta squared ($\eta 2$). Partial eta squared values were classified as small (0.01–0.059), moderate (0.06–0.137) and large (> 0.137). Post hoc comparisons using Tukey's test were conducted to locate the differences between mean values when the main effect or an interaction was found. For pairwise comparisons, ESs were determined by Cohen's d which was characterized as large ($d > 0.8$), moderate (d between 0.8 and 0.5), small (d between 0.49 and 0.20), and trivial ($d < 0.2$). Percent changes with 95% confidence intervals (95CI) were also calculated. Statistical significance was set at $p < 0.05$.

RESULTS

The two-way repeated measures ANOVA did not show statistically significant condition × set interaction for MV (conditions × sets;

TABLE 1. Mean bar velocity during five sets of the bench press exercise under four experimental conditions.

Condition	Set 1 MV [m/s] (95%CI)	Set 2 MV [m/s] (95%CI)	Set 3 MV [m/s] (95%CI)	Set 4 MV [m/s] (95%CI)	Set 5 MV [m/s] (95%CI)	*p* for interaction	*p* for main effect of condition
Control	0.73 ± 0.11 (0.54 to 0.97)	0.72 ± 0.11 (0.53 to 0.94)	0.69 ± 0.09 (0.54 to 0.85)	0.70 ± 0.11 (0.51 to 0.92)	0.72 ± 0.09 (0.59 to 0.91)	0.17	0.58
SHAM	0.70 ± 0.10 (0.56 to 0.86)	0.71 ± 0.09 (0.57 to 0.84)	0.72 ± 0.12 (0.56 to 0.94)	0.69 ± 0.09 (0.52 to 0.81)	0.70 ± 0.12 (0.55 to 0.93)		
50% AOP	0.67 ± 0.09 (0.52 to 0.82)	0.67 ± 0.08 (0.58 to 0.77)	0.70 ± 0.05 (0.60 to 0.77)	0.70 ± 0.07 (0.59 to 0.82)	0.69 ± 0.06 (0.57 to 0.79)		
80% AOP	0.70 ± 0.10 (0.61 to 0.92)	0.68 ± 0.11 (0.50 to 0.86)	0.71 ± 0.15 (0.44 to 0.99)	0.69 ± 0.14 (0.44 to 0.95)	0.69 ± 0.14 (0.45 to 0.89)		

Note: All data are presented as mean with standard deviation while 95% confidence intervals (CI) are presented in parentheses. MV = mean bar velocity; AOP = arterial occlusion pressure; SHAM = sham ischemia.

TABLE 2. Peak bar velocity during five sets of the bench press exercise under four experimental conditions.

Condition	Set 1 PV [m/s] (95%CI)	Set 2 PV [m/s] (95%CI)	Set 3 PV [m/s] (95%CI)	Set 4 PV [m/s] (95%CI)	Set 5 PV [m/s] (95%CI)	*p* for interaction	*p* for main effect of condition
CONTROL	1.03 ± 0.17 (0.90 to 1.15)	1.01 ± 0.15 (0.90 to 1.11)	0.99 ± 0.13 (0.90 to 1.09)	0.98 ± 0.15 (0.88 to 1.09)	1.01 ± 0.13 (0.91 to 1.10)	0.66	0.61
SHAM	1.02 ± 0.15 (0.91 to 1.12)	0.98 ± 0.15 (0.87 to 1.08)	0.99 ± 0.17 (0.87 to 1.11)	0.99 ± 0.15 (0.88 to 1.09)	0.98 ± 0.17 (0.86 to 1.10)		
50%AOP	0.97 ± 0.14 (0.87 to 1.07)	0.97 ± 0.16 (0.85 to 1.08)	0.97 ± 0.12 (0.88 to 1.05)	1.00 ± 0.15 (0.89 to 1.11)	0.97 ± 0.10 (0.90 to 1.04)		
80%AOP	1.00 ± 0.14 (0.90 to 1.09)	0.97 ± 0.17 (0.85 to 1.09)	1.00 ± 0.20 (0.85 to 1.14)	0.97 ± 0.19 (0.83 to 1.11)	0.96 ± 0.19 (0.83 to 1.10)		

Note: All data are presented as mean with standard deviation while 95% confidence intervals (CI) are presented in parentheses. PV = peak bar velocity; AOP = arterial occlusion pressure; SHAM = sham ischemia.

TABLE 3. Differences in effect size between experimental conditions.

Comparision	Set 1		Set 2		Set 3		Set 4		Set 5	
	MV	PV	MV	PV	MV	PV	MV	PV	MV	PV
CONTROL vs SHAM	0.29	0.06	0.1	0.2	0.28	0	0.1	0.07	0.18	0.2
CONTROL vs. 50%AOP	0.6	0.39	0.52	0.26	0.14	0.16	0	0.13	0.38	0.34
CONTROL vs. 80%AOP	0.29	0.19	0.36	0.25	0.16	0.06	0.08	0.06	0.24	0.31
SHAM vs. 50%AOP	0.32	0.34	0.47	0.06	0.22	0.14	0.12	0.07	0.11	0.07
SHAM vs. 80%AOP	0	0.14	0.3	0.06	0.07	0.05	0	0.12	0.08	0.11
50%AOP vs. 80%AOP	0.32	0.21	0.1	0	0.09	0.18	0.09	0.18	0	0.07

Note: MV = mean bar velocity; PV = peak bar velocity; AOP = arterial occlusion pressure; SHAM = sham ischemia.

$p = 0.17$; $\eta^2 = 0.13$; Table 1) as well as no statistically significant condition × set interaction for PV (conditions × sets; $p = 0.66$; $\eta^2 = 0.08$; Table 2). There was also no main effect of condition for MV ($p = 0.58$; $\eta^2 = 0.07$) and PV ($p = 0.61$; $\eta^2 = 0.06$). The effect size comparison between the experimental conditions for all measured variables is presented in Table 3.

DISCUSSION

The main finding of this study was that ischemia or SHAM applied during rest intervals between sets does not induce changes in mean and peak bar velocity during multiple-set of the bench press exercise at 60% 1 RM. The lack of significant differences occurred in both ischemic conditions (~50%AOP, ~80%AOP) and SHAM condition (20 mmHg). Therefore, it might be concluded that neither different cuff pressures nor SHAM influenced acute power performance changes, which is in contrast to our initial hypothesis.

The result of this experiment is in contradiction to previous research related to the acute impact of ischemic intra-conditioning on power performance, however there are several differences between presented and previous study protocols that should be considered [1, 12, 17]. Currently only a few studies investigated the acute effects of ischemic intra-conditioning during resistance exercise on power output or bar velocity changes and reported its positive influence. In one study, which assessed the effects of ischemic pressure (80% AOP) applied during rest intervals between sets of the bench press exercise at 60% 1RM significant increases in power output and bar velocity were recorded [1]. Further, Trybulski et al. [12] reported a significantly lower decline in power output when ischemia was applied between sets of the Keiser squat exercise (60% 1RM; 60% AOP). Finally, the study by Jarosz et al. [17] showed increases in peak bar velocity, but only at loads 20% 1RM and 50% 1RM when ischemia (80% AOP) was applied during rest intervals between 8 sets of 2 repetitions of the bench press exercise (10% increase in subsequent set from 20 to 90% 1RM). First of all, the significance of cuff pressure should be considered. The efficacy of higher cuff pressures regarding the acute impact on power output has been established in previous studies. Gepfert et al. [25] found that the use of extremely high cuff pressure (150% AOP) during the squat exercise (70% 1RM) resulted in significant increases in bar velocity and power output, however such result was not observed when the cuff pressure was set to 100% AOP. Similarly, for the upper-body significant increases in the number of repetitions performed, time under tension and 1RM performance were reported during the bench press exercise when cuffs with pressure value equal to 150% AOP were applied, however the 100% AOP pressure was not sufficient to induce such changes [26]. Nonetheless, these finding are related to ischemia used during resistance exercise and high or extremely high cuff pressures, not examined in our study, which most likely would not be possible to tolerate for the duration of the rest interval (6.5 minutes). Interestingly, previous research related to the impact of cuff pressure on blood flow responses [27, 28] exhibited a not-linear response between cuff pressure and blood flow (blood flow is reduced to approximately the same degree regardless of cuff pressure). Crossley et al. [27] showed that when the cuff is applied at rest ischemic interventions with pressures ranging from 40–80% AOP elicit very similar blood flow responses (measured by Doppler Ultrasound). Further, Mouser et al. [28] reported that pressures from 40% to 90% AOP decrease blood flow to a similar degree. Correspondingly, recent study by Hornikel et al. [29] determined that the 50% AOP is a minimal threshold pressure required to elicit a significant decrease in arterial blood flow in lower-limbs. However, the aforementioned studies are related to measurements performed at rest, therefore the response during exercise may be different. On the other hand, studies comparing different cuff pressures during maximal voluntary contractions (isometric knee extension) showed decreased torque only when higher (60% and 80% AOP) pressures were used compared to lower (40% AOP) pressures [30, 31]. Although, no differences between used cuff pressures occurred in the presented study, the significance of other modalities (subsequently discussed) related to ischemic intra-conditioning should also be considered. Most notably, given that the same cuff pressure (~80% AOP) was used, as in the other study related to this issue, in which significant increases in power output and bar velocity were reported [1].

Further, among other modalities, the impact of the duration of ischemia should be recognized as well. In one study, which assessed the effects of ischemic pressure applied during rest intervals between sets of the bench press exercise at 60% 1RM significant increases in power output and bar velocity were recorded [1]. Although, in the presented study the same external load (60% 1RM), and the same cuff pressure (~80% AOP) was used, we did not observe increases in peak or mean bar velocity. Such discrepancies might be explained by distinct durations of ischemia which in this study was longer compared to the study by Wilk et al. [1] (6.5 vs. 5 minutes, respectively). Furthermore, our study, contrary to the previous research by Wilk et al. [1] utilized a reperfusion period of 30 s following ischemia, which relates to the time between cessation of blood flow restriction and the commencement of exercise. Therefore, the duration of ischemia, as well as the time of the reperfusion period might play an important role in effectiveness of ischemic interventions during rest intervals between sets of resistance exercise, as previously suggested by Trybulski et al. [12]. However, to the best of the authors knowledge there is no study available comparing the direct impact of different durations of reperfusion time following ischemia on exercise performance. Jarosz et al. [17], similarly to the presented study also reported no increases in bar velocity during the bench press exercise against a load of 60% 1RM, however showed increases in peak bar velocity at 20% 1RM and at 50% 1RM. In this study the duration of ischemia during rest intervals between sets significantly differed compared to the presented study (2.5 vs. 6.5 minutes, respectively). Therefore, it seems that the longer (6.5 minutes) duration of ischemia used between sets of resistance exercise (as used in the

presented study) is inferior compared to shorter durations (2.5–5 minutes). Further, it might be concluded that the leading outcomes regarding acute increases in power output performance appear to occur when the ischemia lasts ~5 minutes [1, 12]. Moreover, a clinical study by Ghosh et al. [32] found that only 4 minutes of ischemia is sufficient to reach the threshold for ischemic stimulus in humans. Furthermore, a recent study by Salagas et al. [33] found that a single cycle of short duration (5 minutes) ischemic pre-conditioning increased mean bar velocity and the number of repetitions performed during repeated sets of the bench press exercise. Given that, it might be concluded that the durations of ischemia applied between sets during resistance exercise which are longer than 5 minutes may not be beneficial for acute changes in power output performance, however currently there is no available data regarding shorter durations of ischemia with the use of different cuff pressures. Therefore, for ischemic intra-conditioning, the importance of ischemic duration appears to be superior to cuff pressure, given that both studies mentioned above [1, 17] utilized cuff pressures equal to ~80% AOP, similar to that which was used in our study.

In regard to ischemic intra-conditioning aforementioned factors, including cuff pressures, the duration of ischemia, and the duration of reperfusion seem to be of importance. However, also other factors such as various training variables and the type of exercise (upper- and lower-body) should be taken into consideration. Furthermore, it has been proposed that the acute impact of ischemia may also be related to the characteristics of the occluded limb, thus its circumference [3, 34, 35], length [25], and composition [36]. Therefore, most likely there are numerous factors impacting on the effectiveness of ischemia, however currently there is no sufficient scientific data to corroborate. It should be noted, that despite the fact that no significant increases in mean or peak bar velocity were observed when ischemia or SHAM ischemia were applied, the power performance was not decreased. Moreover, ischemia may induce different physiological responses, which regrettably are beyond the scope of this study. It has been suggested that ischemic intra-conditioning may have a beneficial effect on acute metabolic and hormonal responses [9, 13]. Teixeira et al. (2018) reported higher metabolic stress (accounted for by blood lactate) when ischemia was applied during rest intervals compared to conditions without ischemia and intermittent ischemia, during high-load resistance exercise (3 sets of 8 repetitions; knee extension at 70% 1RM). The mechanism of ischemia used between sets related to improved exercise performance, similarly to ischemic pre-conditioning might be regulated by metabolic and vascular pathways; neuronal, humoral, and systemic responses [7, 37]. Ischemia has been shown to positively impact deoxygenation of muscular Hb/Mb, absorption kinetics of pulmonary O_2, muscle vasodilatation and opening of the ATP-dependent K^+ channels by increasing the energy stocks after ischemia [12, 37, 38]. Moreover, according to Torma et al. [39] ischemic intra-conditioning may impact on the gene expression of angiogenesis and mitochondrial biogenesis, thus affecting the time of muscle repair and muscle hypertrophy, which may be of importance not regarding acute, but chronic responses following ischemia used during rest intervals between sets. However, regrettably this was not evaluated in the presented research, therefore composing a limitation of this study. Thus, this issue, as well as previously mentioned factors such as the duration of ischemia and reperfusion [12] should be addressed in further research regarding ischemic intra-conditioning. Moreover, given that our study similarly to other research related to this topic [1, 17] included resistance-trained subjects (bench press 1 RM exceeding body weight), it remains unclear whether or not this method may be beneficial only for elite, but also recreationally trained or untrained individuals. Interestingly, a systematic review by Incognito et al. [40] showed that recreationally active population is more responsive to ischemic treatment before an exercise compared to trained and highly trained population, therefore this issue should also be further explored.

CONCLUSIONS

It is indicated by the results of this study that ischemic or SHAM treatment (6.5 min ischemia or SHAM + 30 s reperfusion) used during rest intervals between sets does not acutely influence mean and peak bar velocity, regardless of the value of applied pressure. Therefore, we believe future studies should investigate different durations of ischemia during rest intervals between sets, as well as reperfusion period. Further, the power performance was not decreased and the ischemic intra-conditioning intervention may potentially increase physiological responses and therefore mediate positive muscle adaptation not investigated in this study. However, taking into consideration the results of this study, as well as previous research related to this method, it is still not possible to determine which factors are crucial in order to achieve increased power performance following ischemic intra-conditioning.

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Conflict of interest declaration

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

REFERENCES

1. Wilk M, Krzysztofik M, Jarosz J, Krol P, Leznicka K, Zajac A, Stastny P, Bogdanis GC. Impact of Ischemic Intra-Conditioning on Power Output and Bar Velocity of the Upper Limbs. Front Physiol. 2021; 12:626915.
2. Horiuchi M, Endo J, Sato T, Okita K. Jump training with blood flow restriction has no effect on jump performance. Biol Sport. 2018; 35(4):343–348.
3. Sieljacks P, Knudsen L, Wernbom M, Vissing K. Body position influences arterial occlusion pressure: implications for the standardization of pressure during blood flow restricted exercise. Eur J Appl Physiol. 2018; 118(2):303–312.
4. Gepfert M, Jarosz J, Wojdala G, Krzysztofik M, Campos Y, Filip-Stachnik A, Kostrzewa M, Gawel D, Szkudlarek A, Godlewski P, Stastny P, Wilk M. Acute impact of blood flow restriction on strength-endurance performance during the bench press exercise. Biol Sport. 2021; 38(4):653–658.
5. Patterson SD, Hughes L, Warmington S, Burr J, Scott BR, Owens J, Abe T, Nielsen JL, Libardi CA, Laurentino G, Neto GR, Brandner C, Martin-Hernandez J, Loenneke J. Blood Flow Restriction Exercise: Considerations of Methodology, Application, and Safety. Front Physiol. 2019; 10:533.
6. Moriggi R Jr, Mauro HD, Dias SC, Matos JM, Urtado MB, Camarço NF, Neto IS, Nascimento DC, Tibana RA, Assumpção CO, Prestes J, Urtado CB. Similar hypotensive responses to resistance exercise with and without blood flow restriction. Biol Sport. 2015; 32(4):289–94.
7. de Souza HLR, Arriel RA, Mota GR, Hohl R, Marocolo M. Does ischemic preconditioning really improve performance or it is just a placebo effect? PLoS One. 2021; 16(5):e0250572.
8. Daab W, Bouzid MA, Lajri M, Bouchiba M, Rebai H. Brief cycles of lower-limb occlusion accelerate recovery kinetics in soccer players. Phys Sportsmed. 2021; 49(2):143–150.
9. Teixeira EL, Barroso R, Silva-Batista C, Laurentino GC, Loenneke JP, Roschel H, Ugrinowitsch C, Tricoli V. Blood flow restriction increases metabolic stress but decreases muscle activation during high-load resistance exercise. Muscle Nerve. 2018; 57(1):107–111.
10. Teixeira EL, Ugrinowitsch C, de Salles Painelli V, Silva-Batista C, Aihara AY, Cardoso FN, Roschel H, Tricoli V. Blood Flow Restriction Does Not Promote Additional Effects on Muscle Adaptations When Combined With High-Load Resistance Training Regardless of Blood Flow Restriction Protocol. J Strength Cond Res. 2021; 35(5):1194–1200.
11. Okita K, Takada S, Morita N, Takahashi M, Hirabayashi K, Yokota T, Kinugawa S. Resistance training with interval blood flow restriction effectively enhances intramuscular metabolic stress with less ischemic duration and discomfort. Appl Physiol Nutr Metab. 2019; 44(7):759–764.
12. Trybulski R, Jarosz J, Krzysztofik M, Lachowicz M, Trybek G, Zajac A, Wilk M. Ischemia during rest intervals between sets prevents decreases in fatigue during the explosive squat exercise: a randomized, crossover study. Sci Rep. 2022; 12(1):5922.
13. Fostiak K, Bichowska M, Trybulski R, Trabka B, Krzysztofik M, Rolnick N, Filip-Stachnik A, Wilk M. Acute Effects of Ischemic Intra-Conditioning on 30 m Sprint Performance. Int J Environ Res Public Health. 2022; 19(19):12633.
14. Kacin A, Strazar K. Frequent low-load ischemic resistance exercise to failure enhances muscle oxygen delivery and endurance capacity. Scand J Med Sci Sports. 2011; 21(6):e231–41.
15. Schwiete C, Franz A, Roth C, Behringer M. Effects of Resting vs. Continuous Blood-Flow Restriction-Training on Strength, Fatigue Resistance, Muscle Thickness, and Perceived Discomfort. Front Physiol. 2021; 12:663665.
16. Brandner CR, Warmington SA. Delayed Onset Muscle Soreness and Perceived Exertion After Blood Flow Restriction Exercise. J Strength Cond Res. 2017; 31(11):3101–3108.
17. Jarosz J, Trybulski R, Krzysztofik M, Tsoukos A, Filip-Stachnik A, Zajac A, Bogdanis GC, Wilk M. The Effects of Ischemia During Rest Intervals on Bar Velocity in the Bench Press Exercise With Different External Loads. Front Physiol. 2021; 12:715096.
18. Eltzschig HK, Eckle T. Ischemia and reperfusion--from mechanism to translation. Nat Med. 2011; 17(11):1391–401.
19. Levinger I, Goodman C, Hare DL, Jerums G, Toia D, Selig S. The reliability of the 1RM strength test for untrained middle-aged individuals. J Sci Med Sport. 2009; 12(2):310–6.
20. Trybulski R, Gepfert M, Gawel D, Bichowska M, Fostiak K, Wojdala G, Trybek G, Krzysztofik M, Wilk M. Impact of movement tempo on bar velocity and time under tension in resistance exercises with different external loads. Biol Sport. 2022; 39(3):547–554.
21. Wilk M, Krzysztofik M, Filip A, Zajac A, Del Coso J. The Effects of High Doses of Caffeine on Maximal Strength and Muscular Endurance in Athletes Habituated to Caffeine. Nutrients. 2019; 11(8):1912.
22. Filip-Stachnik A, Krzysztofik M, Kaszuba M, Leznicka K, Kostrzewa M, Del Coso J, Wilk M. Effects of Acute Caffeine Intake on Power Output and Movement Velocity During a Multiple-Set Bench Press Exercise Among Mild Caffeine Users. J Hum Kinet. 2021; 78:219–228.
23. Orange ST, Metcalfe JW, Marshall P, Vince RV, Madden LA, Liefeith A. Test-Retest Reliability of a Commercial Linear Position Transducer (GymAware PowerTool) to Measure Velocity and Power in the Back Squat and Bench Press. J Strength Cond Res. 202; 34(3):728–737.
24. Moreno-Villanueva A, Pino-Ortega J, Rico-González M. Validity and reliability of linear position transducers and linear velocity transducers: a systematic review. Sports Biomech. 2021:1–30.
25. Gepfert M, Krzysztofik M, Kostrzewa M, Jarosz J, Trybulski R, Zajac A, Wilk M. The Acute Impact of External Compression on Back Squat Performance in Competitive Athletes. Int J Environ Res Public Health. 2020; 17(13):4674.
26. Wilk M, Krzysztofik M, Filip A, Lockie RG, Zajac A. The Acute Effects of External Compression With Blood Flow Restriction on Maximal Strength and Strength-Endurance Performance of the Upper Limbs. Front Physiol. 2020; 11:567.
27. Crossley KW, Porter DA, Ellsworth J, Caldwell T, Feland JB, Mitchell U, Johnson AW, Egget D, Gifford JR. Effect of Cuff Pressure on Blood Flow during Blood Flow-restricted Rest and Exercise. Med Sci Sports Exerc. 2020; 52(3):746–753.
28. Mouser JG, Dankel SJ, Jessee MB, Mattocks KT, Buckner SL, Counts BR, Loenneke JP. A tale of three cuffs: the hemodynamics of blood flow restriction. Eur J Appl Physiol. 2017; 117(7):1493–1499.
29. Hornikel B, Saffold KS, Mota JA, Esco MR, Fedewa MV, Wind SA, Winchester LJ. Acute Blood Flow Responses to Varying Blood Flow Restriction Pressures in the Lower Limb. Int J Exerc Sci. 2023; 16(2):118–128.
30. Fatela P, Reis JF, Mendonca GV, Avela J, Mil-Homens P. Acute effects of exercise under different levels of blood-flow restriction on muscle activation and fatigue. Eur J Appl Physiol. 2016; 116(5):985–95.
31. Ilett MJ, Rantalainen T, Keske MA, May AK, Warmington SA. The Effects of Restriction Pressures on the Acute Responses to Blood Flow Restriction Exercise. Front Physiol. 2019; 10:1018.
32. Ghosh S, Standen NB, Galiñanes M. Preconditioning the human myocardium by simulated ischemia: studies on the early and delayed protection. Cardiovasc Res. 2000; 45(2):339–50.

33. Salagas A, Tsoukos A, Terzis G, Paschalis V, Katsikas C, Krzysztofik M, Wilk M, Zajac A, Bogdanis GC. Effectiveness of either short-duration ischemic pre-conditioning, single-set high-resistance exercise, or their combination in potentiating bench press exercise performance. Front Physiol. 2022; 13:1083299.
34. McEwen JA., Owensb JG, Jeyasurya J. Why is it Crucial to Use Personalized Occlusion Pressures in Blood Flow Restriction (BFR) Rehabilitation?. J Med Biol Eng. 2019; 39:173–177.
35. Loenneke JP, Fahs CA, Rossow LM, Sherk VD, Thiebaud RS, Abe T, Bemben DA, Bemben MG. Effects of cuff width on arterial occlusion: implications for blood flow restricted exercise. Eur J Appl Physiol. 2012; 112(8):2903–12.
36. Hunt JE, Stodart C, Ferguson RA. The influence of participant characteristics on the relationship between cuff pressure and level of blood flow restriction. Eur J Appl Physiol. 2016; 116(7):1421–32.
37. Hausenloy DJ, Yellon DM. Preconditioning and postconditioning: underlying mechanisms and clinical application. Atherosclerosis. 2009; 204(2):334–41.
38. Kimura M, Ueda K, Goto C, Jitsuiki D, Nishioka K, Umemura T, Noma K, Yoshizumi M, Chayama K, Higashi Y. Repetition of ischemic preconditioning augments endothelium-dependent vasodilation in humans: role of endothelium-derived nitric oxide and endothelial progenitor cells. Arterioscler Thromb Vasc Biol. 2007; 27(6):1403–10.
39. Torma F, Gombos Z, Fridvalszki M, Langmar G, Tarcza Z, Merkely B, Naito H, Ichinoseki-Sekine N, Takeda M, Murlasits Z, Osvath P, Radak Z. Blood flow restriction in human skeletal muscle during rest periods after high-load resistance training down-regulates miR-206 and induces Pax7. J Sport Health Sci. 2021; 10(4):470–477.
40. Incognito AV, Burr JF, Millar PJ. The Effects of Ischemic Preconditioning on Human Exercise Performance. Sports Med. 2016; 46(4):531–44.

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The impact of EEG biofeedback training on the athletes' motivation and bench press performance

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ABSTRACT: The objective of this paper was to determine the impact of EEG-biofeedback training on the motivation and efficiency of powerlifters during the bench press exercise in relation to the external load and the level of training. The study included 18 trained powerlifters who were divided into the intermediate (IG) and the advanced (AG) groups. EEG-biofeedback training was conducted every three days, lasting 27 minutes each time (5 × 3-minute intervals with recovery periods – lying on a bench – between them 4 × 3 minutes), and ended with a final EEG measurement in the second cycle of research. The repeated measures ANOVA showed intra-group differences due to external loading for the FAI (Frontal Alpha Asymmetry) obtained in the EEG both before and after biofeedback training. In AG group analysis revealed significant differences between 65%1RM and 35%1RM. In the IG group between 35%1RM and 50, 65 and 80%1RM. One of the major variables influencing the efficiency of strength training, including bench press workouts, is the level of training. The more successfully an athlete uses motivation when exercising, the better their training, which translates into greater results and a lower chance of injury.

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INTRODUCTION

Athletic strength is determined by a complex interaction of various factors, including motivation, EEG-biofeedback training, and external load. The way in which these factors affect each other can have significant implications for an athlete's ability to perform at their best. In particular, the impact of differences in motivation on performance can be substantial, especially when it comes to high-intensity activities such as weightlifting. The bench press exercise is a staple in many strength and conditioning programs, and it requires both physical and mental effort to perform correctly.

The link between perception and thinking expresses motivation as a certain mental state of tension. In psychological terms, a mental process, is the foundation of involvement in activities, translating directly into the quality and effect of action, which, in the case of sports, can influence the athlete's performance [1]. Concentration plays a crucial role in strength sports, which are characterized by a tendency to continually enhance the level of technique of the performed task. Attention is a neuropsychological process consisting of a specific concentration of cognitive functions on a particular task or the precise awareness of active inputs [2]. Athletes at the professional level experience less satisfaction from the training phases, which may be a reflection of their understanding of the fundamental goal of sports practice. Sufficiently strong motivation focused on a specific objective in an era of regular, frequently repetitive training, is a crucial psychological factor impacting elite training [3]. The brain's bioelectrical activity may reflect mental states, including, in the case of sports, the athlete's capacity to perform a motor task. The bioelectrical activity of the brain is dynamic and can be influenced by both external and internal factors, such as the athlete's mental state. Electroencephalography is able to monitor this process (EEG). Changes in brain electrical activity are seen in real-time, and distinct frequency ranges in specific parts of the cortex. They are associated with a variety of emotional states, including motivation [4, 5]. The motivational factor is very significant in terms of performance, especially with progressive loads in powerlifters. Bench press (BP) is a complicated multi-joint exercise that activates several upper-body muscle groups, allowing to lift large external loads that demand a high level of neuromuscular activation. One of the most popular powerlifting events is the bench press because it is a separate competition in which the world championships are held. The results produced by strongmen in this competition are mostly the product of

developed motor abilities, technique, and dedication (mental attitude). Due to the strength-building potential of the bench press and the popularity of bench press competitions, it is frequently utilized for training, testing, and research [6]. Bench press kinematics [7], the effectiveness of various chest exercises [8], the impact of an unstable surface on upper body muscle activation [9], effects of fatigue [10], and motivational analysis of BP exercises with maximum and submaximal loads have been the subject of previous research [11, 12, 13].

Resuming, athletic performance is determined by a complex interaction of various factors, including motivation, training, and external load. The way in which these factors affect each other can have significant implications for an athlete's ability to perform at their best. In particular, the impact of differences in motivation on performance can be substantial, especially when it comes to high-intensity activities such as weightlifting. The bench press exercise is a staple in many strength and conditioning programs, and it requires both physical and mental effort to perform correctly.

Therefore, the aim of this study was to determine the impact of EEG-biofeedback training on the motivation and efficiency of powerlifters during bench press exercises in relation to the external load and training level.

MATERIALS AND METHODS

Participants

The study included 20 trained powerlifters with a minimum of 4 years of training experience (± 0.5 years) and 20 powerlifters with at least 7 years of training experience (± 0.5 years). Age 24 ± 0.5 years and right-handedness were additional criteria for inclusion in the research groups (scores above 35 points on a scale of 39 points) [14]. Russkam expresses 29 moods and emotions with three levels of intensity [15]. Based on the results of the Russkams set, we removed four athletes (two from each group) from further testing. We made this decision whenever the participant marked feeling at least one of the negative emotions at the highest level. Two study groups were formed as a consequence of the random selection of every second competitor from each list for the appropriate tests: the intermediate group (IG n = 9) and the advanced group (AG n = 9) (Table 1). The participants were informed orally and in writing about the experimental methodology, and the potential of withdrawal at any time, and provided written consent to take part in the study. EEG was used to conduct the measurements in the Laboratory of Psychomotor Fitness and the Laboratory of Muscular Strength and Power at the Academy of Physical Education in Katowice. The University Bioethics Committee for Research (7/2016 for NRSA 4 040 54) approved the research.

Research procedures

EEG measurements were conducted after a 72-hour break from any weightlifting exercises. The studies were conducted in two cycles. Individual measurement cycles were conducted over a 12-day period (each), with 3 athletes per day. The interval between cycles was 8 weeks. The first cycle of research included an initial EEG measurement based on the amount of external load. Next, biofeedback training was conducted for each athlete individually for a period of 8 weeks (15 biofeedback training sessions). We trained on Fp1, Fp2 and Cz points, promoting beta1 and SMR rhythms respectively. For each competitor, we also checked the peak alpha frequency (PAF). The frequency ranges did not require correction.

Motivational training was conducted every three days, lasting 27 minutes each time (5 × 3-minute intervals with recovery periods – lying on a bench – between them 4 × 3 minutes), and ended with a final EEG measurement in the second cycle of research.

EEG Measurement

The EEG recordings were conducted according to the procedures of the International Federation of Clinical Neurophysiology and the American EEG Society. The EEG was recorded using AG/AgCl scalp electrodes, placed according to the international 10–20 system [16]. The EEG recording was made on a 24-channel Deused Truscan system. The sampling frequency was 1024/s. Electrode impedance was maintained below 5 kilohms. A 50 Hz mains filter and a high and low-pass filter (respectively 1 and 40 Hz) were used. The grounding electrode was placed on the ear. An airplane cushion pillow was placed on the bench to reduce muscle artifacts on the neck. The measurement started with a 2-minute EEG recording at rest. First, the recording with closed eyes was checked due to epileptiform electroencephalographic patterns or other abnormalities. The rest of the recording and the entire analysis were performed with open eyes. Fifteen seconds before each bench press, attempt the subject's task was to focus and motivate on the task. The rest intervals between sets were 5 minutes. 15-s segments of the recording before the attempt from electrodes F3 and F4 were analyzed and manually divided into 1-s parts epochs. Those showing artifacts from additional co-occurring muscle activity were removed. The average result was subjected to the Fast Fourier Transform. Spectral power (μV2) at the alpha range (8–13 Hz) was exported. Finally, the alpha power of EEG electrodes F3 and F4 was log-transformed and the asymmetry score of frontal alpha was calculated by subtracting the value at F3 from the value at F4. Therefore, the Frontal Alpha Asymmetry Index (FAI) was calculated for each concentration phase before lifting the barbell according to the formula proposed by Coan and Allen [17].

Each EEG recording was assessed by a neurologist certified by the Polish Society of Clinical Neurophysiology, who was blinded for the subjects.

The Bench press procedures

The measurements were taken in 5 sessions with a 3-minute rest interval between them to avoid potential effects of fatigue. The sessions consisted of performing one repetition of a flat bench press barbell with weights ranging from 35% of one repetition maximum (1RM) to 100% 1RM. A standard warm-up protocol was applied for

each session, including a general warm-up (5 minutes) on a hand-cranked cycle ergometer (heart rate at around 130 beats per minute) and several strength exercises without external load that engaged the upper and lower body. The 1RM value was determined according to the Tilliar and Saeterbakken [10] protocol. The protocol included a "free" barbell press on a horizontal bench. When approaching the barbell press, the participants lay on their backs with EEG connected, their heads resting on an inflatable pillow, their trunk supported on the bench, their knees bent at a right angle at the knee joint, and their feet resting on the floor. The barbell grip width, similar to the static test, was 81 cm between the index fingers and was the maximum allowed by the rules of the International Powerlifting Federation. One person (an experienced coach) controlled and secured the participants during the press. The participants were instructed to lower the barbell in a controlled manner until it touched the chest and then, without stopping, to push it upward until full elbow joint extension. The exercise protocol consisted of a total of 5 sessions that allowed the determination of the variables: S35 – 1 repetition with 35% 1RM load; S50 – with 50% 1RM load; S65 – 1 repetition with 65% 1RM load, S80 – 1 repetition with 80% 1RM load, and S100 – 1 repetition with 100% 1RM load. The rest period between sessions were 3 minutes, and the participants lay on the bench.

Statistical Analysis

Descriptive statistics, such as the arithmetic mean, standard deviation, and coefficient of variation, were used to evaluate the level of analyzed variables. The normality of the variables' distribution was checked using the Shapiro-Wilk test. Levene's test of homogeneity of variances was applied to verify the homogeneity of variables and determine the statistical tools. The results of the tests clearly indicated that the variables had a normal or near-normal distribution ($p > 0.05$).

The homogeneity of variances was examined before and after the training sessions using Levene's test and it showed no similarities, i.e., homogeneity for all variables. The values of the variables in both groups after the training sessions in the Levene test were also homogeneous.

Repeated measures ANOVA was applied to answer questions regarding testing hypotheses about the absence of differences between the values of the individual variables describing the intergroup and intragroup relationships.

The F statistic and level of significance were presented. A significance level of $p < 0.05$ was accepted. Tukey's post hoc tests for equal sample sizes (N) were performed in case of significant differences.

All calculations were performed using the Statistica 15.0 analytical program (Statsoft) and the Excel package (Microsoft Office 13).

RESULTS

Repeated measures ANOVA showed no intra-group differences due to external loading for RH (right hemisphere) and LH (left hemisphere) variables obtained in EEG both before and after the biofeedback training.

The same analysis shows intra-group differences due to external loading for the FAI (Frontal Alpha Asymmetry) obtained in the EEG both before and after the biofeedback training. In the AG group, the analysis revealed significant differences between 65%1RM and 35%1RM, while in the IG group significant differences between 35%1RM and 50, 65, and 80%1RM (Tables 3 and 4, Figures 1 and 2).

At the same time, the repeated measures ANOVA showed significant intergroup differences due to external load for the RH after biofeedback training and for the FAI both before and after biofeedback training (Tables 2 to 4, Figures 3 and 4).

Table 5 shows the results of the bench press exercise before and after 8 weeks of EEG-biofeedback training for both groups.

DISCUSSION

Athletes use a variety of methods and tools to improve their performance and skills. One such innovation includes EEG biofeedback,

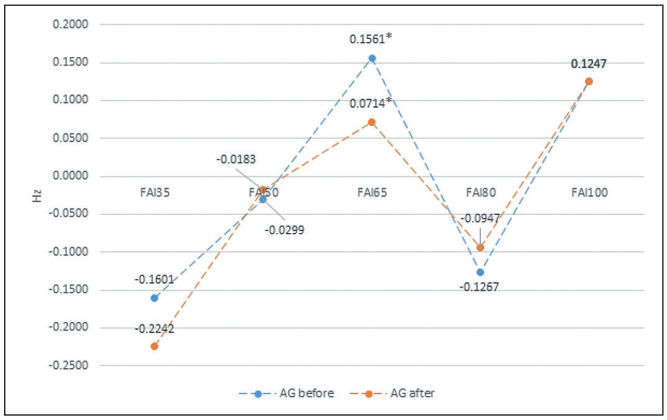


FIG. 1. The intra-group differences in FAI (Frontal Alpha Asymmetry) before biofeedback training, in relation to an external load for AG group. * statistically significant differences.

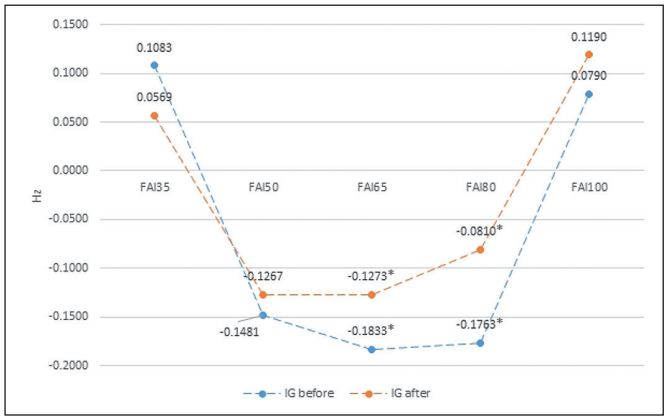


FIG. 2. The intra-group differences in FAI (Frontal Alpha Asymmetry) after biofeedback training, in relation to an external load for IG group. * statistically significant differences.

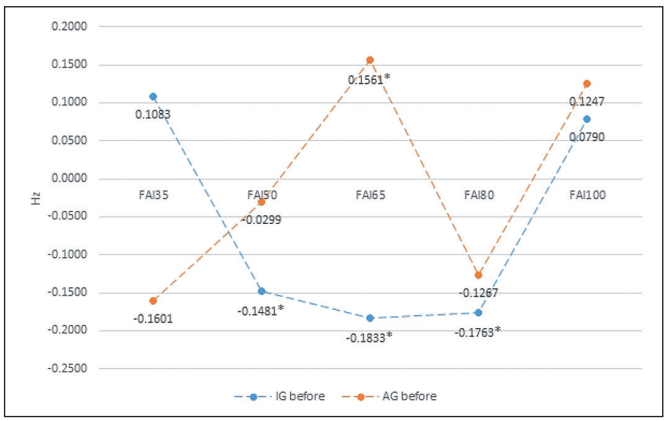


FIG. 3. The intergroup differences in FAI (Frontal Alpha Asymmetry) before biofeedback training, in relation to an external load. * statistically significant differences.

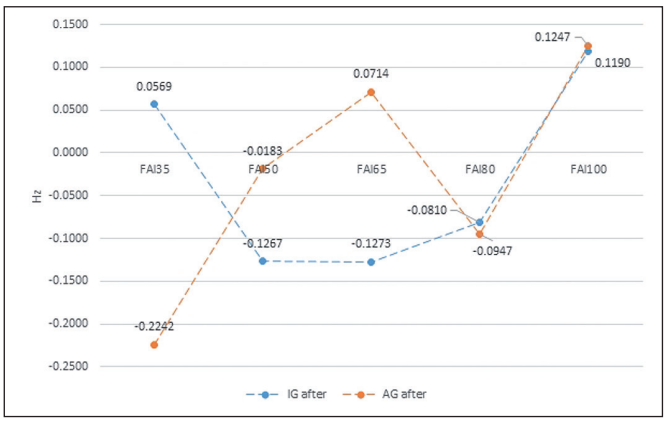


FIG. 4. The intergroup differences in FAI (Frontal Alpha Asymmetry) before biofeedback training, in relation to an external load. * statistically significant differences.

TABLE 1. Characteristics of the study groups (n = 18)

Group	AG		IG		p
Variable	±	SD	±	SD	
BM (kg)	82	2.512	81	1.821	0.781
BH (cm)	181	3	183	4	0.801
BMI (index)	24	1.721	25	1.688	0.832
PBF (%)	7	1.621	8	1.501	0.845
SMM (kg)	45	2.114	42	2.601	0.796

BM-Body mass; BH-Body height; BMI – Body Mass Index; PBF-Body fat percentage; SMM-Skeletal muscle mass; IG – intermediate group, AG advanced group.

TABLE 2. The result of the intergroup analysis of variance with repeated measures for the RH (right hemisphere) after biofeedback training, in terms of external load

Group	External load	35%1RM	50%1RM	65%1RM	80%1RM	100%1RM	35%1RM	50%1RM	65%1RM	80%1RM	100%1RM
AG	35%1RM		0.510	0.550	0.989	0.120	0.937	0.989	0.989	0.989	0.855
AG	50%1RM	0.510		0.989	0.983	0.999	0.999	0.165	0.821	0.796	0.989
AG	65%1RM	0.550	1.000		0.989	0.998	0.999	0.186	0.850	0.827	0.989
AG	80%1RM	0.989	0.983	0.989		0.683	1.000	0.809	0.989	0.989	0.989
AG	100%1RM	0.120	0.999	0.998	0.683		0.866	0.022	0.327	0.301	0.943
IG	35%1RM	0.937	0.999	0.999	0.989	0.866		0.606	0.997	0.996	0.989
IG	50%1RM	0.989	0.165	0.186	0.809	0.022	0.606		0.981	0.986	0.456
IG	65%1RM	0.989	0.821	0.850	0.989	0.327	0.997	0.981		0.989	0.984
IG	80%1RM	0.989	0.796	0.827	0.989	0.301	0.996	0.986	0.989		0.979
IG	100%1RM	0.855	1.000	0.989	0.989	0.943	1.000	0.456	0.984	0.979	

IG – intermediate group, AG advanced group.

TABLE 3. The result of the intra and intergroup analysis of variance with repeated measures for the FAI (Frontal Alpha Asymmetry) before biofeedback training, in relation to an external load

Group	External load	35%1RM	50%1RM	65%1RM	80%1RM	100%1RM	35%1RM	50%1RM	65%1RM	80%1RM	100%1RM
AG	35%1RM		0.915	0.028	0.989	0.071	0.111	0.989	0.989	0.989	0.226
AG	50%1RM	0.915		0.575	0.987	0.795	0.882	0.952	0.802	0.842	0.971
AG	65%1RM	0.028	0.575		0.075	0.989	0.989	0.040	0.013	0.016	0.998
AG	80%1RM	0.989	0.987	0.075		0.170	0.247	0.989	0.989	0.989	0.430
AG	100%1RM	0.071	0.795	0.989	0.170		1.000	0.099	0.036	0.044	0.989
IG	35%1RM	0.111	0.882	0.989	0.247	0.989		0.015	0.035	0.049	0.989
IG	50%1RM	0.989	0.952	0.040	0.989	0.099	0.015		0.989	0.989	0.290
IG	65%1RM	0.989	0.802	0.013	0.989	0.036	0.035	0.989		0.989	0.130
IG	80%1RM	0.989	0.842	0.016	0.989	0.044	0.039	0.989	0.989		0.155
IG	100%1RM	0.226	0.971	0.998	0.430	0.989	0.989	0.290	0.130	0.155	

IG – intermediate group, AG advanced group.

TABLE 4. The result of the intra and intergroup analysis of variance with repeated measures for the FAI (Frontal Alpha Asymmetry) after biofeedback training, in relation to an external load

Group	External load	35%1RM	50%1RM	65%1RM	80%1RM	100%1RM	35%1RM	50%1RM	65%1RM	80%1RM	100%1RM
AG	35%1RM		0.272	0.029	0.819	0.003	0.034	0.965	0.966	0.751	0.003
AG	50%1RM	0.272		0.995	0.997	0.809	0.997	0.953	0.951	0.999	0.843
AG	65%1RM	0.029	0.995		0.731	0.999	0.989	0.450	0.446	0.801	0.989
AG	80%1RM	0.819	0.997	0.731		0.262	0.767	0.989	0.989	0.989	0.297
AG	100%1RM	0.003	0.809	0.999	0.262		0.998	0.106	0.104	0.326	0.989
IG	35%1RM	0.034	0.997	0.989	0.767	0.998		0.025	0.040	0.042	0.999
IG	50%1RM	0.965	0.953	0.450	0.989	0.106	0.025		0.989	0.989	0.124
IG	65%1RM	0.966	0.951	0.446	0.989	0.104	0.040	0.989		0.989	0.122
IG	80%1RM	0.751	0.999	0.801	0.989	0.326	0.042	0.989	0.989		0.366
IG	100%1RM	0.003	0.843	0.989	0.297	0.989	0.999	0.124	0.122	0.366	

IG – intermediate group, AG advanced group.

TABLE 5. Results of the bench press exercise before and after biofeedback training in AG and IG groups with statistical significant intra-group differences

	AG			IG		
	Results before (kg)	Results after (kg)	p for AG	Results before (kg)	Results after (kg)	p for IG
35%1RM	82	86	0.456	75	84	0.175
50%1RM	118	123	0.501	108	120	0.089
65%1RM	153	159	0.389	140	156	0.048*
80%1RM	188	196	0.278	172	192	0.035*
100%1RM	235	245	0.154	215	240	0.028*

* statistically significant differences; IG – intermediate group, AG advanced group.

a training method that statistically monitors brain activity to improve the efficacy of athletic training and, consequently, athletic performance [18, 19, 20, 21, 22]. The studies presented in this paper examine the effectiveness of bench press training using EEG biofeedback, as well as the impact of athletes' motivation, external load, and training intensity (15 biofeedback sessions – 8 weeks).

One of the most important elements affecting the effectiveness of a training program is the athlete's motivation. Highly motivated athletes are more committed to their training and perform better [23, 24]. It has been proven that motivated athletes are more likely to perform exercises correctly, which increases their [25, 26].

The research presented in this paper shows a statistically significant difference of the increasing external load in terms of the strength of positive motivation, especially in the case of loads of 50% 1RM, 60% 1RM, and 80% 1RM. Similar results were obtained by other researchers [27, 28]. This applies not only to athletes who practice strength sports. The dependencies of the external load in terms of motivation and its use to improve the effectiveness of training have been and are used in team sports games and athletic competitions [12, 13, 18]. The size of the external load is an important factor affecting the effectiveness of training. According to scientific studies, muscle mass, and strength increase with progressive external loads [29]. However, athletes' motivation can be undermined by overuse, and unwanted injuries can occur. As a result, it is essential to select the external load properly during training based on the athlete's fitness level [30, 31].

The level of training also has a parallel effect on the effectiveness of training. Well-trained athletes perform better and are less likely to be injured. Scientific studies have shown that the level of training affects the effectiveness of training. An athlete's ability to motivate themselves during exercise increases with the level of training, which translates into improved exercise performance.

The research presented in the paper shows that even small external loads significantly change the athlete's motivation, especially in people with less training experience. The motivation of athletes, especially those with less training experience, decreases with increasing external load. The procedure is different for experienced athletes. At 80% 1RM and 100% 1RM, motivation increases most significantly (determined by EEG). Although the standard deviation was not excessive, the biofeedback training aimed to improve the FAI and thus increase motivation. However, in this study, the effect of this training was particularly visible in the group of IG players. Particularly significant changes in the improvement of bench press efficiency after biofeedback training were obtained for external loads of 65–100% 1RM. In the AG group, changes for the better were also noted, but they were not statistically significant. Similar results have been demonstrated by Standage and Ryan [32] and Xu [33]. This is because players with extensive experience are not as susceptible to biofeedback training as less experienced players. Probably, a much stronger training stimulus must be used in the training of advanced players [32, 33].

However, it is important to note that the amount of time an athlete spends exercising is not the only factor that determines their level of preparation. While consistent and adequate training is crucial for improving performance, it is also important to consider other factors such as nutrition, sleep, and recovery. People who are just starting strength training may have reduced exercise efficiency because they have not yet developed the necessary skills and muscle adaptations. On the other hand, advanced athletes who have been training for years may experience a plateau in their performance due to overtraining or inadequate recovery [34].

Moreover, the level of training is not only influenced by the amount of time an athlete spends training, but also by the quality and specificity of the training. Athletes who set specific and challenging goals for themselves, and who vary their training to target different aspects of performance, are more likely to improve their overall level of fitness and performance. Additionally, athletes who are under pressure to perform at their best may invest more time and energy into their training, but it is important to balance this with adequate rest and recovery to avoid burnout and injury. Overall, a combination of consistent, high-quality training, proper nutrition, recovery, and goal-setting is essential for optimizing athletic performance [34, 35].

There is one more aspect that is very important and affects the overall success of sports training and biofeedback, namely the motivational climate [36]. In addition to an individual's goal orientations, the particular environment or motivational climate created by the teacher, coach, peers, or parents can induce a state of task or ego involvement in sports and exercise situations. Gillet et al. [37] contended that the perceived motivational climate influences an individual's thoughts, feelings, and achievement behaviors. Consistent with task and ego goal orientations, two climates have been found to be dominate in sports and educational environments: a performance (ego) climate and a mastery (task) climate. Research into perceptions of the motivational climate in sports and physical education (e.g. Lazarus [38]) has demonstrated that perceptions of a mastery climate are related to a task goal orientation, intrinsic motivation, a preference for challenging tasks, and beliefs that success is due to effort. Furthermore, a positive attitude, high satisfaction, low boredom and anxiety, high self-rated improvement, continued involvement, and self-determined reasons for participation have also been associated with perceptions of a mastery climate. The topic of the motivational climate was not the subject of this study, however, in the authors' opinion, such an important aspect had to be indicated.

Over the past 40 years, research on motivation and self-perception, or self-confidence, has produced some significant findings [39]. The first step is to use motivation to push through loads that are heavier than the athlete can handle. There may be several scenarios, but only one stands out. Low-ego athletes might not use biofeedback training in a sensible manner. This is especially true when athletes feel inadequate and fear failure. This is likely to result in maladaptive behaviors that affect training efficacy. The research

findings unmistakably show that under such conditions, motivation wanes, commitment to tasks wanes, perseverance wanes, efficiency wanes, satisfaction and joy wanes, relationships with teammates and coaches wane, burnout is more likely, and athletes feel worse about themselves and their accomplishments [39]. This is true for athletes who lack motivation or whose motivation is used inappropriately. So, it's critical to gauge each situation's level of motivation at first [39].

EEG-biofeedback training can even be more beneficial. Positively motivated athletes with high self-esteem who have a good sense of their own competence are able to greatly boost the effectiveness of training [40] self-ego's motivational function in athletes causes them to engage in persistent performance-related actions. But even then, when contextual information is absorbed [41], such as when age becomes a role in sports performance or when an injury occurs, ego-related objectives are more "fragile" and might lead to the maladaptive pursuit of achievement. Hence, other contextually significant criteria for the success of biofeedback training and, indirectly, the effectiveness of strength training are relevant in addition to the level of alpha waves that the research team researched and analyzed.

CONCLUSIONS

In conclusion, in this article, we explored the impact of differences in athletes' motivation on their performance during bench press exercises, with a focus on the magnitude of external load and level of training, and how EEG biofeedback training can help optimize performance. One of the major variables influencing the efficiency of strength training, including bench press exercise, is the level of training. The more successfully an athlete uses motivation when exercising, the better their training, which translates into better results and a lower chance of injury. Yet, consistency in training as well as the right amount of time and effort put into it is required to reach a high level of training. When modifying the intensity of the exercise, one should take into account the level of training and, consequently, the planned objectives of boosting the efficacy of overcoming external loads during bench press workouts.

Conflict of interest declaration

The authors decleared no conflict of interest.

REFERENCES

1. Gracz J, Sankowski T. Sports psychology. In: Psychology of sports activity. Academy of Physical Education in Poznań. Poland. 2007; 4,9,16:23–233.
2. Yarrow K, Brown P, Krakauer J. Inside the brain of an elite athlete: the neural processes that support high achievement in sports. Nat Revi Neurosc. 2009; 10(8):585–596.
3. Ericsson KA, Krampe RT, Romer C. The role of deliberate practice in the acquisition of expert performance. Psychol. 1993; 100:363–406.
4. Thompson M, Thompson L. The Neurofeedback Book 2nd Edition: An Introduction to Basic Concepts in Applied Psychophysiology. The Association for Applied Psychophysiology. 2015.
5. Demo JN. Getting Started with EEG Neurofeedback Second Edition. W.W. Norton & Company. 2019.
6. Baechle TR, Earle RW. Essentials of Strength Training and Conditioning. Champaign, IL: Human Kinetics. 2008.
7. van den Tillaar R., Ettema G. The "sticking period" in a maximum bench press. J Sports Sci. 2010; 28:529–535.
8. Welsch EA, Bird M, Mayhew JL. Electromyographic activity of the pectoralis major and anterior deltoid muscles during three upper-body lifts. J Strength and Cond Res. 2005; 19:449–452.
9. Anderson KG, Behm DG. Maintenance of EMG activity and loss of force output with instability. J Strength and Cond Res. 2004; 18:637–640.
10. van den Tillaar R., Saeterbakken A.H. Fatigue effects upon sticking region and electromyography in a six-repetition maximum bench press. J Sports Sci. 2013; 31:1823–1830.
11. Lebon F., Collet C., Guillot A. Benefits of motor imagery training on muscle strength. J Strength Cond Res. 2010; 24(6):1680–7.
12. Colquhoun RJ, Gai CM, Walters J, Brannon AR, Kilpatrick MW, D'Agostino DP, Campbell BI. Comparison of Powerlifting Performance in Trained Men Using Traditional and Flexible Daily Undulating Periodization. J Strength Cond Res. 2017; 31(2):283–291.
13. Saeterbakken AH, Mo DA, Scott S, Andersen V. The effects of bench press variations in competitive athletes on muscle activity and performance. J Hum Kinet. 2017; 57:61–71.
14. Chapman LJ, Chapman JP. The measurement of handedness. Brain Cogn. 1987; 6(2):175–83.
15. Sánchez A, Hernández NP, Penagos-Corzo JC, Ostróvskaya Y. Conveying mood and emotion in instant messaging by using a two-dimensional model for affective states. Proceeding IHC. 2006; 66–72.
16. Jaspers HH. The ten 20 electrodes system of the international federation. Electroencephal Clin Neurophysiol. 1958; 10:371–375.
17. Coan JA, Allen JJB. Frontal EEG asymmetry and the behavioral activation and inhibition systems. Psychophysiol. 2003; 40(1):106–114.
18. Baric R, Bucik V. Motivational differences in athletes trained by coaches of different motivational and leadership profiles. Kinesio. 2009; 41:181–194.
19. Bentzen M, Lemyre PN, Kenttä G. Changes in motivation and burnout indices in high-performance coaches over the course of a competitive season. J. Appl. Sport Psychol. 2016; 28:28–48.
20. Bentzen M, Lemyre PN, Kenttä G. Development of exhaustion for high-performance coaches in association with workload and motivation: A person-centered approach. Psychol Sport Exerc. 2016; 22:10–19.
21. Duda J L. Motivation in sport. In A.J. Elliot & C.S. Dweck (Eds.), Handbook of competence and motivation. New York, NY: Guilford Press. 2005; 318–335.
22. Dweck CS, Leggett EL. A social-cognitive approach to motivation and personality. Psychol Rev. 1988; 95:265–273.
23. Miller BW, Roberts GC, Ommundsen Y. Effect of motivational climate on sportspersonship among competitive youth male and female football players. Scand J Med Sci Sports. 2004; 14:193–202.
24. Mouratidis A, Michou A. Perfectionism, self-determined motivation, and coping among adolescent athletes. Psychol Sport Exerc. 2011; 12:355–367.
25. Papaioannou AG, Ziurbanos N, Krommidas C, Ampatatzoglou G. The place of achievement goals in the context of sport: A comparison of Nicholls's and Elliot's models. In G.C. Roberts & D.C. Treasure (Eds.), Advances in Motivation in sport and exercise. Champaign, IL: Human Kinetics. 2012; 59–90.
26. Pensgaard AM, Roberts GC. The relationship between motivational climate, perceived ability and sources of distress among elite athletes. Sports Sci. 2000; 18:191–200.

27. Cronin JB, McNair PJ, Marshall RN. Force-velocity analysis of strength-training techniques and load: implications for training strategy and re-search. J Strength Cond Res. 2003; 17:148–55.57.
28. Cronin JB, McNair PJ, Marshall RN. The role of maximal strength and loadon initial power production. Med Sci Sports Exerc. 2000; 32:1763–9.
29. Shaun J, McLaren TW, Macpherson AJ, Coutts CH, Spears IC, Weston M. (2018). The Relationships Between Internal and External Measures of Training Load and Intensity in Team Sports: A Meta-Analysis. Sports Med. 2018; 48:641–658.
30. Roberts GC. Understanding the dynamics of motivation in physical activity: The influence of achievement goals on motivational processes. In Roberts (Ed.), Advances in motivation in sport and exercise. Champaign, IL: Human Kinetics. 2001.
31. Roberts GC. Motivation in sport and exercise from an achievement goal theory perspective: After 30 years, where are we? In Roberts, Treasure (Eds.), Advances in motivation in sport and exercise. Champaign, IL: Human Kinetics. 2012; 3:5–58.
32. Standage M, Ryan R. Self-determination theory and exercise motivation: Facilitating self-regulatory processes to support health and well-being. In Roberts, Treasure (Eds.), Advances in motivation in sport and exercise. Champaign, IL: Human Kinetics. 2012; 233–269.
33. Xu Z. Effect of HRV feedback training on sportsmen's mental fatigue. J Shandong Inst Physic Edu 2009; 25(11):46–48.
34. Solstad B. Toward a better understanding of the dynamics of sport coaching at the children's level. Unpublished doctoral dissertation, Norwegian School of Sport Science, Oslo, Norway. 2016.
35. Wang CKJ, Biddle SJH. Young people's motivational profiles in physical activity: A cluster analysis. J Sport Exerc Psychol. 2001; 23:1–22.
36. Morgan K, Sproule J. Motivation in Sport and Exercise. In book: IB Course Companion: Sport, Exercise and Health Science. Oxford Press. 2012; 231–241.
37. Gillet N, Vallerand RJ, Lafreniere MAK, Bureau JS. The mediating role of positive and negative affect in the situational motivation-performance relationship. Motiv Emot. 2013; 37(3):465–479.
38. Lazarus RS. How emotions influence performance in competitive sports. Sport Psychol. 2000; 14(3):229–252.
39. Roberts GC, Nerstad CGL, Lemyre P.N. Motivation in Sport and Performance. Printed in Oxford Research Encyclopedias, Psychology. https://doi .org/10.1093/acrefore/9780190236557.013.150; Published online: 2018.
40. Pensgaard AM, Roberts GC. Elite athletes' experiences of the motivational climate: The coach matters. Scand J Med Sci Sports2002; 12:54–60.
41. Dweck CS, Leggett EL. A social-cognitive approach to motivation and personality. Psychol. Rev. 1988; 95:265–273.

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Exploring sex differences in blood-based biomarkers following exhaustive exercise using bioinformatics analysis

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ABSTRACT: This study examined the acute effects of exercise testing on immunology markers, established blood-based biomarkers, and questionnaires in endurance athletes, with a focus on biological sex differences. Twenty-four healthy endurance-trained participants (16 men, age: 29.2 ± 7.6 years, maximal oxygen uptake ($\dot{V}O_{2max}$): 59.4 ± 7.5 ml · min^{-1} · kg^{-1}; 8 women, age: 26.8 ± 6.1 years, $\dot{V}O_{2max}$: 52.9 ± 3.1 ml · min^{-1} · kg^{-1}) completed an incremental submaximal exercise test and a ramp test. The study employed exploratory bioinformatics analysis: mixed ANOVA, k-means clustering, and uniform manifold approximation and projection, to assess the effects of exhaustive exercise on biomarkers and questionnaires. Significant increases in biomarkers (lymphocytes, platelets, procalcitonin, hemoglobin, hematocrit, red blood cells, cell-free DNA (cfDNA)) and fatigue were observed post-exercise. Furthermore, differences pre- to post-exercise were observed in cytokines, cfDNA, and other blood biomarkers between male and female participants. Three distinct groups of athletes with differing proportions of females (Cluster 1: 100% female, Cluster 2: 85% male, Cluster 3: 37.5% female and 65.5% male) were identified with k-means clustering. Specific biomarkers (e.g., interleukin-2 (IL-2), IL-10, and IL-13, as well as cfDNA) served as primary markers for each cluster, potentially informing individualized exercise responses. In conclusion, our study identified exercise-sensitive biomarkers and provides valuable insights into the relationships between biological sex and biomarker responses.

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INTRODUCTION

Assessing the physiological response to exercise is important for athletes, coaches, and sports scientists to optimize training load management and improve performance. Acute and strenuous exercise initiates stress and might lead to muscular damage, immune response, and inflammatory processes [1–3]. Exercise-induced responses are commonly monitored through objective monitoring tools (e.g., biomarkers) [4, 5]. Established blood-based biomarkers (for simplicity, we will continue to refer as biomarkers), such as blood lactate (LA) and creatine kinase (CK), are widely used but have limited informative value in the acute exercise setting when used solely in the absence of other biomarkers. Therefore, further exercise-sensitive biomarkers or biomarker panels have been suggested to comprehensively assess the physiological exercise response [6, 7]. These include, for instance, cytokines (e.g., tumor necrosis factor-alpha (TNF-α)-, interleukin-6 (IL-6)) or markers of aseptic inflammation (such as cell-free DNA (cfDNA)) which have been proposed as reliable markers of exercise sensitivity [3, 8–13]. Previous studies have found that IL-6 concentrations depend on exercise intensity and increase immediately after exercise, possibly up to 100-fold after a marathon race [11, 14, 15]. In a professional soccer setting, cfDNA showed promising results at rest [16] and directly after a soccer game, where median cfDNA increased 23-fold, and correlated with the total distance covered [8].

However, athlete responses to exercise are highly intra- and inter-individual as biomarkers are influenced by training status, exercise duration and intensity [7, 17, 18]. To date, there is limited information on how acute exercise responses are influenced by biological sex. This limitation arises in part from selective recruitment of men in previous studies, due to the complexity of hormonal variations and unique responses associated with the female menstrual cycle [19, 20].

Lobo et al. showed that a single bout of strenuous aerobic exercise induced similar responses in both sexes in leukocyte counts and cytokine levels [20]. In contrast, Bernadi et al. observed higher baseline concentrations in certain cytokines (i.e., IL-6, IL-1β, and TNF-α) in men compared to women but found no association with testosterone levels, implying that hormone levels may not fully explain the observed sex differences [21]. In addition, reference ranges for many biomarkers do not yet exist in the athlete population, which complicates their use for regular training load monitoring. Thus, the development of a reliable and exercise-sensitive panel of biomarkers for monitoring acute exercise responses is needed to gain a comprehensive understanding of immune responses to exercise. This may help to elucidate the complex interplay between biological sex, hormonal variations, and exercise responses in athletes, ultimately advancing the knowledge in this field.

The aim of the present study was to examine the acute effects of exhaustive exercise on various biomarkers (inflammatory cytokines, blood count, cfDNA, CK, and urea) in well-trained endurance athletes, with a focus on biological sex differences. This will be achieved by using exploratory bioinformatic analyses (e.g., mixed analysis of variance (ANOVA), k-means clustering, and uniform manifold approximation and projection (UMAP)) to provide novel insights into the relationships between sex, biomarkers, and exercise, ultimately contributing to the development of sex-specific biomarker assessments. In addition, we examined the subjective exercise response using questionnaires to assess fatigue, vitality, motivation, and energy. We hypothesized that blood markers would show a significant response to the exercise test, with differential effects between sexes.

MATERIALS AND METHODS

Ethics and experimental design

The study was registered (ClinicalTrials.gov identifier: NCT05067426). All procedures have been approved by a local ethical board (University of Salzburg, GZ 2/2021) and conform to the standards of the Declaration of Helsinki. Participants were informed of the risks and benefits of study participation and gave written informed consent. The data described in the present manuscript were collected during exercise testing [22]. Before and after exercise testing, participants underwent venous blood sampling and completed questionnaires.

Participants

Twenty-four (16 men and 8 women) endurance-trained athletes were recruited. All participants had been involved in regular endurance training (running, trail running, triathlon, canoeing, biking, and soccer), completing an average of 4.7 ± 1.4 endurance training sessions per week. Participants' characteristics are presented in Table 1.

TABLE 1. Anthropometric data and physiological data of the exercise testing (mean ± SD).

Variables	Overall (n = 24)	Men (n = 16)	Women (n = 8)
Age (years)	28.4 ± 7.1	29.2 ± 7.6**	26.8 ± 6.1
Height (cm)	177 ± 9	181 ± 7***	169 ± 6
Weight (kg)	69.8 ± 10.9	74.9 ± 7.8***	59.5 ± 9.0
BMI (kg/m^2)	22.2 ± 2.2	22.9 ± 1.8*	20.9 ± 2.4
Body Fat (%)	11.8 ± 5.6	9.3 ± 3.2**	16.7 ± 6.3
$\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	57.2 ± 5.4	59.4 ± 7.5**	52.9 ± 3.1
HR_{max} (bpm)	190 ± 9	191 ± 10	187 ± 8
RPE (AU)	19.0 ± 0.6	19.1 ± 0.6	19 ± 0.5
RER (AU)	1.20 ± 0.06	1.21 ± 0.04	1.19 ± 0.08
peak LA ($mmol \cdot L^{-1}$)	9.7 ± 2.4	10.4 ± 1.7*	8.1 ± 2.8
PPO (W)	398 ± 83	445 ± 41***	300 ± 52
Relative PPO ($W \cdot kg^{-1}$)	5.7 ± 0.7	6.0 ± 0.5***	5.0 ± 0.4
TTE total (min:sec)	26:35 ± 2:07	26:25 ± 2:15	26:56 ± 1:54
TTE ramp (min:sec)	6:23 ± 1:07	6:34 ± 1:07	5:59 ± 1:05
HR at LT (bpm)	159 ± 9	158 ± 9	162 ± 7
LT (km/h)	12.2 ± 1.2	12.3 ± 1.3	12.0 ± 1.2

BMI, body mass index; $\dot{V}O_{2max}$, maximal oxygen uptake during ramp test; HR max, maximal heart rate; RPE, rate of perceived exhaustion; RER, respiratory exchange rate; AU, arbitrary units; LA, lactate; PPO, peak power output during ramp test; TTE, time to exhaustion; LT, lactate threshold during submaximal exercise test; *p < 0.05, **p < 0.01, ***p < 0.001 indicate significant differences in men and women.

Physiological exercise testing

Prior to exercise testing, participants were instructed to refrain from strenuous exercise, alcohol, and caffeine for at least 24 h. Endurance performance was tested with a two-phase test on a treadmill (Saturn, HP Cosmos, Traunstein, Germany) with a breath-by-breath gas collection system (Quark CPET, Cosmed, Rome, Italy) [22]. Briefly, participants performed an incremental submaximal running test (with increases of 1.5 km/h every 3 min), followed by an 8 min recovery period, and a running ramp test until voluntary exhaustion on a treadmill. Heart rate (HR) was measured during the treadmill tests via a HR chest strap (HRM 3-SS, Kansas City, MO, USA). Running peak power output (PPO) was measured with the Stryd footpod (Stryd Wind V3, Stryd, Boulder, CO, USA) in absolute (W) and relative ($W \cdot kg^{-1}$) terms. Lactate was measured from capillary blood taken from the earlobe (Biosen S-line Clinic, EKF diagnostic GmbH, Magdeburg, Germany) throughout the incremental test. Peak LA was determined as the highest concentration collected immediately, five minutes, and 15 minutes after the ramp test. Rating of perceived exertion (RPE) on a scale from 6 to 20 [23] was collected immediately after completion of the ramp test. $\dot{V}O_{2max}$ was determined as the highest 10 s breath rolling average. Analysis of further parameters such as lactate threshold (LT) and total time of test duration were determined, as described elsewhere [22], and are listed in Table 1.

Blood parameters

Venous blood samples (3 ml EDTA and 3.5 ml serum) were obtained from the antecubital vein prior to the exercise test in a fasted condition and immediate after the ramp test. Venous blood count, i.e., white blood cell count (WBC), red blood cell count (RBC), absolute lymphocytes (LYM), percentage of lymphocytes (LYM%), absolute monocytes (MO), percentage of monocytes (MO%), absolute granulocytes (GR), percentage of granulocytes (GR%), procalcitonin (PCT), platelet (PLT), hemoglobin (HGB), hematocrit (HCT), red blood cell distribution width (RDWCV), mean platelet volume (MPV), mean corpuscular hemoglobin (MCH), mean corpuscular hemoglobin concentration (MCHC), mean corpuscular volume (MCV), and platelet distribution width (PDW) were determined using fresh whole blood by a Celltac MEK 6400 system (Nihon Kohden, Tokyo, Japan). EDTA samples were centrifuged at 1600 × g for 10 min at 4 °C, and serum samples were centrifuged at 3000 × g for 10 min at 4 °C. Samples were separated into aliquots and stored at ≤ −20°C until further analysis.

Multiple cytokines (IL-2, IL-4, IL-5, IL-6, IL-9, IL-10, IL-13, IL-17A, IL-17F, IL-22, TNF-α, interferon-gamma (INF-γ)), related to different T-helper cell types were analyzed simultaneously, in duplicates, using a bead-based immunoassay multiplex approach (LEGENDplexTM HU Th Cytokine Panel (12-plex), BioLegend, San Diego, California, U.S) and was measured via flow cytometry (CytoFLEX S, Beckman Coulter, Brea, California, U.S). All steps were performed according to the manufacturer´s protocol with some minor changes: (i) downscaling of used kit components to a fifth based on a preliminary titration of the standard (ii) and adding 50 µl of individual sera without pre dilution. Venous cfDNA (cfDNA with 90 and 222 base pairs) was quantified by analyzing unpurified plasma via quantitative real-time PCR, as described elsewhere [24]. CK and urea were measured with a light emitting diode photometer (Eurolyser CCA180, Eurolyser Diagnostica GmbH, Salzburg, Austria).

Vitality and fatigue assessment

Questionnaires were administered prior (pre) to exercise testing and in the evening between 6 PM and 8 PM (post). The modified German Subjective Vitality Scale (SVS-GM) with the 3-item ("I feel alive and vital", "I am full of drive", "I have energy and spirit"), as well as the 1-item ("I feel vital, full of drive, and spirited") version were assessed on an 11-point Likert scale (0 = not true at all to 10 = totally true) [25] to measure perception of vitality, motivation, and energy. In addition, fatigue was assessed on an 11-point Likert scale (0 = not fatigued at all to 10 = total fatigue and exhaustion – nothing left) [26].

Statistical analysis

Data are reported as means ± standard deviation (SD), while fold-changes from pre- to post-exercise are presented as median (all blood parameters; Tables 2 and 3) or mean fold-changes and 95% confidence intervals (CI) (all questionnaires; Table 4). To investigate the effects of exercise testing on blood parameters, questionnaire scores, and to identify differences between sexes in the physiological data of exercise testing (Table 1), pairwise t-tests were conducted for normally distributed data, and Wilcoxon-Tests for non-normally distributed data. Time × sex interactions were determined using mixed ANOVA. Effect sizes are reported as partial eta squared ($_p\eta^2$; small: $|0.01| \leq {}_p\eta^2 < |0.06|$; medium: $|0.06| \leq {}_p\eta^2 < |0.14|$; large ${}_p\eta^2 \geq |0.14|$) [27]. The significance level was set at $p < 0.05$. The analyses were performed using IBM SPSS Statistics 26 (IBM GmbH, Munich, Germany).

To ensure mathematical comparability for unsupervised machine learning, all continuous variables were normalized and scaled using min-max scaling in R Studio (R Studio Inc., Boston, MA, United States, version 4.2.1). Missing values (i.e., cytokine levels that were below or exceeded the standard curve) accounted for 9% of the data. Using the Mice package (version 3.15.0), these missing values were imputed [28]. The "umap" package (version 0.92) was used to construct a UMAP – a technique for visualizing high-dimensional data in two dimensions, and subsequent control-correlations were performed to compare athletes versus biomarkers (Figure 3B, Supplement Figure A [29]).

For K-means unsupervised clustering, the "mlr3" package (version 2.19.1) was used [30]. Cytokines and blood markers were used relative to absolute values. This decision was necessary because relative values reduce the risk of overfitting, which can occur when the number of variables exceeds the number of observations. In addition, relative values account for differences in baseline values,

inter-individual variances and better reflect each athlete's physiological status than absolute numbers. Finally, relative values can limit the impact of extraneous factors like time of collection or modest methodological variances, which may affect absolute levels but not relative changes. The optimal number of clusters was determined using a cluster screening technique, which suggested that three clusters provided the best fit to the model, and three clusters were chosen for further analysis (Supplement Figure B). Participants belonging to each cluster and the weight of importance of each biomarker for each cluster were obtained (Figure 3A).

Figures were generated using GraphPad Prism version 9 (Prism, GraphPad Software, San Diego, CA, USA) and the package ggplot2 3.2.0 (R Studio Inc., Boston, MA, United States, version 4.2.1). The overall statistical analysis process is illustrated in Figure 1.

RESULTS

Table 1 presents the characteristics of physiological data collected from the 24 participants during exercise testing. Mean $\dot{V}O_{2max}$ was 57.2 ± 5.4 ml $\cdot$ min^{-1} $\cdot$ kg^{-1}, with men showing a slightly higher value compared to women on both outcomes ($p < 0.01$). The mean maximum LA concentration was 9.7 ± 2.4 mmol $\cdot$ L^{-1} for all participants with higher concentrations in men compared to women ($p < 0.05$). Mean PPO was 398 ± 83 W, and the relative PPO was 5.7 ± 0.7 W $\cdot$ kg^{-1} for all participants, with men showing higher values compared to women ($p < 0.001$). Other physiological characteristics showed no significant differences between the sexes.

Table 2 outlines time × sex interactions in biomarker concentrations. Significant interactions were observed for cfDNA^{90} ($p = 0.031$, $_p\eta^2 = 0.20$), cfDNA^{222} ($p = 0.044$, $_p\eta^2 = 0.18$), and PCT ($p = 0.028$, $_p\eta^2 = 0.20$). In these cases, male participants had higher fold-changes than female participants (cfDNA^{90}: 12.5 vs. 7.2, cfDNA^{222}: 11.6 vs. 8.7, PCT: 1.4 vs. 1.3). In addition, significant interactions were found in LYM ($p = 0.016$, $_p\eta^2 = 0.24$) and WBC ($p = 0.038$, $_p\eta^2 = 0.18$), with female participants showing higher fold-changes than male participants (LYM: 3.1 vs. 2.6, WBC: 2.4 vs. 1.9; Figure 2A i-v). No significant interactions were found for all cytokines ($p > 0.05$).

Tables 2 and 3 present the acute effects of exercise testing on biomarker concentrations. Significant increases were found for both the overall population, as well as male and female participants, in cfDNA^{90}, cfDNA^{222}, LYM, LYM%, MO, WBC, GR, GR%, PCT, PLT, HGB, HCT, RBC, MCH, MCV ($p < 0.01$; Figure 2C i-xiii). RDWCV and CK increased in all participants ($p < 0.001$), as well as CK in male participants ($p = 0.005$). IL-2 ($p = 0.027$) and IL-6 ($p = 0.038$) increased in male participants, while no changes in the female participants were found (Figure 2B i, ii). Other cytokines showed no significant differences ($p > 0.05$). Individual changes for all significantly increased variables are shown in Figure 2.

Table 4 presents the effects of exercise testing on vitality and fatigue data. Neither changes nor interactions between time and sex were found in vitality, motivation, and energy. However, fatigue increased overall ($p < 0.001$), but no interactions of time × sex were identified ($p = 0.334$; Figure 2C xii).

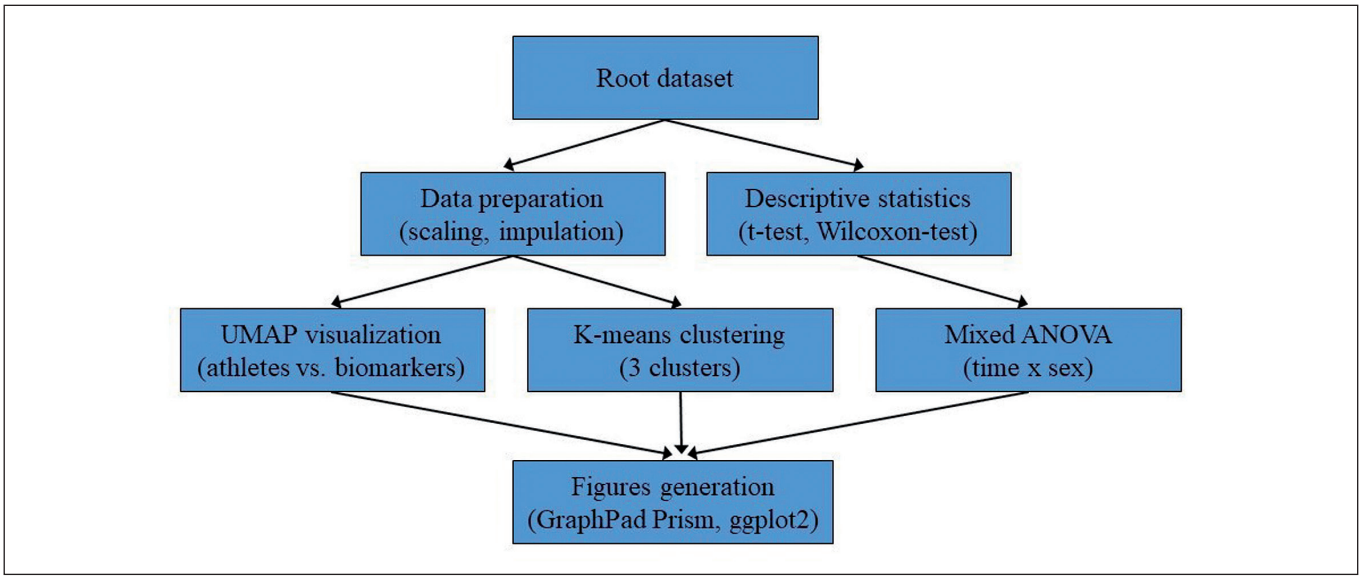


FIG. 1. Flowchart illustrating the statistical analysis process employed in the study. The root dataset was used for both data preparation (scaling and imputation) and descriptive statistics (t-tests and Wilcoxon-Test). Data preparation was followed by UMAP visualization and K-means clustering, while descriptive statistics were followed by mixed ANOVA analysis. The results from the mixed ANOVA, UMAP visualization, and K-means clustering were then used to generate figures using GraphPad Prism and ggplot2 in R.

TABLE 2. Acute changes in cfDNA and blood count.

		Overall					Men					Women				ANOVA
Variable	**Test**	**Pre**	**Post**	**FC (95% CI)**	**p-value**	**N**	**Pre**	**Post**	**FC (95% CI)**	**p-value**	**N**	**Pre**	**Post**	**FC (95% CI)**	**p-value**	**Time × Sex (p-value)**
cfDNA^{90} (ng/ml)	Pairwise T-Test	9.3 (3.6)	103.2 (49.1)	11.3 (9.4 to 13.6)	**< 0.001**	16	9.4 (3.9)	117.8 (49.6)	12.5 (10.3 to 15.6)	**< 0.001**	8	8.9 (2.8)	74.1 (34.3)	7.2 (5.2 to 12.1)	**< 0.001**	**0.031**
cfDNA^{222} (ng/ml)	Pairwise T-Test	5.0 (1.7)	52.1 (24.8)	10.8 (8.9 to 12.2)	**< 0.001**	15	5.4 (1.6)	59.7 (25.6)	11.6 (9.1 to 13.5)	**< 0.001**	8	4.4 (1.8)	37.8 (16.1)	8.7 (6.4 to 11.8)	**< 0.001**	**0.044**
LYM (10^3/μl)	Pairwise T-Test	1.5 (0.4)	3.8 (0.8)	2.7 (2.4 to 3.0)	**< 0.001**	16	1.5 (0.5)	3.6 (0.7)	2.6 (2.3 to 3.0)	**< 0.001**	8	1.5 (0.4)	4.2 (0.7)	3.1 (2.5 to 3.5)	**< 0.001**	**0.016**
MO (10^3/μl)	Pairwise T-Test	0.4 (0.2)	0.9 (0.3)	2.3 (2.1 to 2.9)	**< 0.001**	16	0.4 (0.2)	0.8 (0.2)	2.3 (1.9 to 2.9)	**< 0.001**	8	0.5 (0.2)	1.1 (0.4)	2.5 (1.8 to 3.5)	**< 0.001**	0.094
WBC (10^3/μl)	Pairwise T-Test	4.8 (1.0)	10.0 (1.8)	2.0 (2.0 to 2.3)	**< 0.001**	16	4.7 (1.0)	9.5 (1.8)	1.9 (1.9 to 2.2)	**< 0.001**	8	5.0 (1.0)	11.1 (1.4)	2.4 (1.9 to 2.6)	**< 0.001**	**0.038**
GR (10^3/μl)	Pairwise T-Test	2.9 (0.9)	5.3 (1.2)	1.8 (1.7 to 2.0)	**< 0.001**	14	2.9 (0.7)	5.1 (1.05)	1.7 (1.6 to 2.0)	**< 0.001**	8	3.0 (1.2)	5.8 (1.4)	2.0 (1.6 to 2.4)	**< 0.001**	0.172
CK (U/L)	Wilcoxon-Test	203.3 (231.4)	306.2 (365.5)	1.4 (1.4 to 1.6)	**< 0.001**	13	192.7 (185.7)	292.5 (287.8)	1.6 (1.4 to 1.7)	**0.005**	7	222.8 (316)	331.4 (506.2)	1.4 (1.3 to 1.6)	0.183	0.896
PCT (%)	Wilcoxon-Test	0.1 (0.03)	0.2 (0.04)	1.4 (1.4 to 1.6)	**< 0.001**	16	0.1 (0.04)	0.2 (0.05)	1.4 (1.4 to 1.6)	**< 0.001**	8	0.1 (0.02)	0.2 (0.1)	1.3 (1.3 to 1.4)	**< 0.001**	**0.028**
PLT (10^3/μl)	Wilcoxon-Test	202.1 (37.2)	279.0 (38.5)	1.4 (1.3 to 1.5)	**< 0.001**	16	202.0 (43.2)	281.1 (43.3)	1.4 (1.3 to 1.5)	**< 0.001**	8	200.3 (24.7)	274.6 (31.2)	1.3 (1.3 to 1.4)	**< 0.001**	0.57
LYM (%)	Pairwise T-Test	30.6 (7.5)	37.8 (5.8)	1.3 (1.2 to 1.4)	**< 0.001**	16	30.9 (7.0)	37.6 (6.1)	1.3 (1.2 to 1.3)	**< 0.001**	8	30.0 (8.8)	38.1 (5.5)	1.3 (1.1 to 1.5)	**0.001**	0.443
MO (%)	Pairwise T-Test	8.7 (3.6)	9.5 (2.9)	1.2 (1.0 to 1.5)	0.166	16	8.0 (2.7)	9.1 (2.4)	1.2 (1.0 to 1.5)	0.178	8	10.2 (4.9)	10.2 (3.9)	1.2 (0.7 to 1.6)	0.968	0.445
HGB (g/dl)	Pairwise T-Test	14.2 (1.2)	15.8 (1.0)	1.1 (1.1 to 1.1)	**< 0.001**	16	14.7 (0.8)	16.3 (0.6)	1.1 (1.1 to 1.1)	**< 0.001**	8	13.3 (1.2)	15.0 (1.0)	1.1 (1.1 to 1.2)	**< 0.001**	0.689
HCT (%)	Wilcoxon-Test	43.7 (3.1)	48.3 (3.6)	1.1 (1.1 to 1.1)	**< 0.001**	16	45.0 (1.8)	49.9 (1.4)	1.1 (1.1 to 1.1)	**< 0.001**	8	41.0 (3.5)	45.0 (4.4)	1.1 (1.1 to 1.1)	**< 0.001**	0.143
RBC (10^6/μl)	Wilcoxon-Test	4.9 (0.3)	5.3 (0.4)	1.1 (1.1 to 1.1)	**< 0.001**	16	5.0 (0.2)	5.5 (0.3)	1.1 (1.1 to 1.1)	**< 0.001**	8	4.6 (0.4)	5.0 (0.5)	1.1 (1.0 to 1.1)	**< 0.001**	0.233
RDWCV (%)	Pairwise T-Test	12.2 (0.5)	12.6 (0.6)	1 (1.0 to 1.1)	**< 0.001**	16	12.1 (0.5)	12.5 (0.5)	1.0 (1.0 to 1.1)	0.444	8	12.3 (0.6)	12.9 (0.6)	1.0 (1.0 to 1.1)	0.191	0.396
MPV (fL)	Wilcoxon-Test	6.1 (1.4)	6.3 (1.3)	1 (1.0 to 1.1)	0.209	16	6.2 (1.5)	6.4 (1.4)	1.0 (1.0 to 1.1)	0.074	8	6.0 (1.2)	5.9 (1.1)	1.0 (0.9 to 1.0)	0.664	0.149
MCH (pg)	Pairwise T-Test	29.3 (2.0)	29.7 (1.9)	1 (1.0 to 1.0)	**< 0.001**	16	29.6 (2.0)	30.0 (1.9)	1.0 (1.0 to 1.0)	**0.003**	8	28.5 (2.1)	29.1 (2.0)	1.0 (1.0 to 1.0)	**0.007**	0.508
Urea (mg/dl)	Wilcoxon-Test	32.4 (9.4)	32.6 (8.5)	1 (0.9 to 1.1)	0.627	13	34.4 (9.7)	34.5 (7.7)	1.0 (0.9 to 1.2)	0.928	7	28.9 (8.4)	29.0 (9.3)	1.0 (0.9 to 1.1)	0.916	0.981
MCHC (g/dl)	Wilcoxon-Test	32.6 (0.7)	32.6 (0.7)	1 (1.0 to 1.0)	0.796	16	32.6 (0.8)	32.7 (0.8)	1.0 (1.0 to 1.0)	0.815	8	32.3 (0.8)	32.5 (0.7)	1.0 (1.0 to 1.0)	0.53	0.714
MCV (fl)	Pairwise T-Test	89.8 (4.8)	90.9 (4.8)	1 (1.0 to 1.0)	**< 0.001**	16	90.6 (4.9)	91.7 (4.9)	1.0 (1.0 to 1.0)	**< 0.001**	8	88.4 (4.6)	89.4 (4.5)	1.0 (1.0 to 1.0)	**0.002**	0.709
PDW (%)	Wilcoxon-Test	17.2 (1.7)	17.3 (1.9)	1 (0.9 to 1.0)	0.455	16	16.8 (1.9)	16.8 (2.1)	1.0 (1.0 to 1.0)	0.986	8	17.9 (0.8)	18.1 (1.3)	1.0 (0.9 to 1.1)	0.686	0.734
GR (%)	Pairwise T-Test	61.5 (9.7)	55.0 (10.0)	0.9 (0.8 to 0.9)	**< 0.001**	14	62.4 (7.4)	57.0 (10.4)	0.9 (0.9 to 1.0)	**0.015**	8	59.9 (13.3)	51.7 (9.1)	0.8 (0.8 to 1.0)	**0.018**	0.389

Pre and post values are shown in mean and SD; pre, before exercise test; post, immediate after exercise test; FC, median fold change; 95% CI, 95% confidence interval; N, number of participants; time × sex ANOVA; cfDNA, cell-free DNA; WBC, white blood cell count; RBC, red blood cell count; LYM, lymphocytes; MO, monocytes; GR, absolute granulocytes; CK, creatine kinase; PCT, procalcitonin; PLT, platelet; HGB, hemoglobin; HCT, hematocrit; RDWCV, red blood cell distribution width; MPV, mean platelet volume; MCH, mean corpuscular hemoglobin; MCHC, mean corpuscular hemoglobin concentration; MCV, mean corpuscular volume; PDW, platelet distribution width; highlighted are significant p values < 0.05. N differences are due to analysis.

TABLE 3. Acute changes in cytokines.

		Overall					Men					Women				ANOVA
Variable	**Test**	**Pre**	**Post**	**FC (95% CI)**	**p-value**	**N**	**Pre**	**Post**	**FC (95% CI)**	**p-value**	**N**	**Pre**	**Post**	**FC (95% CI)**	**p-value**	**Time × Sex**
IL-6 (pg/ml)	Pairwise T-Test	29.5 (21.8)	36.7 (21.4)	1.4 (0.9 to 2.6)	0.082	12	33.0 (26.1)	44.0 (23.8)	1.4 (0.7 to 3.5)	**0.038**	8	24.1 (13.2)	25.7 (10.9)	1.3 (0.7 to 1.8)	0.823	0.25
IL-17α (pg/ml)	Wilcoxon-Test	7.8 (7.0)	6.8 (5.1)	1.3 (0.9 to 1.6)	0.91	11	6.5 (7.0)	5.9 (4.8)	1.4 (0.9 to 1.9)	0.737	4	11.3 (6.5)	9.4 (5.5)	0.9 (0.6 to 1.1)	0.121	0.659
IL-17F (pg/ml)	Pairwise T-Test	253.2 (325.8)	255.7 (309.1)	1.2 (0.4 to 3.4)	0.794	12	276.9 (389.9)	287.0 (370.5)	1.3 (-0.6 to 4.6)	0.399	6	205.8 (150.2)	193.2 (126.1)	1.0 (0.7 to 1.3)	0.475	0.271
IL-4 (pg/ml)	Wilcoxon-Test	85.4 (119.8)	82.3 (124.2)	1.2 (1.0 to 1.8)	0.236	15	56.6 (76.6)	60.6 (62.3)	1.2 (1.7 to 2.1)	0.631	8	139.5 (168.0)	123.0 (194.5)	1.0 (0.5 to 1.5)	0.652	0.464
IL-22 (pg/ml)	Pairwise T-Test	12.6 (9.2)	13.3 (8.1)	1.1 (0.9 to 1.7)	0.679	11	12.9 (10.1)	14.0 (8.2)	1.0 (0.9 to 1.9)	0.556	5	12.0 (8.0)	11.7 (8.6)	1.1 (0.3 to 2.2)	0.931	0.692
IL-2 (pg/ml)	Wilcoxon-Test	4.2 (3.5)	4.2 (3.0)	1.1 (1.0 to 1.4)	0.08	11	3.9 (3.1)	4.4 (3.0)	1.1 (1.0 to 1.4)	**0.027**	8	4.7 (4.2)	3.8 (3.1)	1.1 (0.7 to 1.6)	0.492	0.197
IL-9 (pg/ml)	Wilcoxon-Test	33.4 (29.7)	33.7 (27.8)	1.1 (1.0 to 1.2)	0.094	15	31.5 (27.9)	33.1 (25.6)	1.1 (1.0 to 1.3)	0.147	8	37.1 (34.5)	34.9 (33.4)	1.0 (0.8 to 1.3)	0.716	0.393
IL-10 (pg/ml)	Wilcoxon-Test	6.2 (3.8)	6.1 (3.5)	1.1 (0.9 to 1.2)	0.566	13	6.1 (4.3)	6.1 (3.6)	1.0 (0.9 to 1.2)	0.975	8	6.3 (3.3)	6.1 (3.6)	1.1 (0.7 to 1.5)	0.938	0.916
TNF-α (pg/ml)	Pairwise T-Test	49.6 (37.5)	47.1 (32.8)	1.0 (0.8 to 1.5)	0.424	11	48.3 (45.1)	49.0 (39.4)	1.1 (0.8 to 1.9)	0.831	5	52.5 (13.0)	43.0 (11.2)	0.9 (0.6 to 1.1)	0.203	0.124
IFN-γ (pg/ml)	Pairwise T-Test	66.5 (59.1)	72.1 (58.5)	1.0 (0.5 to 2.7)	0.364	8	80.8 (72.5)	84.6 (71.2)	1.0 (-0.1 to 3.8)	0.602	5	56.6 (23.7)	66.0 (25.6)	1.1 (0.6 to 2.0)	0.511	0.684
IL-13 (pg/ml)	Wilcoxon-Test	27.7 (22.1)	22.9 (15.2)	1.0 (0.7 to 1.3)	0.433	9	26.9 (22.1)	25.6 (16.0)	1.1 (0.8 to 1.5)	0.69	5	29.2 (24.6)	18.0 (14.1)	0.5 (0.1 to 1.3)	0.267	0.228
IL-5 (pg/ml)	Wilcoxon-Test	20.7 (17.2)	18.5 (12.3)	0.9 (0.8 to 1.2)	0.36	12	23.9 (20.2)	20.2 (14.6)	0.9 (0.9 to 1.1)	0.209	6	14.3 (6.3)	15.3 (4.9)	1.1 (0.5 to 2.0)	0.76	0.313

Pre and post values are shown in mean and SD; pre, before exercise test; post, immediate after exercise test; FC, median fold change; 95% CI, 95% confidence interval; N, number of participants; time × sex ANOVA; IL, interleukin; TNF-α, tumor necrosis factor-alpha; highlighted are significant p values < 0.05. N differences are due to analysis.

TABLE 4. Acute changes in vitality and fatigue.

		Overall					Men					Women				ANOVA
Variable	**Test**	**Pre**	**Post**	**FC (95% CI)**	**p-value**	**N**	**Pre**	**Post**	**FC (95% CI)**	**p-value**	**N**	**Pre**	**Post**	**FC (95% CI)**	**p-value**	**Time × Sex**
Fatigue	Pairwise T-Test	2.1 (0.9)	4.8 (1.8)	2.4 (0.6 to 1.4)	**< 0.001**	16	1.9 (0.9)	4.4 (1.6)	2.4 (1.9 to 3.6)	**< 0.001**	8	2.4 (0.9)	5.6 (1.9)	2.5 (1.2 to 4.7)	**0.005**	0.334
SVS-GM-3 vitality	Pairwise T-Test	6.9 (1.7)	6.5 (1.5)	0.9 (0.8 to 1.2)	0.375	16	7.1 (1.6)	6.9 (1.1)	0.9 (0.9 to 1.2)	0.615	8	6.5 (2.0)	5.6 (1.9)	0.9 (0.6 to 1.4)	0.495	0.573
SVS-GM-3 motivation	Pairwise T-Test	7.1 (1.8)	5.9 (1.8)	0.9 (0.7 to 1.1)	0.05	16	7.1 (1.7)	6.2 (1.2)	0.9 (0.8 to 1.1)	0.095	8	7.1 (2.1)	5.3 (2.7)	0.8 (0.3 to 1.4)	0.25	0.431
SVS-GM-3 energy	Pairwise T-Test	7.3 (1.9)	6.3 (1.8)	0.9 (0.8 to 1.1)	0.079	16	7.5 (1.8)	6.6 (1.3)	0.8 (0.8 to 1.1)	0.084	8	7.0 (2.1)	6.6 (1.3)	1.0 (0.4 to 1.4)	0.368	0.628
SVS-GM-1 overall	Pairwise T-Test	7.1 (1.5)	6.1 (1.7)	0.9 (0.8 to 1.1)	0.062	16	7.4 (1.3)	6.5 (1.3)	0.9 (0.8 to 1.0)	0.063	8	6.6 (1.9)	5.4 (2.2)	0.8 (0.4 to 1.4)	0.375	0.738

Pre and post values are shown in mean and SD; pre, before exercise test; post, evening post-exercise test; SVS-GM, 1-item, and 3-item modified German Subjective Vitality Scale; FC, mean fold change; 95% CI, 95% confidence interval; N, number of participants; time × sex ANOVA; highlighted are significant p values < 0.05.

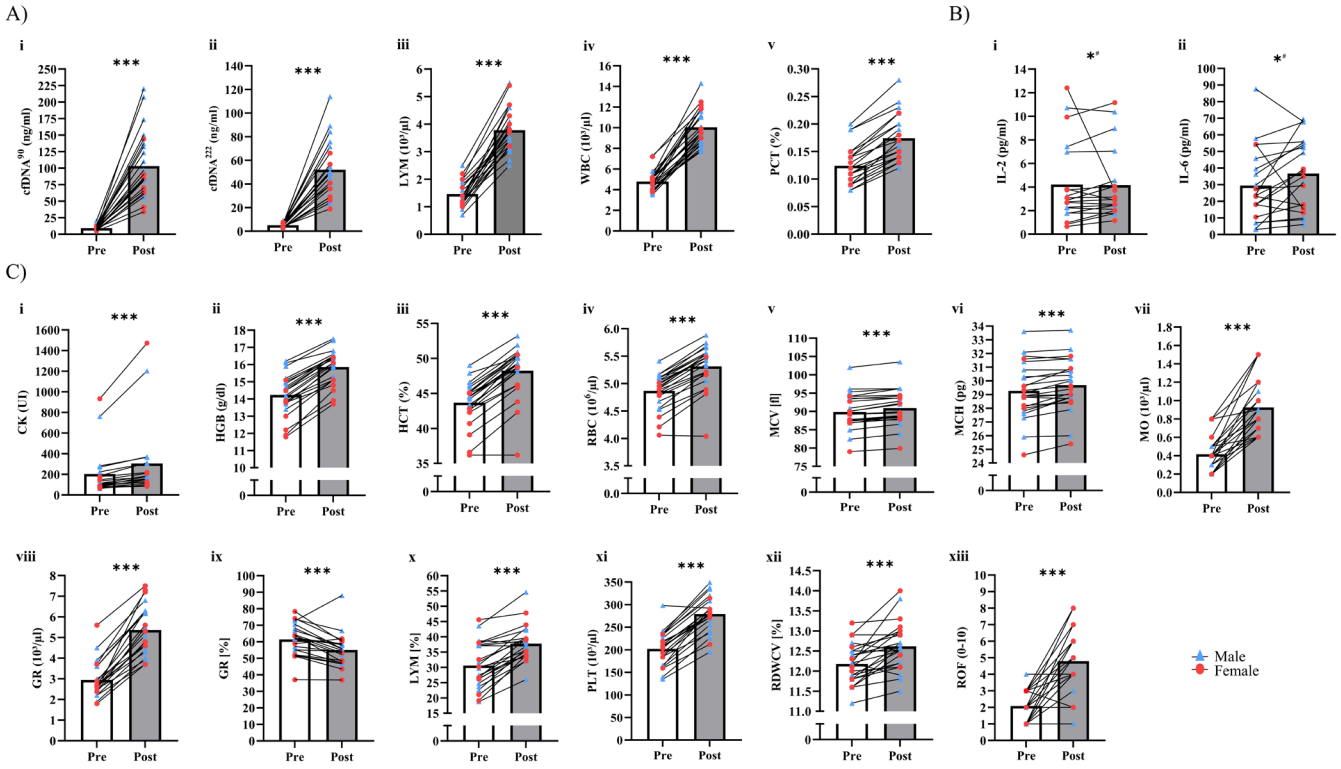


FIG. 2. Acute increases of blood-based biomarkers and questionnaires. A) Blood-based biomarkers with significant time × sex ANOVA. B) Female vs. male acute increase of cytokines. C) Overall acute increases of blood-based biomarkers and questionnaires. Red dots, female participants; blue triangle, male participants; bars represent mean values; white bar, pre; grey bar, immediate post-exercise; CK, creatine kinase; WBC, white blood cell count; RBC, red blood cell count; HGB, hemoglobin; HCT, hematocrit; MCV, mean corpuscular volume; MCH, mean corpuscular hemoglobin; PLT, platelet; LYM, lymphocytes; MO, monocytes; GR, absolute granulocytes; RDWCV, red blood cell distribution width; PCT, procalcitonin; ROF, rate of fatigue; * $p < 0.05$, *** $p < 0.001$, # male.

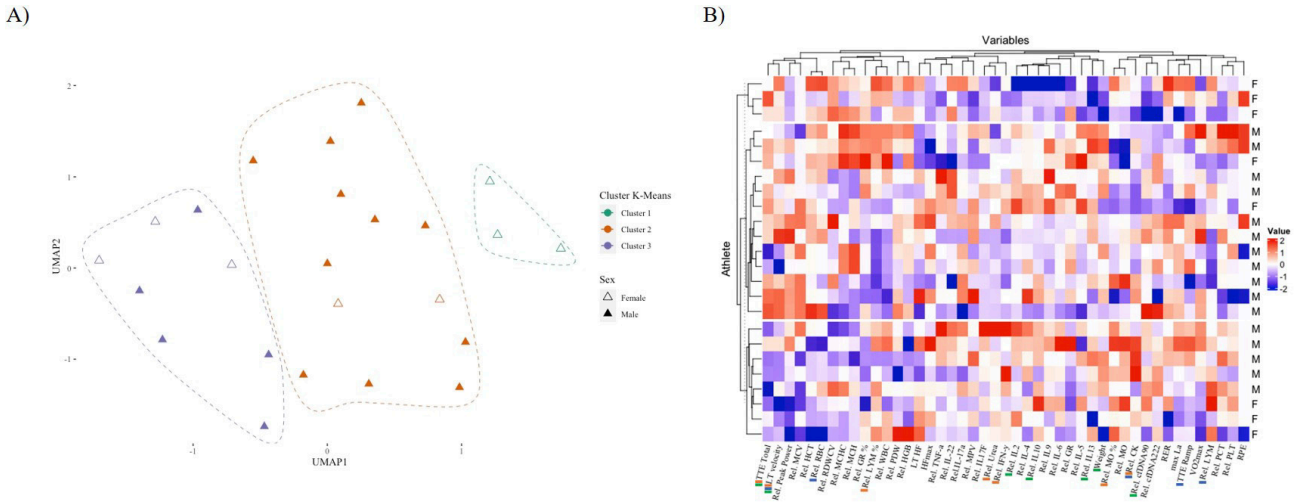


FIG. 3. Characterization of three distinct athlete clusters based on key biomarkers. A) UMAP plot illustrating the distribution of athletes according to sex and k-means clustering with three clusters: "Cluster 1" (n = 3), "Cluster 2" (n = 13, 2 females), and "Cluster 3" (n = 8, 3 females). Female athletes are represented by unfilled triangles, while male athletes are represented by colored filled triangles. B) Heatmap displaying the standardized values of 46 variables (rows) for each athlete (columns), with row annotations indicating the sex (F: Female, M: Male) of each athlete. Clusters are color-coded according to the same scheme used in (A). The top markers are represented as colored bars in the names, being green (Cluster 1), red (Cluster 2), and blue (Cluster 3).The three clusters exhibit distinct patterns of biomarkers, with significant differences in their sex compositions (X-squared = 7.9471, df = 2, p-value = 0.02).

K-means clustering identified three distinct groups of athletes with differing proportions of female participants, which could be classified as "cluster 1" (n = 3, 100% female), "cluster 2" (n = 13, 85% male), and "cluster 3" (n = 8, 37.5% female and 65.5% male) (Figure 3A). The correlation revealed distinct patterns among the three groups of athletes (Figure 3B). Each cluster was distinguished by a particular combination of biomarkers and exercise testing performance parameters. Loadings derived from k-means clustering offer insights into the distribution of variables within each cluster and serve as descriptive summaries of the central tendencies of variables within each cluster (Supplement Figure C). Specifically, a positive loading for a particular variable within a cluster signifies that cluster members exhibit higher values for that variable in comparison to members of other clusters. Conversely, a negative loading implies the opposite.

Cluster 1 was characterized by negative loadings for weight, $\dot{V}O_{2max}$, maximal HR (HR_{max}), and relative PPO but a positive loading for RPE. Most of the inflammatory markers had negative loadings, suggesting lower levels of these markers in this cluster. This aligns with the observation that relative IL-2, relative IL-10, relative IL-13, relative $cfDNA^{90}$, total TTE, LT, and body weight served as the primary markers for the cluster consisting of females, only. Cluster 2 had a negative loading for $\dot{V}O_{2max}$ and relative PPO but a positive loading for HR_{max}. The loadings for inflammatory markers were mixed, but many were positive, suggesting higher levels of these markers compared to cluster 1. This is characterized by relative MO, relative IFN-y, relative LYM, relative CK, relative urea, relative PPO, total TTE, and LT serving as the primary markers for the cluster consisting primarily of men. Cluster 3 exhibited predominantly positive loadings for most of the exercise testing performance parameters. In terms of the inflammatory markers, the loadings were mixed, with many showing a positive, indication a diverse immune response. Nevertheless, it is crucial to recognize the variability in sex distribution within this cluster. A chi-squared test was performed on the contingency table of clusters and sex, and the results showed a significant difference (X-squared = 7.9471, df = 2, p = 0.02).

To provide a comprehensive understanding of this process, a full description of the variable importance is included in the supplementary data, which is represented in the form of a heatmap of the centers (Supplement Figure C). This heatmap serves as a visual representation of the variables' contribution to the k-means clustering and provides insight into their relative importance for each level of clustering (1, 2, and 3), rather than for the individual levels of the athletes' variables.

DISCUSSION

The present study examined established and novel biomarkers, such as various cytokines and cfDNA, in an acute exhaustive exercise setting with respect to sex differences. Acute increases in venous blood count markers and cfDNA were observed in male and female athletes, while cytokines were unaffected, except for IL-2 and IL-6, which showed larger increases in men. Male and female athletes exhibited similar acute responses in blood count markers. Cell-free DNA^{222} and $cfDNA^{90}$ increased significantly in male and female athletes, with male athletes showing higher increases than their female counterparts. In contrast, post-exercise WBC and LYM concentrations were higher in female athletes. For questionnaires, only fatigue was affected by the exercise test. This study innovatively applies the k-means clustering method to detect potential distributions in biomarker profiles between biological sexes. Three distinct groups of athletes with varying proportions of female participants were identified. Notably, in the exclusively female cluster, relative changes in cytokines such as IL-2, IL-10, IL-13, and $cfDNA^{90}$ were the primary markers that differed from the other clusters.

Cell-free DNA and cytokines have been increasingly adopted in studies of acute and chronic stress responses in recent years [31]. Particularly, cfDNA has demonstrated good reliability with marked acute responses during aerobic running [12], incremental testing [32], and intermittent exercise, even demonstrating a relationship with distance covered in soccer players [8]. In line with previous findings, cfDNA significantly increased after exercise testing, further highlighting cfDNA as an exercise responsive biomarker. For the first time, sex differences were shown for both $cfDNA^{90}$ and $cfDNA^{222}$ (Figure 2A i, ii, and Table 2). The more pronounced increases in cfDNA concentrations in males may be attributed to the longer duration of the exercise test, higher LA concentration, and a higher relative PPO (Table 2) [31]. Hormonal differences, including menstrual cycle fluctuations in women, could also contribute to sex differences in relative changes in cfDNA [33], although literature on this topic is scarce [34]. To our knowledge, only Pölcher et al. [34] have shown that cfDNA levels do not differ during the different phases of the menstrual cycle when studying healthy participants and cancer patients. Our study did not control for the menstrual cycle, which could have affected the immune response. Therefore, it remains to be determined which factors impact sex differences in cfDNA.

Previous studies have shown an increase in cytokine concentrations during prolonged running [11, 14] with athletes generally showing an attenuated response [3, 35]. Our results showed slight significant increases in IL-2 and IL-6 in males (Table 3), while other studies have demonstrated acute increases in other cytokines as well (e.g., TNF-α, IL-10, IL-1 receptor antagonist) [3, 10, 14, 18, 20, 35]. In particular, IL-6 has been identified as an exercise-sensitive biomarker [18]. Lobo et al. [20] observed similar responses in IL-6 levels in females and males (2.8- and 2.3-fold) after a fatiguing aerobic exercise protocol, suggesting similar immunological responses between sexes. Conversely, we found a significant increase in IL-6 concentrations in male participants, while baseline values in females were lower and did not change significantly. Bernardi et al. [21] found higher baseline values in IL-6, IL-1β, and TNF-α in healthy males compared to females.

Whole blood count markers (e.g., MCV, HGB, PLT, RBC, HCT, and MCHC) have been shown to be reliable and sensitive to acute

exercise [18]. This is consistent with our results, as 15 biomarkers were acutely elevated in male and female participants, as an exercise-induced stress response (Table 2). The highest overall increases (2.0–2.7-fold) were observed in leukocytes (i.e., WBC, LYM, MO) which is in line with other studies [10, 20, 36]. Our data disagrees with the findings from Lobo et al. [20] who reported similar changes in both sexes in WBC and LYM. However, the training protocol differed from the current protocol with participants having a lower training level compared to our participants [20]. Alis et al. [37] reported, concurring with our results, an increase in platelets after exhaustive exercise. Low HGB concentration in athletes, specifically in females can be to the results of iron deficiency [38], even though our results showed no acute differences in male and female participants. Conflicting results regarding sex differences and limited information for athletes persist about haematological markers and require further investigation [37].

Creatine kinase has been used in acute and chronic situations to monitor internal load and an immediate exercise-induced increase has been observed in various modes of exercise, in accordance with our data [39]. However, peak levels can be observed 48 hours to five days after exercise, and men generally have higher resting serum CK concentrations than women [40–42]. Similarly, in our study, CK levels immediately increased after the exercise in two participants who had higher baseline values, while others increased slightly (Figure 2B i). This shows that post-exercise CK levels have high variability, e.g., due to different types of responders [43, 44].

We observed no significant changes in subjective vitality, motivation, or energy (Table 4). However, motivation declined from morning to evening and reached borderline significance ($p = 0.05$). The original SVS by Ryan and Frederick [45] has shown to be influenced by long-term exercise, however, the SVS-GM has not been used in an acute exercise setting. Buchner et al. [25] reported an increase in vitality throughout the day in an everyday life scenario rather than an acute response. Hereby, it requires further investigation if lower exercise intensities than in our study lead to increases in subjective vitality. Fatigue increased significantly in male and female participants, reflecting the exhaustive nature of the exercise test (RPE > 19).

The study identified three distinct groups of athletes with differing proportions of female participants, which emphasizes the relevance of sex-specific biomarker profiles and individualized exercise response within athletic populations. In the exclusively female cluster, markers such as IL-2, IL-10, IL-13, and $cfDNA^{90}$ were identified, suggesting the possibility of targeted interventions to modulate immune responses specifically in female athletes. In cluster 2 (primarily composed of males), relevant markers included MO, IFN-y, LYM, and CK, whereas cluster 3 (featured both males and females) exhibited RBC, LYM, and CK markers. Since previous studies have reported mixed findings regarding sex-related differences in exercise-induced immune responses [11, 14, 20, 21, 46, 47], it remains uncertain whether biological sex influenced the observed negative correlation between IL-2, IL-10, and IL-13 and female participants in cluster 1 (Supplement Figure C). In addition, our cluster classification accounts for all levels of cytokine distributions, which is essential for a comprehensive understanding of immune response. Similar to a study by Xiong et al. [48], where k-means clustering was employed as part of a machine learning approach, aiming to elucidate the distribution patterns of cytokines and their significance in the context of cytokine release syndrome detection. Despite prior research investigating biomarkers associated with exercise and physical performance, only one study has explored the potential differences in biomarker profiles based on biological sex and resulting clustering patterns [49].

Utilizing cluster analysis based on biological sex may provide insights into potential sex-related differences in biomarker response to exercise. Furthermore, the holistic examination of multiple biomarkers remains essential for a comprehensive understanding of immune responses to exercise. Through k-means clustering, we identified distinct patterns among the biomarkers. However, it is important to note that the small sample size may limit the generalizability of the findings. One inherent limitation of k-means clustering is its sensitivity to unbalanced group sizes. The algorithm aims to minimize within-cluster variance, which can be dominated by larger clusters, potentially overshadowing smaller but significant clusters [50]. To address these limitations and improve the robustness of our analyses, a larger sample size with a more balanced sex distribution would be beneficial. This would enable more robust statistical analyses and further improve the machine learning predictions, enhancing the evaluation of the predictive power of the identified biomarkers. Consequently, replication studies on a larger sample size would advance work in this area.

Our observations are limited to two time points and do not indicate whether there are any cluster-specific effects in the kinetics of these biomarkers returning to baseline. In addition, the evaluation of the subjective assessment in the evening may have been influenced by uncontrolled factors (e.g., stress in personal and work life). This study did not control for the menstrual cycle phase of female participants, which could have impacted the biomarker concentrations. Investigating menstrual shifts in hormonal status could provide further detail regarding sex differences in the acute exercise response. Lastly, further analysis for biomarker sensitivity is essential as reference ranges for athletes are missing, and there are high intra-individual differences. In particular, the cytokine results showed a certain variability and data were missing because there was not a concentration detected for each cytokine.

CONCLUSIONS

In summary, our results identified exercise-sensitive biomarkers ($cfDNA^{90}$, $cfDNA^{222}$, and blood count markers) for monitoring the acute exercise response. While sex differences were found in certain blood count markers and cfDNA, the k-means cluster analysis revealed three distinct groups with varying proportions of female participants and different cytokine levels. This suggests that investigating

sex-specific cytokine profiles, particularly related to IL-2, IL-10, IL-13, and cfDNA[90], may play a crucial role in exercise research and practice. Differences between women and men in certain biomarkers highlight the need for establishing a set of biomarkers for exercise testing and to further investigate sex differences in athletes.

Acknowledgements

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Conflict of interest

The study has received funding from the Red Bull Athlete Performance Center. The funding body has not peer-reviewed the manuscript. This sponsor was not involved in the study design, the writing of the manuscript, or the decision to submit the manuscript for publication.

Data availability

The dataset used and analyzed during the current study is available from the corresponding author on reasonable request.

Ethics declarations

All participants are informed orally about the aims and risks of the study and must give their written consent before participating. All procedures have been approved by the local ethical board (University of Salzburg, GZ 2/2021).

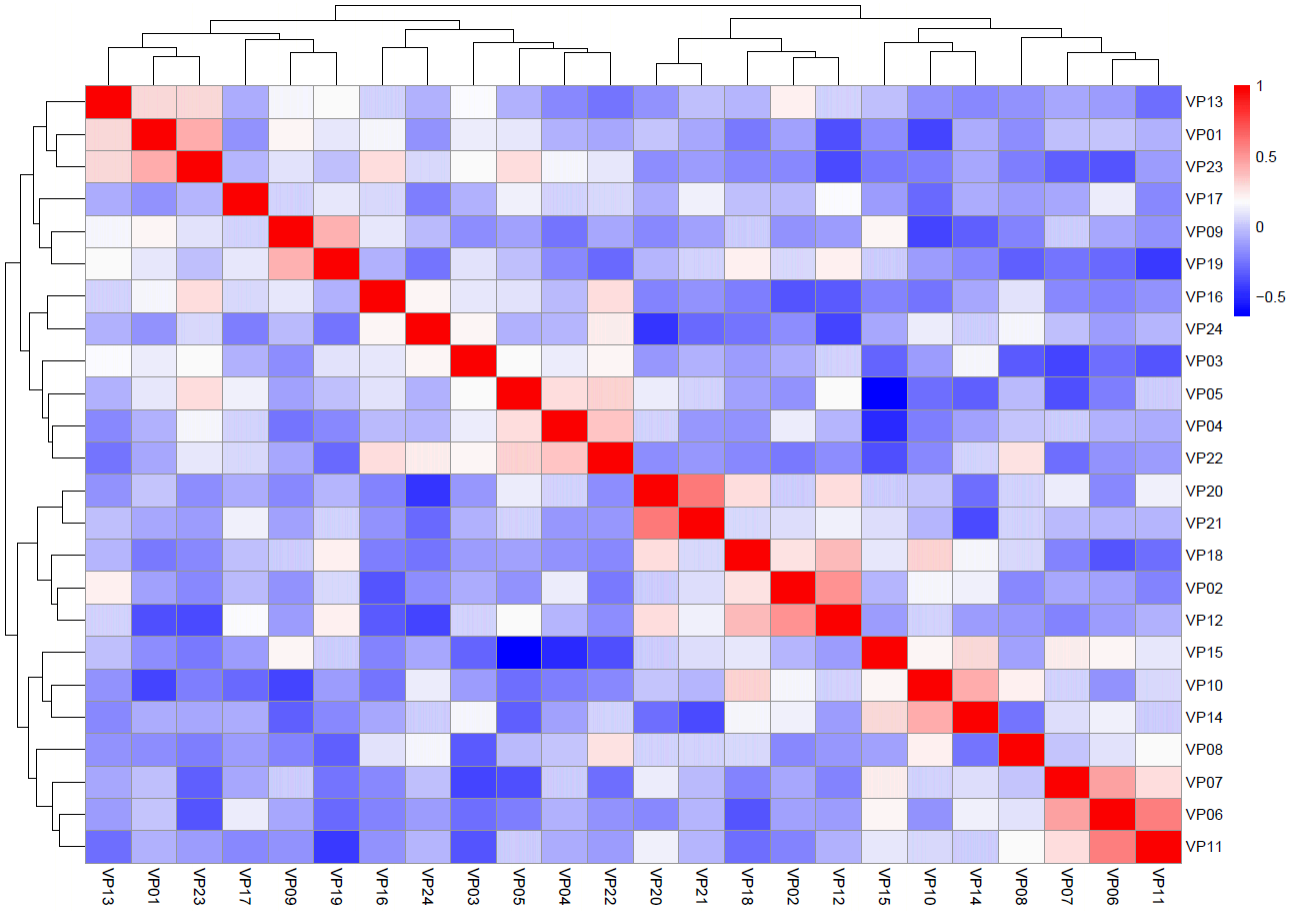
REFERENCES

1. Lee EC, Fragala MS, Kavouras SA, Queen RM, Pryor JL, Casa DJ. Biomarkers in Sports and Exercise: Tracking Health, Performance, and Recovery in Athletes. J Strength Cond Res. 2017; 31(10):2920–37. Epub 2017/07/25. doi: 10.1519/JSC.0000000000002122. PubMed PMID: 28737585; PubMed Central PMCID: PMC5640004.
2. Palacios G, Pedrero-Chamizo R, Palacios N, Maroto-Sanchez B, Aznar S, Gonzalez-Gross M, et al. Biomarkers of physical activity and exercise. Nutr Hosp. 2015; 31 Suppl 3:237–44. Epub 2015/02/27. doi: 10.3305/nh.2015.31.sup3.8771. PubMed PMID: 25719791.
3. Scott JP, Sale C, Greeves JP, Casey A, Dutton J, Fraser WD. Cytokine response to acute running in recreationally-active and endurance-trained men. Eur J Appl Physiol. 2013; 113(7):1871–82. Epub 20130306. doi: 10.1007/s00421-013-2615-x. PubMed PMID: 23463480.
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. Epub 2019/01/08. doi: 10.1123/ijspp.2018-0935. PubMed PMID: 30614348.
5. 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(Suppl 2):S22–S8. Epub 2017/03/03. doi: 10.1123/ijspp.2016-0388. PubMed PMID: 28253038.
6. Halson SL. Monitoring training load to understand fatigue in athletes. Sports Med. 2014; 44 Suppl 2(Suppl 2): S139–47. doi: 10.1007/s40279-014-0253-z. PubMed PMID: 25200666; PubMed Central PMCID: PMC4213373.
7. Haller N, Behringer M, Reichel T, Wahl P, Simon P, Kruger K, et al. Blood-Based Biomarkers for Managing Workload in Athletes: Considerations and Recommendations for Evidence-Based Use of Established Biomarkers. Sports Med. 2023:1–19. Epub 20230519. doi: 10.1007/s40279-023-01836-x. PubMed PMID: 37204619; PubMed Central PMCID: PMC10197055.
8. Haller N, Helmig S, Taenny P, Petry J, Schmidt S, Simon P. Circulating, cell-free DNA as a marker for exercise load in intermittent sports. PLoS One. 2018; 13(1):e0191915. Epub 2018/01/26. doi: 10.1371/journal.pone.0191915. PubMed PMID: 29370268; PubMed Central PMCID: PMC5784997.
9. Pedersen BK, Toft AD. Effects of exercise on lymphocytes and cytokines. Br J Sports Med. 2000; 34(4):246–51. Epub 2000/08/23. doi: 10.1136/bjsm.34.4.246. PubMed PMID: 10953894; PubMed Central PMCID: PMC1724218.
10. Petersen AM, Pedersen BK. The anti-inflammatory effect of exercise. J Appl Physiol (1985). 2005; 98(4):1154–62. Epub 2005/03/18. doi: 10.1152/japplphysiol.00164.2004. PubMed PMID: 15772055.
11. Ostrowski K, Schjerling P, Pedersen BK. Physical activity and plasma interleukin-6 in humans--effect of intensity of exercise. Eur J Appl Physiol. 2000; 83(6):512–5. Epub 2001/02/24. doi: 10.1007/s004210000312. PubMed PMID: 11192058.
12. Haller N, Tug S, Breitbach S, Jorgensen A, Simon P. Increases in Circulating Cell-Free DNA During Aerobic Running Depend on Intensity and Duration. Int J Sports Physiol Perform. 2017; 12(4):455–62. Epub 2016/09/13. doi: 10.1123/ijspp.2015-0540. PubMed PMID: 27617389.
13. Haller N, Reichel T, Zimmer P, Behringer M, Wahl P, Stoggl T, et al. Blood-Based Biomarkers for Managing Workload in Athletes: Perspectives for Research on Emerging Biomarkers. Sports Med. 2023. Epub 20230621. doi: 10.1007/s40279-023-01866-5. PubMed PMID: 37341908.
14. Ostrowski K, Hermann C, Bangash A, Schjerling P, Nielsen JN, Pedersen BK. A trauma-like elevation of plasma cytokines in humans in response to treadmill running. J Physiol. 1998; 513 (Pt 3)(Pt 3):889–94. Epub 1998/11/24. doi: 10.1111/j.1469-7793.1998.889ba.x. PubMed PMID: 9824725; PubMed Central PMCID: PMC2231318.
15. Fischer CP. Interleukin-6 in acute exercise and training: what is the biological relevance? Exerc Immunol Rev. 2006; 12:6–33. PubMed PMID: 17201070.
16. Haller N, Ehlert T, Schmidt S, Ochmann D, Sterzing B, Grus F, et al. Circulating, Cell-Free DNA for Monitoring Player Load in Professional Football. Int J Sports Physiol Perform. 2019; 14(6):718–26. Epub 20190701. doi: 10.1123/ijspp.2018-0756. PubMed PMID: 30427238.
17. Burgess DJ. The Research Doesn't Always Apply: Practical Solutions to Evidence-Based Training-Load Monitoring in Elite Team Sports. Int J Sports Physiol Perform. 2017; 12(Suppl 2):S2136–s41. Epub 20161214. doi: 10.1123/ijspp.2016-0608. Epub 2016 Dec 14. PubMed PMID: 27967277.
18. Reichel T, Bosslau TK, Palmowski J, Eder K, Ringseis R, Mooren FC, et al. Reliability and suitability of physiological exercise response and recovery markers. Sci Rep. 2020; 10(1):11924. Epub 20200717. doi: 10.1038/s41598-020-69280-9. PubMed PMID: 32681124; PubMed Central PMCID: PMC7368084.
19. Northoff H, Symons S, Zieker D, Schaible EV, Schafer K, Thoma S, et al. Gender- and menstrual phase dependent regulation of inflammatory gene expression in response to aerobic exercise. Exerc Immunol Rev. 2008; 14:86–103. PubMed PMID: 19203086.
20. Lobo LF, de Morais MG, Marcucci-Barbosa LS, Martins-Junior FAD, Avelar LM, Vieira ELM, et al. A Single Bout of

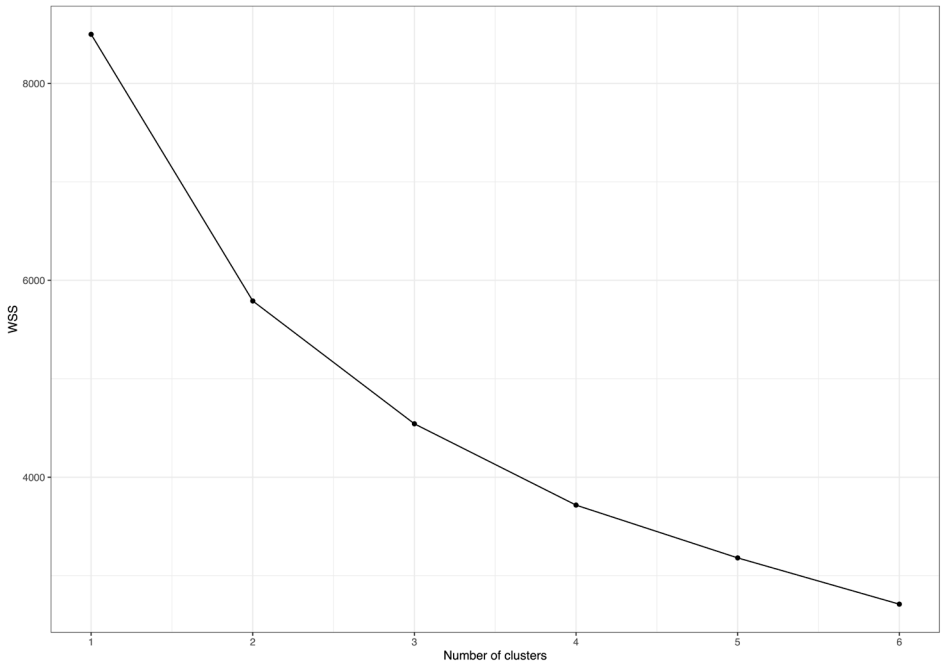
Fatiguing Aerobic Exercise Induces Similar Pronounced Immunological Responses in Both Sexes. Front Physiol. 2022; 13:833580. Epub 20220608. doi: 10.3389/fphys.2022.833580. PubMed PMID: 35755444; PubMed Central PMCID: PMC9213785.
21. Bernardi S, Toffoli B, Tonon F, Francica M, Campagnolo E, Ferretti T, et al. Sex Differences in Proatherogenic Cytokine Levels. Int J Mol Sci. 2020; 21(11). Epub 20200529. doi: 10.3390/ijms21113861. PubMed PMID: 32485823; PubMed Central PMCID: PMC7311959.
22. Stoggl TL, Blumkaitis JC, Strepp T, Sareban M, Simon P, Neuberger EWI, et al. The Salzburg 10/7 HIIT shock cycle study: the effects of a 7-day high-intensity interval training shock microcycle with or without additional low-intensity training on endurance performance, well-being, stress and recovery in endurance trained athletes-study protocol of a randomized controlled trial. BMC Sports Sci Med Rehabil. 2022; 14(1):84. Epub 2022/05/08. doi: 10.1186/s13102-022-00456-8. PubMed PMID: 35526065; PubMed Central PMCID: PMC9077880.
23. Borg G. Perceived exertion as an indicator of somatic stress. Scand J Rehabil Med. 1970; 2(2):92–8. PubMed PMID: 5523831.
24. Neuberger EWI, Brahmer A, Ehlert T, Kluge K, Philippi KFA, Boedecker SC, et al. Validating quantitative PCR assays for cfDNA detection without DNA extraction in exercising SLE patients. Sci Rep. 2021; 11(1):13581. Epub 20210630. doi: 10.1038/s41598-021-92826-4. PubMed PMID: 34193884; PubMed Central PMCID: PMC8245561.
25. Buchner L, Amesberger G, Finkenzeller T, Moore SR, Wurth S. The modified German subjective vitality scale (SVS-GM): Psychometric properties and application in daily life. Front Psychol. 2022; 13:948906. Epub 2022/08/16. doi: 10.3389/fpsyg.2022.948906. PubMed PMID: 35967701; PubMed Central PMCID: PMC9374102.
26. Micklewright D, St Clair Gibson A, Gladwell V, Al Salman A. Development and Validity of the Rating-of-Fatigue Scale. Sports Med. 2017; 47(11):2375–93. Epub 2017/03/12. doi: 10.1007/s40279-017-0711-5. PubMed PMID: 28283993; PubMed Central PMCID: PMC5633636.
27. Cohen J. Statistical Power Analysis for the Behavioral Sciences. The SAGE Encyclopedia of Research Design. 1969.
28. van Buuren S, Groothuis-Oudshoorn K. mice: Multivariate Imputation by Chained Equations in R. J Stat Softw. 2011; 45(3):1–67. doi: 10.18637/jss.v045.i03.
29. McInnes L, Healy J, Saul N, Grossberger L. UMAP: Uniform Manifold Approximation and Projection. J Open Source Softw. 2018; 3:861. doi: 10.21105/joss.00861.
30. Lang M, Binder M, Richter J, Schratz P, Pfisterer F, Coors S, et al. mlr3: A modern object-oriented machine learning framework in R. J Open Source Softw. 2019; 4:1903. doi: 10.21105/joss.01903.
31. Breitbach S, Tug S, Simon P. Circulating cell-free DNA: an up-coming molecular marker in exercise physiology. Sports Med. 2012; 42(7):565–86. doi: 10.2165/11631380-000000000-00000. PubMed PMID: 22694348.
32. Breitbach S, Sterzing B, Magallanes C, Tug S, Simon P. Direct measurement of cell-free DNA from serially collected capillary plasma during incremental exercise. J Appl Physiol (1985). 2014; 117(2):119–30. Epub 2014/05/31. doi: 10.1152/japplphysiol.00002.2014. PubMed PMID: 24876361.
33. Bruinvels G, Burden R, McGregor A, Ackerman K, Dooley M, Richards T, et al. Sport, exercise and the menstrual cycle: where is the research? : BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine; 2017. p. 487–8.
34. Polcher M, Ellinger J, Willems S, El-Maarri O, Holler T, Amann C, et al. Impact of the menstrual cycle on circulating cell-free DNA. Anticancer Res. 2010; 30(6):2235–40. Epub 2010/07/24. PubMed PMID: 20651374.
35. Gokhale R, Chandrashekara S, Vasanthakumar KC. Cytokine response to strenuous exercise in athletes and non-athletes--an adaptive response. Cytokine. 2007; 40(2):123–7. Epub 20071022. doi: 10.1016/j.cyto.2007.08.006. PubMed PMID: 17950614.
36. Gleeson M, Bishop NC, Stensel DJ, Lindley MR, Mastana SS, Nimmo MA. The anti-inflammatory effects of exercise: mechanisms and implications for the prevention and treatment of disease. Nat Rev Immunol. 2011; 11(9):607–15. Epub 20110805. doi: 10.1038/nri3041. PubMed PMID: 21818123.
37. Alis R, Sanchis-Gomar F, Risso-Ballester J, Blesa JR, Romagnoli M. Effect of training status on the changes in platelet parameters induced by short-duration exhaustive exercise. Platelets. 2016; 27(2):117–22. Epub 2015/05/30. doi: 10.3109/09537104.2015.1047334. PubMed PMID: 26023745.
38. Mercer KW, Densmore JJ. Hematologic disorders in the athlete. Clin Sports Med. 2005; 24(3):599–621, ix. doi: 10.1016/j.csm.2005.03.006. PubMed PMID: 16004921.
39. Baird MF, Graham SM, Baker JS, Bickerstaff GF. Creatine-kinase- and exercise-related muscle damage implications for muscle performance and recovery. J Nutr Metab. 2012; 2012:960363. Epub 20120111. doi: 10.1155/2012/960363. PubMed PMID: 22288008; PubMed Central PMCID: PMC3263635.
40. Mougios V. Reference intervals for serum creatine kinase in athletes. Br J Sports Med. 2007; 41(10):674–8. Epub 2007/05/29. doi: 10.1136/bjsm.2006.034041. PubMed PMID: 17526622; PubMed Central PMCID: PMC2465154.
41. Brancaccio P, Maffulli N, Limongelli FM. Creatine kinase monitoring in sport medicine. Br Med Bull. 2007; 81–82:209–30. Epub 2007/06/16. doi: 10.1093/bmb/ldm014. PubMed PMID: 17569697.
42. Muller E, Proller P, Ferreira-Briza F, Aglas L, Stoggl T. Effectiveness of Grounded Sleeping on Recovery After Intensive Eccentric Muscle Loading. Front Physiol. 2019; 10:35. Epub 20190128. doi: 10.3389/fphys.2019.00035. PubMed PMID: 30745882; PubMed Central PMCID: PMC6360250.
43. Heled Y, Bloom MS, Wu TJ, Stephens Q, Deuster PA. CK-MM and ACE genotypes and physiological prediction of the creatine kinase response to exercise. J Appl Physiol (1985). 2007; 103(2):504–10. Epub 20070503. doi: 10.1152/japplphysiol.00081.2007. PubMed PMID: 17478608.
44. Machado M, Willardson JM. Short recovery augments magnitude of muscle damage in high responders. Med Sci Sports Exerc. 2010; 42(7):1370–4. doi: 10.1249/MSS.0b013e3181ca7e16. PubMed PMID: 20019640.
45. Ryan RM, Frederick C. On energy, personality, and health: subjective vitality as a dynamic reflection of well-being. J Pers. 1997; 65 3:529–65.
46. Souglis AG, Papapanagiotou A, Bogdanis GC, Travlos AK, Apostolidis NG, Geladas ND. Comparison of Inflammatory Responses to a Soccer Match Between Elite Male and Female Players. J Strength Cond Res. 2015; 29(5):1227–33. doi: 10.1519/jsc.0000000000000767. PubMed PMID: 00124278-201505000-00010.
47. Klein SL, Flanagan KL. Sex differences in immune responses. Nat Rev Immunol. 2016; 16(10):626–38. Epub 20160822. doi: 10.1038/nri.2016.90. PubMed PMID: 27546235.
48. Xiong F, Janko M, Walker M, Makropoulos D, Weinstock D, Kam M, et al. Analysis of cytokine release assay data using machine learning approaches. Int Immunopharmacol. 2014; 22(2):465–79. Epub 20140805.

doi: 10.1016/j.intimp.2014.07.024. PubMed PMID: 25107440.
49. Borjesson A, Lehtihet M, Andersson A, Dahl ML, Vicente V, Ericsson M, et al. Studies of athlete biological passport biomarkers and clinical parameters in male and female users of anabolic androgenic steroids and other doping agents. Drug Test Anal. 2020; 12(4):514–23. Epub 20200129. doi: 10.1002/dta.2763. PubMed PMID: 31925932.
50. Franti P, Sieranoja S. K-means properties on six clustering benchmark datasets. Appl Intell. 2018; 48(12):4743–59. doi: 10.1007/s10489-018-1238-7. PubMed PMID: WOS:000450446800014.

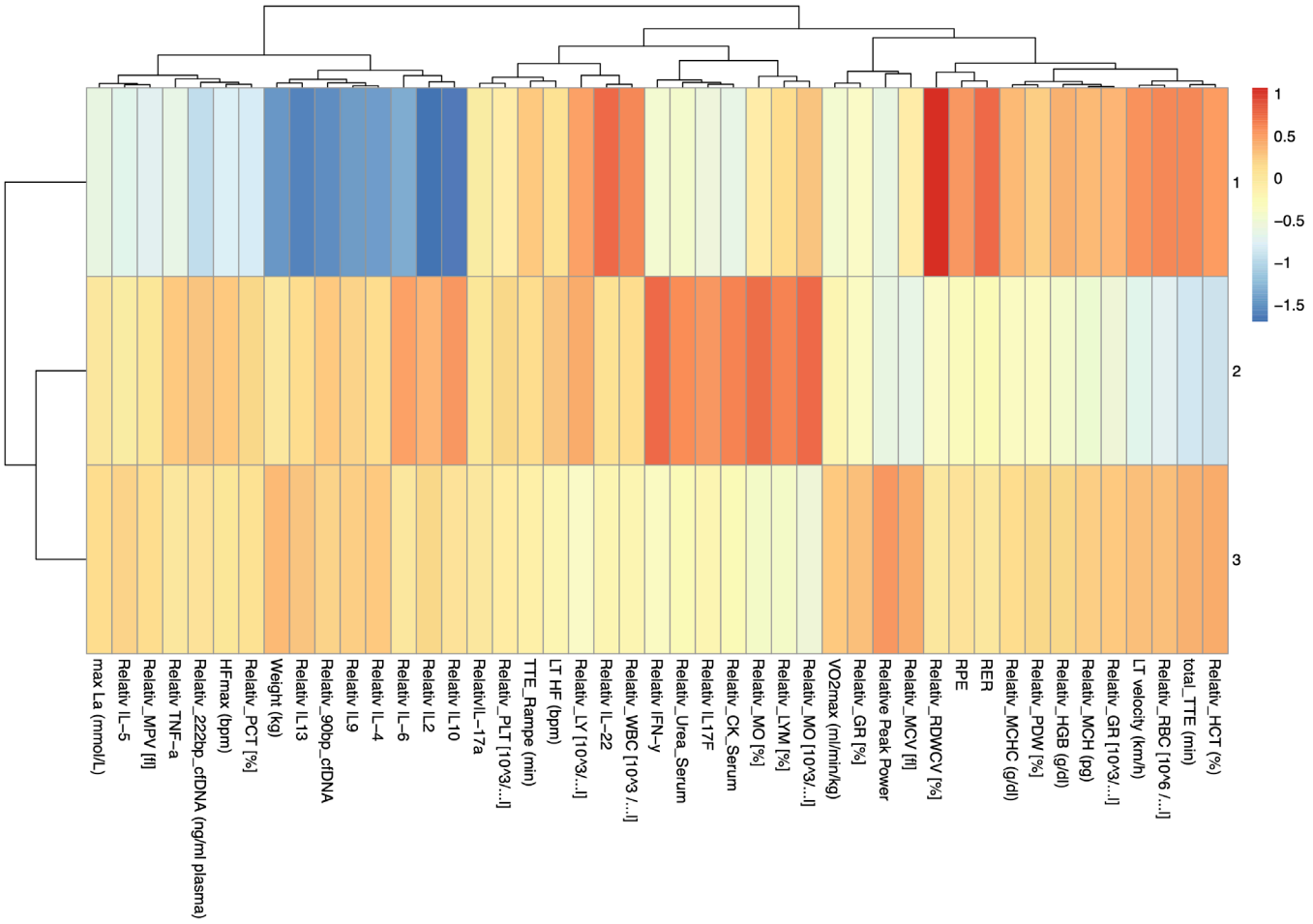
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SUPPLEMENT FIGURE A: Heatmap of Spearman's correlation matrix of log-scaled data. This figure shows the heatmap of the Spearman's correlation matrix of the log-scaled data. The heatmap provides a visual representation of the correlations between each pair of variables, with red indicating positive correlations and blue indicating negative correlations.



SUPPLEMENT FIGURE B: Plot of WSS versus number of clusters. This figure shows the plot of the Within-Cluster-Sum-of-Squares (WSS) versus the number of clusters in the K-means algorithm. The WSS is a measure of the sum of distances between data points and the centroid of their respective clusters. The plot provides a visual representation of how the WSS changes with the number of clusters, and can be used to determine the optimal number of clusters.



SUPPLEMENT FIGURE C: Heatmap of Cluster Centers. This figure shows the heatmap of the cluster centers after being clustered using the K-means algorithm with 3 clusters. The heatmap provides a visual representation of the cluster centers, which are the average of the data points in each cluster. The center values represent the importance of each variable in representing the cluster.

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Comparative analysis of standard and contrast elastic resistance band training effects on physical fitness in female adolescent handball players

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ABSTRACT: This study aimed to compare the effects of two elastic band 10-week training programmes on the athletic performance in adolescent female handball players. Participants aged 16.0 ± 0.5 years were randomly assigned to control (CNT, n = 12), standard elastic band (SEB, n = 12), or contrast elastic band (CEB, n = 12) programmes, each performed twice a week supplementing the regular training. The sprint (10 m and 20 m), modified Illinois change-of-direction test (COD), squat jump (SJ), countermovement jump (CMJ), standing long jump (SLJ), back extensor strength (BES), medicine ball throw (MBT), 1-RM bench press, 1-RM half squat, repeated sprint ability, and force-velocity (F-V) tests were measured before and after the intervention. Both CEB and SEB similarly improved sprint ($p < 0.01$ and $p < 0.01$) and COD ($p < 0.001$ and $p < 0.01$) when compared to CNT. Jumping performance improved significantly (SJ $p < 0.01$; CMJ $p < 0.05$) only in CEB, compared to CNT. Strength improved in both experimental groups ($p < 0.01$; ES: $0.73 < d < 1.59$) compared to CNT, and there was a greater increase for CEB than SEB ($p < 0.05$) in the medicine ball throw (Table 3). Both CEB and SEB increased all RSA scores compared to CNT ($p < 0.01$; ES: $0.10 < d < 1.22$), without significant difference between them. All F-V scores increased significantly in CEB and SEB compared to CNT ($p < 0.01$; ES: $0.45 < d < 2.47$). In addition, CEB showed substantial gains in performance for PP_{abs}, PP_{rel}, and F0 ($p < 0.001$, $p < 0.001$ and $p < 0.05$, respectively) compared to SEB. Ten-week elastic band training conducted within the competitive season improved limb strength, power and F-V profile in female handball players, with a superior effect of the contrast elastic band training mode for upper-limb strength and F-V characteristics.

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INTRODUCTION

Handball, a physically demanding team sport, necessitates a combination of strength, power, speed, agility and others [1–5]. To excel in this sport, athletes must possess a well-rounded physical profile, including optimal muscular strength and power [6]. Consequently, training methods that enhance these attributes are pivotal for the development of adolescent female handball players [7–9].

One such increasingly popular training method is elastic band training, offering versatility and accessibility for resistance training. It provides various benefits, including accommodating resistance, enhancing joint stability, and increasing muscle activation [8–12]. Recently, researchers and practitioners have explored diverse elastic band training variations to maximize its effectiveness and tailor it to specific athletic needs [8–12].

A notable variant is contrast elastic band training, which combines standard elastic bands with those of higher resistance or different elastic properties [9]. This method capitalizes on the post-activation potentiation (PAP) phenomenon, where a high-intensity contraction is followed by subsequent performance improvement in explosive activities [13]. By integrating contrast elastic bands into training protocols, athletes may achieve greater muscular power and improved performance compared to traditional elastic band training alone [9].

Despite extensive studies on elastic band training in various athletic populations [8, 9, 14, 15], limited research has focused specifically on its effects on adolescent female handball players. Understanding the potential benefits and distinctions between standard elastic band training and contrast elastic band training in female handball players is essential for development of an evidence-based training programme that optimizes their athletic performance.

Hence, this study's objective was to compare two types of elastic band strength training methods aimed at developing muscle force, explosiveness, muscle power, and assessing sprint, change

of direction, vertical and horizontal jump, strength, power, and RSA scores. This comparison is critical for designing an evidence-based training programme tailored to a crucial phase in the playing season.

MATERIALS AND METHODS

Participants

A total of forty-five female players were selected from three national handball teams, all affiliated with a sports school. Their demographic information is as follows: age (16.2 [0.3] years), body mass (63.8 [5.3] kg), height (1.66 [0.3] m), and body fat percentage (23.4% [2.1%]). On average, these athletes possessed six years of experience in handball competition.

Approval for all procedures involving human subjects was obtained from the University Institutional Review Committee, ensuring ethical compliance. Informed consent, encompassing both verbal and written explanations of the experimental protocol, its potential risks, and benefits, was acquired from the athletes and their legal guardians. Participants were assured that they could withdraw from the trial at any point without incurring any penalties.

Prior to their participation, all athletes underwent a comprehensive examination by the team physician. This examination focused on identifying any conditions that might preclude them from engaging in plyometric training, particularly recent muscular or joint injuries. Importantly, all participants were found to be in good health.

Study Design

In the week preceding the intervention, players underwent two familiarization sessions lasting 80 to 90 minutes each, aimed at acquainting them with all test procedures. The actual measurements were conducted over four days: both immediately before and four days after the final plyometric training session.

To ensure consistency and accuracy, several protocols were followed. Participants refrained from engaging in strenuous exercise for a 24-hour period prior to testing, and abstained from consuming any food or caffeine-containing beverages for at least two hours before testing. Additionally, a standardized warm-up was implemented before all tests, comprising 10 to 20 minutes of low- to moderate-intensity aerobic exercise and dynamic stretching.

The testing sequence was as follows: On the first test day, anthropometric measurements were taken, followed by a 30-m sprint and the modified Illinois change-of-direction test. Each of these tests allowed for three trials, with a 6- to 8-minute recovery period between trials, and the best performance times were recorded using paired photocells (Microgate, Bolzano, Italy). The second day was dedicated to jumping assessments, including the squat jump and countermovement jump, followed by 1-RM bench press and 1-RM half squat measurements. On the third day, back extensor strength assessments were conducted, followed by the standing long jump and a force-velocity test. The fourth day encompassed the medicine ball throw and the evaluation of repeated sprint ability.

Anthropometry

Anthropometric measurements included standing and sitting body height (stadiometer accuracy of 0.1 cm; Holtain, Crosswell, Crymych, Pembrokeshire, United Kingdom) and body mass (0.1 kg; Tanita BF683W scales, Munich, Germany). The overall percentage of body fat was estimated from the biceps, triceps, subscapular, and suprailiac skinfolds, using the Durnin and Womersley [16] for children and adolescent females:

$$\% \text{ Body fat} = (495/D)-450$$

where D = 1.1369–0.0598 (log sum of 4 skinfolds)

Maturity offset status was calculated from peak height velocity [17]:

Maturity offset = −9.38 + (0.000188 × leg length × sitting height) + (0.0022 × age × leg length) + (0.00584 × age × sitting height) + (0.0769 × weight / height ratio)

20 m sprint performance

During the sprint tests, players initiated the sprint from a split stance standing position, with their front foot positioned 0.2 m from the first photocell beam. Upon receiving the command, they sprinted for a distance of 20 m. Split times were recorded at both the 10-m and 20-m marks for subsequent analysis [18]. Notably, the reliability of these measurements was high, with intra-class correlation coefficients (ICC) of 0.91 for the 10-m sprint and 0.90 for the 20-m sprint. The coefficients of variation (CV) for these measurements were also low, standing at 2.6% for the 10-m sprint and 2.3% for the 20-m sprint.

TABLE 1. Physical characteristics of intervention and control groups (mean ± SD).

	Age (years)	Body mass (kg)	Height (cm)	% Body fat	APHV (years)	Predicted years from APHV
CEB group (n = 12)	16.2 ± 0.3	64.3 ± 4.0	167.1 ± 3.7	23.3 ± 1.0	3.3 ± 0.4	12.9 ± 0.3
SEB group (n = 12)	16.2 ± 0.4	63.8 ± 3.3	165.5 ± 3.2	23.0 ± 1.1	3.3 ± 0.3	13.0 ± 0.4
CNT group (n = 12)	16.3 ± 0.3	63.5 ± 4.4	167.6 ± 3.6	23.9 ± 1.4	3.3 ± 0.4	13.0 ± 0.4

APHV: age of peak height velocity; CEB = contrast elastic band; SEB = standard elastic band; CNT = control

Change of direction performance

To measure change of direction performance, the modified Illinois test was used [19]. It utilized a configuration of four cones to delineate the change-of-direction area. In this test, players were instructed to sprint 5 m on command, make a turn, return to the starting line, and then navigate through the four markers with swerving movements to complete two additional 5-m sprints. While no specific technique was prescribed, players were directed to complete the test as swiftly as possible while avoiding crossing over the markers. If an athlete inadvertently "cut" a marker during the task, the trial was repeated. Three trials were permitted for both the 30-m sprint performance and the modified Illinois test, with a recovery period of 6 to 8 minutes between trials. The best time performances were recorded using paired photocells (Microgate, Bolzano, Italy). The results demonstrated strong reliability, with an intra-class correlation coefficient (ICC) of 0.91, indicating consistent measurements. The coefficient of variation (CV) was low, at 2.2%, attesting to the precision and reliability of the test.

Vertical jumping

To measure jump height, the Optojump System (Microgate SARL in Bolzano, Italy), was utilized. Under the supervision of researchers, participants performed two types of vertical jumps: the squat jump (SJ) and the countermovement jump (CMJ). For the squat jump, participants initiated the jump with their knees bent at a 90-degree angle before executing the jump. For the countermovement jump, individuals commenced from a standing position, swiftly bending their knees to a 90-degree angle, and then launched themselves into the jump.

The reliability of these jump height measurements was noteworthy, with intra-class correlation coefficients (ICCs) of 0.88 for the squat jump (SJ) and 0.89 for the countermovement jump (CMJ). Furthermore, the coefficients of variation (CVs) for these measurements were 8.7% for the squat jump and 7.9% for the countermovement jump.

Standing long jumping

In the beginning posture, players stood with their feet at the same height, legs bent and arms back, horizontal. Participants countermoved with their arms and legs as soon as the command ready, set, go was given before leaping as high as they could in the air. Participants could not fall forward or backward, and they had to land with both feet at the same time. With a tape measure, we measured the horizontal distance to the closest millimetre between the starting line and the heel of the back foot. The ICC is 0.88. The CV value is 8.5%.

Strength performance

Determining an individual's one-repetition maximum (1-RM) for both the half squat and bench press involved a methodical practice regimen. Participants executed a series of lifting sets, with up to six sets in total, and observed a four-minute recovery period between sets. During this process, the weight loads were systematically increased, typically by 5% to 10% of the participant's 1-RM for the bench press and 10% to 20% of the 1-RM for the half squats. The objective was to progressively increase the weight until reaching the point at which the participant could perform just one successful repetition. This weight, defined as the 1-RM, represents the maximum load that an individual can lift for a single repetition [20, 21].

The Force-Velocity Profile

A Sweden Monark, model 894 E was used for this test, which aims to determine the strength of the upper limbs from the most intense short sprint runs (maximum duration 7 s) of pedalling against a load of 1.5%, 2%, 2.5%, 3%, 4.5%, and 2.5% of body mass in the upper limb. Peak power (W), peak power per kilogram of body mass (W/kg), maximum pedalling velocity (rpm), and maximum braking force are the terms used to describe performance (N). For more details, see Chelly et al. 2010 [22].

Medicine ball throw

The test was performed using 21.5-cm diameter, 3-kg rubber medicine balls (Tigar, Pirot, Serbia) powdered with magnesium carbonate. A familiarization session included a brief description of the optimal technique [23]. The seated player grasped the medicine ball with both hands, and on a signal forcefully pushed the ball from the chest. The score was measured from the front of the sitting line to the powder-marked spot where the ball landed. The ICC is 0.86. The CV value is 16.7%.

Repeated sprint ability (RSA) test

The repeated sprint ability consisted of recording six sets of two 20-m sprint round trips using paired photocells. Each sprint was performed once every 20 s [24]. Four scores were determined: best and total sprint times and fatigue index [24].

Training programme

All players engaged in handball training five to six times per week and participated in one official game per week. Standard training sessions typically lasted 80 to 100 minutes, focusing on various skill activities, offensive and defensive strategies, and 25 to 30 minutes of continuous play, with minimal interruptions by the coach.

Both contrast elastic band training (CEB) and standard elastic band training (SEB) were integrated into their training regimens for ten weeks, replacing certain low-intensity technical-tactical handball drills on Tuesdays and Thursdays (as detailed in Table 2). The training programme was designed to be progressive and spanned a total of 20 sessions. During these biweekly sessions, which took place on Tuesdays and Thursdays, eight exercises were performed, with four targeting the upper limbs (flies, rows with high elbows, trunk rotation, and standing presses) and four focusing on the lower limbs (knee extension, knee flexion, half-squats, and hip adduction). The exercises alternated between upper and lower limb exercises for all experimental groups. Thera-Bands, an elastic band system

TABLE 2. Training programme of both contrast and standard elastic band training.

Exercises	Week 1	Week 2	Week 3	Week 4	Week 5
Load	Sets × Reps				
Upper limb					
Resistance at 250 and 100% elongation	Red elastic band (3.2 and 1.8 kg)	Green elastic band (4.4 and 2.3 kg)			Blue elastic band (6 and 3.2 kg)
Flies, row with high elbows, trunk rotation and standing press	3 × (6+6)	3 × (6+6)	4 × (6+6)	5 × (6+6)	3 × (6+6)
Lower limb					
Resistance at 250 and 100% elongation	Red elastic band folded (6.4 and 3.6 kg)	Green elastic band (8.8 kg and 4.6 kg)			Blue elastic band folded (12 and 6.4 kg)
Knee extension and flexion, half squat and hip adduction	3 × (6+6)	3 × (6+6)	4 × (6+6)	5 × (6+6)	3 × (6+6)

	Week 6	Week 7	Week 8	Week 9	Week 10
Upper limb					
Resistance at 250 and 100% elongation	Blue elastic band (6 and 3.2 kg)			Black elastic band (8 and 4.4 kg)	
Flies, row with high elbows, trunk rotation and standing press	4 × (6+6)	5 × (6+6)	3 × (6+6)	4 × (6+6)	5 × (6+6)
Lower limb					
Resistance at 250 and 100% elongation	Blue elastic band folded (12 and 6.4 kg)			Black elastic band folded (16 and 8.8 kg)	
Knee extension and flexion, half squat and hip adduction	4 × (6+6)	5 × (6+6)	3 × (6+6)	4 × (6+6)	5 × (6+6)

Participants performed the first 6 reps at 250% elongation of the initial length of the elastic band directly followed by 6 repetitions at 100% elongation.

comprising four latex bands (red, green, blue, and black), were used. The length and load of each elastic band are documented in Table 2. Both CEB and EB groups performed the same exercises, the same number of sets, and the same number of repetitions. The key distinction between CEB and EB was in the repetition scheme. EB completed 12 repetitions with the same load (i.e., 12 reps at 250% of the length of the elastic band), while CEB performed 6 repetitions at 250% of the length of the elastic band, followed by 6 repetitions at 100% of the length of the elastic band.

Each training session commenced with a 15-minute warm-up and lasted for 30 minutes, resulting in a total session duration of 45 minutes.

Statistical analyses

Statistical analyses were carried out using the IBM SPSS Statistics (version 20.0, IBM Corp., Armonk, NY, USA). Normality of all variables was verified using the Kolmogorov-Smirnov procedure. Levene's test was used to determine homogeneity of variance. Means and standard deviations (SDs) were calculated using standard statistical methods. Training-related effects were assessed by 2-way analyses of variance with repeated measures (group × time). If a significant F value was observed, Tukey's post hoc procedure was applied to locate pair-wise differences. A $p \leq 0.05$ was accepted as the criterion of statistical significance, whether a positive or a negative difference was seen (i.e., a 2-tailed test was adopted). Effect sizes were reported for a main effect of group, a main effect of time and a main effect of group × time interaction; values were classified as small ($0.00 \leq d \leq 0.49$), medium ($0.50 \leq d \leq 0.79$), or large ($d \geq 0.80$), as suggested by Cohen [25]. The reliabilities of all dependent variables were assessed by calculating 2-way mixed intra-class correlation coefficients (ICC), and coefficients of variation (CV).

RESULTS

Intraclass correlation coefficients assessing the reliability and the coefficient of variance of sprint, COD, jump, and medicine ball throw tests are displayed in each protocol test. Test results before and after

TABLE 3. Sprint, change of direction, jump, and upper limb strength performance in all groups before and after the 10-week intervention.

	CEB Group			SEB Group			CNT Group			ANOVA group * time interaction	
	Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ	P	d
Sprint											
10 m (s)	2.24 ± 0.05	2.10 ± 0.06 **μμ**	6.1 ± 1.6	2.24 ± 0.06	2.09 ± 0.05 **αα**	7 ± 1.1	2.24 ± 0.06	2.20 ± 0.08	1.7 ± 2.4	0.003	0.88
20 m (s)	3.69 ± 0.10	3.24 ± 0.10 **μμμ**	12.3 ± 1.1	3.76 ± 0.10	3.36 ± 0.09 **ααα**	10.5 ± 1.1	3.75 ± 0.05	3.64 ± 0.07	1.9 ± 1.2	0.003	0.88
COD											
Illinois-MT (s)	13.11 ± 0.37	11.28 ± 0.77 **μμμ**	6.3 ± 1.1	13.13 ± 0.23	12.40 ± 0.20 **αα**	5.6 ± 0.3	13.16 ± 0.39	13.05 ± 0.38	0.7 ± 0.2	0.001	0.97
Jump											
SJ (cm)	23.2 ± 2	27.3 ± 2.3 **μμ**	17.9 ± 4.1	22.4 ± 1.7	26.4 ± 1.4	17.3 ± 6.3	22.8 ± 2.4	23.7 ± 1.9	4.4 ± 4.8	0.012	0.75
CMJ (cm)	23.1 ± 2.5	28 ± 1.9 **μ**	19.4 ± 2.9	23.4 ± 1.6	27.5 ± 2.1	17.5 ± 2.7	24 ± 2.3	25.2 ± 2.1	4.4 ± 3.8	0.007	0.81
Standing long jump (m)	1.50 ± 0.10	1.60 ± 0.10	6.8 ± 4.6	1.50 ± 0.13	1.59 ± 0.11	6.5 ± 3.5	1.53 ± 0.16	1.71 ± 0.18	12.8 ± 14.1	0.430	0.32
Strength											
Back extensor (N)	737 ± 92	1149 ± 92 **μμμ**	56.5 ± 6.6	753 ± 58	1170 ± 143 **ααα**	55.4 ± 14.6	744 ± 35	866 ± 83	16.2 ± 7.2	0.000	1.59
Medicine ball throw (m)	3.33 ± 0.36	5.03 ± 0.58 **μμμ β**	62.4 ± 11.9	3.38 ± 0.37	4.35 ± 0.46 **αα**	28.7 ± 4.6	3.26 ± 0.57	3.49 ± 0.62	7.41 ± 0.59	0.000	1.23
1-RM bench press (kg)	41.2 ± 10.7	60.4 ± 9 **μμ**	54.8 ± 25.1	40.7 ± 39.5	54.8 ± 12 **α**	40.7 ± 39.5	40.2 ± 11.5	44.2 ± 11.2	5.8 ± 9.2	0.016	0.73
1-RM half squat (kg)	72.3 ± 9.1	96.8 ± 11.2 **μμ**	34.6 ± 12.8	78.8 ± 12	96 ± 8.9 **ααα**	23.1 ± 10.2	72.6 ± 16.6	82.2 ± 13.4	17.8 ± 17.3	0.012	0.75

COD = change of direction; CEB = contrast elastic band group; SEB = standard elastic band group; CNT = control group; T-Modified = modified change of direction T-test; CMJ = counter-movement jump; CMJA = counter-movement jump with arm swing; **μ** = significant difference between CEB and CNT at $p < 0.05$; **μμ** = significant difference between CEB and CNT at $p < 0.01$; **μμμ** = significant difference between CEB and CNT at $p < 0.001$; **α** = significant difference between SEB and CNT at $p < 0.05$; **αα** = significant difference between SEB and CNT at $p < 0.01$; **ααα** = significant difference between SEB and CNT at $p < 0.001$; **β** = significant difference between CEB and SEB at $p < 0.05$.

interventions are outlined in Tables 3 and 4. No significant differences were observed before training between groups. After intervention, both CEB and SEB significantly increased sprint ($p < 0.01$; $d = 0.88$) and COD ($p < 0.001$; $d = 0.97$) relative to C, without a difference between them. Jump performance improved significantly (SJ ($p < 0.01$); CMJ ($p < 0.05$)) only in CEB relative to C. All strength test results increased significantly in both experimental groups ($0.73 < d < 1.59$) relative to C, with a slight difference between CEB and SEB ($p < 0.05$) in medicine ball throw (Table 3). Both CEB and SEB significantly increased all RSA scores relative to the controls ($0.10 < d < 1.22$), without a difference between them (Table 4). All force-velocity scores increased significantly in CEB and SEB relative to C ($0.45 < d < 2.47$). In addition, the CEB showed substantial gains of performance for PP_{abs}, PP_{rel}, and F0 ($p < 0.001$, $p < 0.001$ and $p < 0.05$, respectively) relative to SEB (Table 4).

DISCUSSION

In our study, we investigated the effects of two types of strength training, namely contrast elastic band training (CEB) and standard elastic band training (SEB), on various performance parameters critical for adolescent female handball players during a crucial phase in the playing season. Most measures demonstrated comparable gains in both groups, except for the medicine ball throw and upper limb force-velocity scores.

In line with findings from other researchers, our study highlights the advantages of applying an elastic band programme in both standard and contrast training for sprint performance. Our results align with those of Hammami et al. [9], who observed significant improvements in 5 m ($p = 0.02$, $d = 0.80$ (large)) and 30 m ($p = 0.02$, $d = 2.60$ (large)) in young female athletes. Also, the authors found increases in all sprint performances after 10-week elastic band

TABLE 4. Repeated sprint ability and force-velocity performance in all groups before and after the 10-week intervention.

	CEB Group			SEB Group			CNT Group			ANOVA group * time interaction	
	Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ	P	d
RSA											
RSA-BT (s)	7.55 ± 0.12	7.31 ± 0.12 ***μμ***	3.1 ± 0.8	7.55 ± 0.08	7.31 ± 0.09 **ααα**	3.1 ± 0.4	7.55 ± 0.08	7.51 ± 0.07	0.5 ± 0.4	0.000	1.02
RSA-MT (s)	7.67 ± 0.10	7.42 ± 0.11 ***μμ***	3.2 ± 0.6	7.67 ± 0.04	7.44 ± 0.07 **ααα**	3.1 ± 0.2	7.71 ± 0.07	7.67 ± 0.06	0.6 ± 0.5	0.000	1.22
RSA-TT (s)	46 ± 0.58	44.51 ± 0.64 ***μμ***	3.2 ± 0.6	46.04 ± 0.41	44.61 ± 0.42 **ααα**	3.1 ± 0.2	46.29 ± 0.43	46.03 ± 0.35	0.6 ± 0.5	0.000	1.22
RSA-FI	1.59 ± 0.40	1.46 ± 0.34 ***μμ***	5.4 ± 19.8	1.70 ± 0.37	1.67 ± 0.49 **αα**	1.7 ± 20.1	2.21 ± 0.64	2.18 ± 0.59	0.8 ± 20.5	0.920	0.10
Force-velocity test											
PP_{abs} (W)	145.8 ± 18.2	271.8 ± 24.5 ***μμ*** **βββ**	89.7 ± 35.1	144.7 ± 23.4	197.6 ± 21.8 **ααα**	37.8 ± 8.8	142.4 ± 23.8	162.3 ± 22.4	14.7 ± 8.3	0.000	2.47
PP_{rel} ($W \cdot kg^{-1}$)	2.28 ± 0.32	4.23 ± 0.36 ***μμ*** **βββ**	86.7 ± 35.1	2.27 ± 0.38	3.11 ± 0.37 **αα**	37.8 ± 8.8	2.23 ± 0.28	2.55 ± 0.23	14.7 ± 8.3	0.000	2.20
V0 (rpm)	90.4 ± 16.9	103.2 ± 9.5 ***μ***	17.4 ± 22.9	90.5 ± 16.6	102.4 ± 13.7 **αα**	15.6 ± 18.6	85.7 ± 17.7	84.8 ± 9	2.6 ± 22	0.190	0.45
F0 (N)	6.7 ± 1	10.2 ± 1.3 ***μμ*** **β**	55.5 ± 22.3	6.5 ± 0.7	8.9 ± 1.5 **αα**	37.3 ± 19.7	6.4 ± 1.2	7.1 ± 0.7	13.2 ± 25.6	0.000	1.13

CEB = contrast elastic band group; SEB = standard elastic band group; CNT = control group; RSA = repeated sprint ability; BT = best time; MT = mean time; TT = total time; FI = fatigue index; PP = peak power; V0 = maximal pedalling velocity; F0 = maximal breaking force; ***μμ*** = significant difference between CEB and CNT at $p < 0.01$; ***μμμ*** = significant difference between CEB and CNT at $p < 0.001$; **αα** = significant difference between SEB and CNT at $p < 0.01$; **ααα** = significant difference between SEB and CNT at $p < 0.001$; **β** = significant difference between CEB and SEB at $p < 0.05$; **βββ** = significant difference between CEB and SEB at $p < 0.001$.

training in young female handball players [15]. Similarly, when examining U-17 male soccer players, it was reported that both 8-week contrast and standard strength training programmes improved sprint performance (specifically in the 5-m and 40-m sprints), with no significant differences between the two groups [26]. The improvement in sprint performance observed in female adolescent handball players following both CEB and SEB can be attributed to the improved neuromuscular adaptations. Elastic band training necessitates the activation of stabilizer muscles and fosters neuromuscular coordination. These bands offer variable resistance, thereby challenging the muscles to adapt and coordinate their contractions effectively. This, in turn, could result in improved recruitment of motor units, synchronization, and overall enhancement of neuromuscular efficiency, all of which are crucial for sprint performance.

Handball, known for its fast-paced nature, demands quick changes in movement direction [1, 2]. Female handball players must navigate the court, evade opponents, and position themselves for both offensive and defensive actions. Effective change of direction is essential for swift reactions to in-game situations, making sharp cuts, and maintaining control over movements [1, 2]. Elastic band training has been recommended to enhance fundamental handball movements, including sprints and COD actions [9, 15]. Our findings support the positive impact of elastic band training on COD abilities in handball players, with significant improvements observed in both CEB and SEB groups ($p < 0.001$ and $p < 0.01$ respectively). These results are consistent with those of Aloui et al. [14], who reported similar improvements in junior male handball players after an 8-week programme of strength training with elastic bands. However, our findings contradict those of Anderson et al. [27], who observed no significant change in agility after a 6-week elastic band strength training programme in young female handball players. These discrepancies may be attributed to variations in test methodologies, intervention durations, and the specific characteristics of the training protocols used in the studies.

The discrepancies in the results may be attributed to variations in test techniques and interventions, such as the frequency, duration, and progression of training relative to the playing season. The observed improvements in change of direction (COD) performance among female adolescent handball players can be attributed to a combination of factors, including increased strength and power, improved proprioception and balance, enhanced neuromuscular coordination, greater agility and quickness, improved eccentric strength, and the transfer of these gains to sport-specific movements through elastic band training. Both standard and contrast formats of elastic band training contribute to the enhancement of the physical attributes and motor skills necessary for executing effective and efficient changes

of direction on the handball court.

Concerning jump performance, we observed that the CEB group achieved small to large improvements across the measured jump performance parameters (with effect sizes ranging from d = 0.31 to d = 0.82) compared to the control group ($p < 0.05$; $p < 0.01$ in CMJ and SJ respectively). These findings align with those of Hammami et al. [9], who observed significant increases in jump performance (SJ, CMJ, and CMJ with arm swing) following contrast elastic band training in female handball players. Our results did not reveal a significant difference between SEB and the control group in jump performance. This contradicts the findings of another study [15], which reported medium-sized increases in SJ and CMJ performance after elastic band training in female handball players. These discrepancies between studies may arise from various factors, including differences in the type of elastic band used (type, length, colour), as well as variations in the demographic characteristics (age and sex) of the participants. It seems that both contrast and standard elastic band training methods can effectively enhance jump abilities, with the contrast format capitalizing on the potentiation effect and power development aspects of the training stimulus, resulting in slightly superior jump performance improvements in female adolescent handball players.

Strength and power are pivotal in enhancing handball performance. The sport demands explosive actions such as throwing, jumping, sprinting, and tackling [2–4, 28]. Developing strength and power empowers players to generate greater force and speed, resulting in more forceful throws, higher jumps, and swifter movements on the court [2–4, 28]. In this context, both training programmes, CEB and SEB, showed notable improvements in various performance traits.

Firstly, after the band training there were substantial enhancements in back extensor strength, a key component in athletic movements, with an effect size of 1.59. Additionally, players demonstrated significant improvement in the medicine ball throw, which measures upper body explosive strength and power, with an effect size of 1.23. Moreover, the evaluation of maximal strength through the 1-RM bench press and 1-RM half squat also showed considerable improvement, with effect sizes of 0.73 and 0.75, respectively.

When comparing CEB and SEB, it was noted that CEB displayed a slight, but significant advantage in the medicine ball throw. This suggests that contrast elastic band training had a more pronounced impact on medicine ball throw performance than standard elastic band training. Several research studies have consistently highlighted improvements in both upper and lower limb strength, regardless of variations in the specific tests and evaluation instruments used. For instance, Anderson et al. [27] reported enhanced ball throwing velocity and bench press performance following a 6-week elastic band strength training programme. Similarly, Mascarin et al. [29] observed an increase in the average power of shoulder internal rotation, along with improved ball throwing speed from a standing position and during jumping, after a 6-week elastic band strength training programme in young female handball players. In another study by Mascarin et al. [12], elastic band strength training contributed to enhanced muscular strength in the external rotator muscles, promoting muscular balance in female youth handball players. The improvements in back extensor strength, medicine ball throw performance, 1-RM bench press, and 1-RM half squat observed after both CEB training and SEB training in female adolescent handball players can be attributed to various factors. These include the combination of increased muscle strength, improved power output, enhanced muscle activation and coordination, improved rate of force development, specificity of training, and increased joint stability and core strength. Collectively, these factors contribute to the observed enhancements in these crucial physical attributes. The selected studies suggest that a programme involving medicine ball workouts facilitates improvements in key components of physical performance [30]. The integration of varied means into the training process of pre-adolescent female athletes further optimises the impact of exercise influences. An intriguing avenue for exploration may involve a comparative analysis of the effects of these different training modalities.

In the context of handball, where short, maximum sprints interspersed with rapid recovery intervals are common during matches, the ability to repeatedly execute sprints is a critical fitness component. In this study, both the CEB and SEB groups demonstrated enhanced RSA scores compared to the C group, and there was no significant difference between CEB and SEB groups in this regard (Table 5). Several studies have reported an increase in RSA scores after training with elastic bands. This improvement in repeated sprint ability can be attributed to a combination of factors, including enhanced anaerobic capacity, increased muscular endurance, improved speed and acceleration, neuromuscular adaptations, enhanced recovery capacity, and mental toughness. These factors collectively contribute to the observed enhancements in the ability to perform repeated sprints, which is crucial in handball [24, 31–35]. The findings of this study also demonstrated substantial improvements in upper limb force-velocity performance in both the CEB and SEB groups compared to the C group. Effect sizes (d values) ranged from 0.45 to 2.47 across all scores, indicating a significant effect. Notably, there was a significant difference between CEB and SEB in favour of the former (Table 5). Similar results were obtained in the study by Gaamouri et al. in 2023 [8], where they observed increases in all upper limb force-velocity scores with effect sizes [d values) ranging from 0.56 to 1.66 after a 10-week strength training programme using elastic bands in youth handball players. Similarly, Aloui et al. in 2019 [10] reported an increase in upper limb force-velocity scores during an 8-week, in-season training programme using upper limb elastic bands in junior handball players, with effect sizes (eta squared) ranging from 0.183 to 0.591. The greater improvement in upper limb force-velocity test performance following CEB compared to SEB in female adolescent handball players can be attributed to the specific training stimulus provided by the contrast format. This effect

occurs when the muscles experience a contrasting stimulus, such as going from a resisted movement to an unresisted movement [11, 36]. The bands provide resistance during the eccentric phase of the movement and then release tension during the concentric phase, resulting in a rapid transition to an unloaded movement [11, 36]. This contrast of resistance levels enhances the muscle's ability to produce force and power, leading to greater improvements in upper limb force-velocity test performance.

CONCLUSIONS

In terms of practical implications, the study demonstrates that both the CEB and SEB groups exhibited significant improvements in various aspects of athletic performance over the 10-week intervention period and the findings provide insights into how coaches and athletes can apply the results of our study in designing effective training regimens. Nevertheless, it is noteworthy that specific measures of athletic performance, such as the medicine ball throw and force-velocity performance, exhibited more substantial enhancements following the 10-week CEB regimen compared to the SEB training. These findings underline the potential advantages of contrast elastic band training (CEB) in targeting and enhancing particular athletic performance parameters in adolescent female handball players.

Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. Luteberget LS, Spencer M. High-Intensity Events in International Women's Team Handball Matches. Int J Sports Physiol Perform. 2017; 12(1):56–61.
2. Luteberget LS, Trollerud HP, Spencer M. Physical demands of game-based training drills in women's team handball. J Sports Sci. 2018; 36(5):592–8.
3. 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):1708–19.
4. Pérez Armendáriz M, Spyrou K, E. Alcaraz P. Match demands of female team sports: a scoping review. Biol Sport. 2024; 41(1):175–199. doi:10.5114/biolsport.2024.129476.
5. 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.
6. Wilson GJ, Newton RU, Murphy AJ, Humphries BJ. The optimal training load for the development of dynamic athletic performance. Med Sci Sports Exerc. 1993; 25(11):1279–86.
7. Chaabene H, Prieske O, Moran J, Negra Y, Attia A, Granacher U. Effects of Resistance Training on Change-of-Direction Speed in Youth and Young Physically Active and Athletic Adults: A Systematic Review with Meta-Analysis. Sports Med (Auckland, NZ). 2020; 50(8):1483–99.
8. Gaamouri N, Hammami M, Cherni Y, Oranchuk DJ, Bragazzi N, Knechtle B, et al. The effects of upper and lower limb elastic band training on the change of direction, jump, power, strength and repeated sprint ability performance in adolescent female handball players. Front Sports Act Living. 2023; 5:1021757.
9. Hammami M, Gaamouri N, Suzuki K, Shephard RJ, Chelly MS, Hill L, et al. Effects of contrast strength training with elastic band program on sprint, jump, strength, balance and repeated change of direction in young female handball players. Int J Sports Sci and Coaching. 2021; 17(5):1147–57.
10. Aloui G, Hermassi S, Hammami M, Gaamouri N, Bouhafs EG, Comfort P, et al. 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: Organ der Gesellschaft fur Orthopadisch-Traumatologische Sportmedizin. 2019; 33(3):133–41.
11. Lopes JSS, Machado AF, Micheletti JK, de Almeida AC, Cavina AP, Pastre CM. Effects of training with elastic resistance versus conventional resistance on muscular strength: A systematic review and meta-analysis. SAGE Open Medicine. 2019; 7:2050312119831116.
12. Mascarin NC, de Lira CAB, Vancini RL, da Silva AC, Andrade MS. The effects of preventive rubber band training on shoulder joint imbalance and throwing performance in handball players: A randomized and prospective study. J Bodyw Mov Ther. 2017; 21(4):1017–23.
13. Cormier P, Freitas TT, Rubio-Arias J, Alcaraz PE. Complex and Contrast Training: Does Strength and Power Training Sequence Affect Performance-Based Adaptations in Team Sports? A Systematic Review and Meta-analysis. J Strength Cond Res. 2020; 34(5):1461–79.
14. Aloui G, Hammami M, Fathloun M, Hermassi S, Gaamouri N, Shephard RJ, et al. 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):1804–15.
15. Hammami M, Gaamouri N, Wagner H, Pagaduan JC, Hill L, Nikolaidis PT, et al. Effects of strength training with elastic band programme on fitness components in young female handball players: a randomized controlled trial. Biol Sport. 2022; 39(3):537–45.
16. Durnin JV, Womersley J. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. Br J Nutr. 1974; 32(1):77–97.
17. Mirwald RL, Baxter-Jones AD, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. Med Sci Sports Exerc. 2002; 34(4):689–94.
18. Hammami M, Gaamouri N, Aloui G, Shephard RJ, Chelly MS. Effects of a Complex Strength-Training Program on Athletic Performance of Junior Female Handball Players. Int J Sports Physiol Perform. 2019; 14(2):163–9.
19. Hachana Y, Chaabene H, Ben Rajeb G, Khlifa R, Aouadi R, Chamari K, et al. Validity and reliability of new agility test among elite and subelite under 14-soccer players. PloS one. 2014; 9(4):e95773.
20. Grgic J, Lazinica B, Schoenfeld BJ, Pedisic Z. Test-Retest Reliability of the One-Repetition Maximum (1RM) Strength Assessment: a Systematic Review. Sports Med – open. 2020; 6(1):31.
21. Seo DI, Kim E, Fahs CA, Rossow L, Young K, Ferguson SL, et al. Reliability of the one-repetition maximum test based on muscle group and gender. J Sports Sci Med. 2012; 11(2):221–5.
22. Chelly MS, Hermassi S, Shephard RJ. Relationships between power and strength of the upper and lower limb muscles and throwing velocity in male handball players. J Strength Cond Res. 2010; 24(6):1480–7.
23. Gillespie J, Keenum S. A validity and reliability analysis of the seated shot put as a test of power. J Hum Mov Stud. 1987(13):97–105.

24. Buchheit M, Mendez-Villanueva A, Delhomel G, Brughelli M, Ahmaidi S. Improving repeated sprint ability in young elite soccer players: repeated shuttle sprints vs. explosive strength training. J Strength Cond Res. 2010; 24(10):2715–22.
25. Cohen J. Statistical Power Analysis for the Behavioral Sciences. Hillsdale, NJ: Lawrence Erlbaum. 1988.
26. Hammami M, Negra Y, Shephard RJ, Chelly MS. The Effect of Standard Strength vs. Contrast Strength Training on the Development of Sprint, Agility, Repeated Change of Direction, and Jump in Junior Male Soccer Players. J Strength Cond Res. 2017; 31(4):901–12.
27. Andersen V, Fimland MS, Cumming KT, Vraalsen O, Saeterbakken AH. Explosive Resistance Training Using Elastic Bands in Young Female Team Handball Players. Sports Med Int. Open. 2018; 2(6):E171–e8.
28. Karcher C, Buchheit M. On-court demands of elite handball, with special reference to playing positions. Sports Med (Auckland, NZ). 2014; 44(6):797–814.
29. 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):245–52.
30. Chukhlantseva N. Medicine ball training in the sequence of complex handball training versus only hand-ball training: effects on physical fitness in pre-adolescence female handball players. Balt J Health Phys Act. 2023; 15(4):Article2. https://doi.org/10.29359/BJHPA.15.4.02
31. Bishop D, Spencer M. Determinants of repeated-sprint ability in well-trained team-sport athletes and endurance-trained athletes. J Sports Med Phys Fitness. 2004; 44(1):1–7.
32. Bishop D, Spencer M, Duffield R, Lawrence S. The validity of a repeated sprint ability test. J Sci Med Sport. 2001; 4(1):19–29.
33. Anderson K, Behm DG. The impact of instability resistance training on balance and stability. Sports Med. 2005; 35(1):43–53.
34. Iacono AD, Eliakim A, Meckel Y. Improving fitness of elite handball players: small-sided games vs. high-intensity intermittent training. J J Strength Cond Res. 2015; 29(3):835–43.
35. Glaister M. Multiple sprint work: physiological responses, mechanisms of fatigue and the influence of aerobic fitness. Sports Med (Auckland, NZ). 2005; 35(9):757–77.
36. Aboodarda SJ, Page PA, Behm DG. Eccentric and concentric jumping performance during augmented jumps with elastic resistance: a meta-analysis. Int J Sports Phys Ther. 2015; 10(6):839–49.

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A comparison of morning priming exercise using traditional-set and cluster-set configurations on afternoon explosive performance

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ABSTRACT: The impact of two priming exercise protocols using traditional (TS) or cluster-set (CS) arrangements on explosive performance 6 hours later were examined. Sixteen male collegiate athletes performed three testing sessions (one baseline without any prior exercise in the morning and two experimental sessions) separated by 72 hours. Participants completed two morning (9–11 am) priming protocols in a randomized order, either using a TS (no rest between repetitions) or CS (30 seconds of rest between repetitions) configuration. The protocols consisted of 3 sets × 3 repetitions of barbell back squat at 85% of 1 repetition maximum, with 4 minutes of rest between sets. In the afternoon (3–5 pm) of each trial, after a 6-hour rest period, a physical test battery was conducted that replicated baseline testing, including countermovement jump, 20-meter straight-line sprint, and T-test abilities. Across both conditions, participants exhibited increased countermovement jump height, 20-meter sprint time and T-test time compared to baseline ($P < 0.05$). Improvements in countermovement jump height ($+4.4 \pm 5.4\%$; $P = 0.008$) and 20-meter sprint time ($+1.3 \pm 1.7\%$; $P = 0.022$), but not T-test time ($+1.1 \pm 3.3\%$; $P = 0.585$), were significantly greater for CS than TS. In conclusion, compared to a traditional set arrangement, a morning-based priming protocol using a cluster-set configuration led to superior explosive performance benefits in the afternoon.

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INTRODUCTION

Performing a low-volume resistance exercise, typically executed at maximal or near-maximal velocity, in the hours leading up to competition is a common priming exercise protocol [1]. According to a recent survey, external resistance workouts (e.g., jumping, squatting, pressing, and pulling derivatives) are often used in high performance sport to enhance afternoon explosive neuromuscular performance after completing the morning priming exercise [2]. Specifically, these delayed performance improvements have included enhanced force and power production during competitive actions, such as jumping [3, 4], sprinting [5, 6], or agility [5], after various priming exercises performed up to 48 h beforehand. While unloaded exercises and exercises utilizing elastic bands for external resistance are common loading strategies [1, 7], current evidence supports the use of resistance exercises, such as the back squat and bench press, performed in 2–4 sets of 3–5 repetitions at high resistance load (≥ 80% of 1 repetition maximum [1RM]) for lower body exercises [3, 5].

Literature indicates that morning priming exercise can improve afternoon explosive performance in swimmers [8], throwers [9], and rugby union players [6], while other studies have reported limited changes to countermovement (CMJ) performance following this practice [6, 10]. In the majority of available studies, the exercise set structure consisted of executing each repetition in sequence without rest between repetitions, known as a 'traditional set' structure [11]. One potential challenge with the traditional set (TS) structure is the ability to sustain high-velocity patterns throughout the session at least for moderate-to-high loads due to the accumulation of fatigue, which may be caused by decreased adenosine triphosphate and phosphocreatine availability, and increased lactate and/or ammonia accumulation [12]. This phenomenon is especially noticeable when lifting movements commonly used as priming exercises involve a small number of repetitions at higher loads in multiple sets [13].

To overcome the fatigue that comes with lifting heavier loads during priming exercises, one strategy is to adjust the set configuration [1, 7]. Cluster set (CS) structure is a technique that entails breaking down a set's repetitions into smaller clusters with rest periods of ~20 to 40 seconds between them [11, 14]. Compared to a TS structure, a CS configuration may lead to better maintenance of movement velocity and power across sets and an entire exercise session [11, 15, 16, 17]. To date, CS arrangements in morning priming

exercise literature have received limited attention, which has left many questions regarding their application and eventual benefits on explosive measures later in the day, including less frequently studied aspects such as sprinting and agility [7].

This study aimed to examine the impact of two priming exercise protocols, each featuring a different set arrangement (TS and CS), on performance measures including jumping, sprinting, and agility. It was hypothesized that a morning squat-based priming exercise utilizing a CS configuration would lead to greater enhancements in neuromuscular performance six hours after the end of the session compared to a TS structure.

MATERIALS AND METHODS

Participants

A repeated measures analysis of variance power calculation ($\alpha = 0.05$, $1\text{-}\beta = 0.8$) was conducted with G*Power (Version 3.1.9.3) to determine sample size based on one of our primary variables: sprint performance. The effect size of a priming exercise protocol on acute changes in sprint time, based on expected performance improvement after six hours of recovery, is 0.41 [5]. To express our results with 95% confidence, a minimum sample size of 15 participants was obtained. Therefore, to account for potential drop-outs or injuries, sixteen healthy males (age: 22.0 ± 2.16 years; height: 1.78 ± 0.05 m; body mass: 76.2 ± 8.3 kg) were recruited. Participants were classified as 'Highly trained/National level' (Tier 3) using established criteria [18], 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: 146.1 ± 22.1 kg). The study was approved by Beijing Sport University Review Board for Human Participants (no. 2018018 H), and complied with the principles of the Declaration of Helsinki, with written informed consent obtained from participants.

Study design

The participants underwent five separate laboratory sessions, which included two familiarization sessions (visits 1 and 2), one baseline testing session (visit 3), and two main experimental sessions that were conducted in a randomized order (visits 4 and 5) over a period of three weeks. The visits were spaced 3–7 days apart. All participants were familiar with the testing procedures through their regular physical performance assessments in their clubs. Participants were instructed to avoid alcohol and caffeine consumption and refrain from strenuous training for 24 hours before each session. They were also asked to maintain a 24-hour food diary before the baseline testing session and to replicate their diet before the other two remaining trials. The participants were instructed to maintain their normal diet, avoiding nutritional supplements, during the testing protocol. Air temperature was maintained constant at ~22°C. An overview of the study design is depicted in Figure 1.

Experimental visits

Familiarization sessions

During both sessions, participants visited the laboratory in the afternoon (3–5 pm), which coincided with the time of performance assessment during the two main experimental visits. The first step was to explain and demonstrate the detailed procedures and correct techniques for all the tests. Afterwards, participants practiced three sets of five repetitions of the barbell back squat with a light load (≤ 50% 1RM) on a Smith machine. To familiarize themselves with the test protocols and procedures, they performed a series of CMJ, 20-meter sprint, and T-test [3, 5, 19]. This included three repetitions

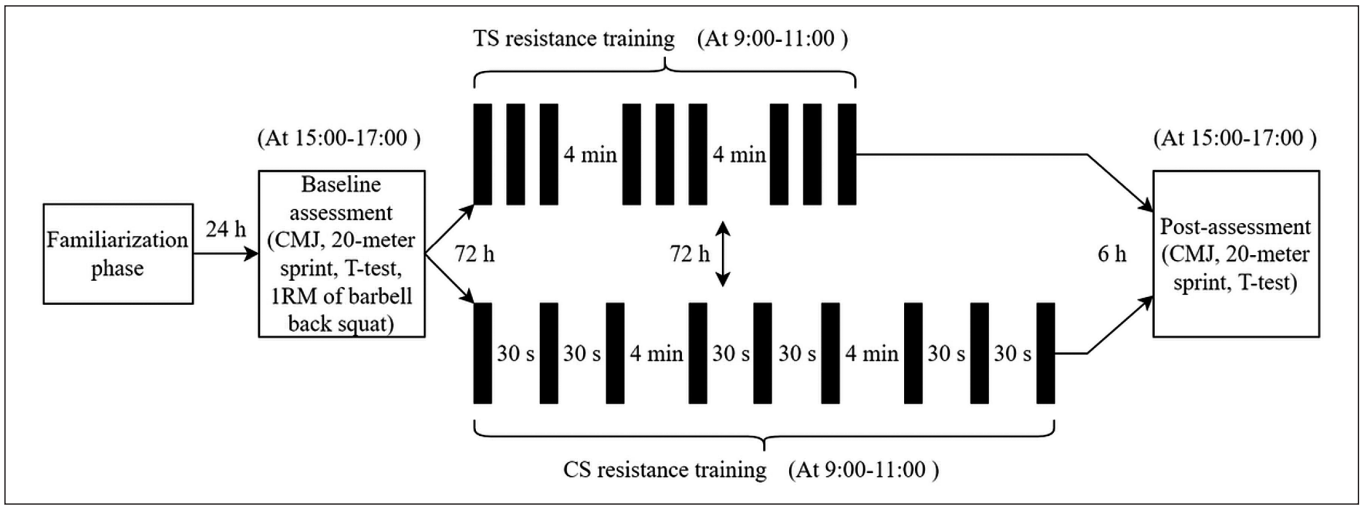


FIG. 1. Study design. CMJ, countermovement jump. TS, traditional sets. CS, cluster sets.

of technique practices and three repetitions of maximal efforts, with ~3 minutes of recovery between each repetition.

Baseline testing session

The baseline testing session was conducted in the afternoon (3–5 pm). Participants were first instructed to complete an 8-minute standardized warm-up routine, which consisted of five minutes of running and three minutes of dynamic stretching of hip and ankle mobility. Baseline values were then obtained for CMJ height, peak power, take-off velocity and push-off impulse, as well as 20-meter sprint performance and T-test performance. Each test was repeated three times, and the best trial was recorded for statistical analysis. Lastly, the 1 RM of the barbell back squat was determined.

Main experimental sessions

Participants completed the standardized warm-up from the baseline testing session upon arriving at the laboratory. After a 5-minute rest in a passive seating position, they began a protocol consisting of three sets of three repetitions of barbell back squat at 85% of their 1RM on a Smith machine (Technogym Equipment, Italy). This was done in one of two experimental conditions: no rest between repetitions (TS) or a 30-second interval between repetitions (CS), with a 4-minute interval between sets in both cases [20]. After a 6-hour rest period, the testing routine was performed in a manner similar to the baseline testing session.

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 [21]. 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 jump test

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, take-off velocity, and push-off impulse were all calculated using the MARS software (version 4.0; Kistler Corporation, Switzerland). Participants completed three trials of the CMJ, with a 1-minute rest between each trial. The mean of three trials was used for final analysis.

20-meter sprint test

To prepare for the 20-meter straight-line sprint test, participants underwent a 5-minute warm-up consisting of light drills, followed by 50% and 80% intensity efforts over the 20-meter distance. Participants started the test in a 2-point stance and then completed three

TABLE 1. Variables at baseline, traditional set (TS) and cluster sets (CS).

Variables	Conditions			ANOVA	Baseline – TS	Baseline – CS	TS – CS
	Baseline	TS	CS	*P value (η_p^2)*	ES; MD*(95% CI)*	ES; MD*(95% CI)*	ES; MD*(95% CI)*
CMJ height (cm)	46.5 ± 7.9	48.3 ± 8.0*	50.4 ± 8.3*#	**P < 0.001*(0.58)***	**0.23**; -1.8*(-3.2;-0.5)*	**0.48**; -3.9*(-5.9;-2.0)*	**0.25**; -2.1*(-3.7;-0.5)*
CMJ peak power (W/kg)	62.18 ± 8.34	62.55 ± 10.01	64.42 ± 8.92*#	**P = 0.004*(0.34)***	0.04; -0.04*(-3.54;-0.95)*	**0.26**; -1.88*(-3.68;-0.07)*	**0.20**; 0.006*(-0.007;0.019)*
CMJ take-off velocity (m/s)	3.05 ± 0.26	3.16 ± 0.27*	3.21 ± 0.28*	**P < 0.001*(0.51)***	**0.41**; -0.11*(-0.18;-0.03)*	**0.57**; -0.05*(-0.13;0.03)*	0.17; 0.11*(-0.01;0.22)*
CMJ push-off impulse (Ns)	227.5 ± 23.8	233.8 ± 25.0*	237.3 ± 27.0*	**P < 0.001*(0.50)***	**0.25**; -6.3(-10.9*;-1.7)*	**0.37**; -9.7(-15.4*;-4.0)*	0.13; -3.4*(-7.5;0.7)*
20-m sprint time (s)	3.08 ± 0.12	3.01 ± 0.12*	2.97 ± 0.14*#	**P < 0.001*(0.61)***	**0.58**; 0.07*(0.02;0.12)*	**0.85**; 0.11*(0.07;0.15)*	**0.31**; 0.04*(0.01;0.07)*
T-test time (s)	10.39 ± 0.65	9.92 ± 0.64*	9.80 ± 0.53*	**P < 0.001*(0.54)***	**0.74**; 0.12*(0.16;0.79)*	**0.99**; 0.11*(0.29;0.88)*	0.20; 0.09*(-0.11;0.35)*

*Values are Mean ± SD (n = 16). ES, effect size; MD, mean difference; 95% CI, 95% confidence interval. * and # significantly different from Baseline and TS, respectively. Statistically significant ANOVA P values (partial eta-squared or η_p^2) and large effect sizes are listed in bold.*

maximal 20-meter sprints with a 2-minute walk-back recovery between each sprint. All tests were performed in a competitive manner, and the mean of three trials was used for final analysis. An automated light gate system (SmartSpeed™, Fusion Sport, Australia) with 0.01 s accuracy was used to record all times.

T-test

The T-test involved arranging four cones in a T-shape, with one cone positioned 9.14 meter from the starting point and the other two cones placed 4.57 meter from either side of the second cone [22]. Participants were instructed to sprint 9.14 meter forward from the starting line to the first cone and touched it with their right hand. Then, they were required to move 4.57 meter to the left to reach the second cone and touch it with their left hand, followed by advancing 9.14 meter to the right to reach the third cone and touch it with their right hand. They then moved 4.57 meter to the left to the middle cone and touched it with their left hand before running backward to the starting line. The timing began with a sound signal and ended when the participant passed the timing gate when returning. If a participant failed to touch the designated cone, or crossed the legs while moving, or did not face forward throughout the testing period, the trial was considered unsuccessful. The timing was assessed using the same automated light gate system as for the 20-meter sprint.

Statistical Analysis

Values are expressed as mean ± SD and 95% confidence interval (CI). For all dependent variables, the effect of condition was determined by a single factor analysis of variance for repeated measures (Baseline, TS, and CS). 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 analysis of variance, 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, respectively. To aid interpretation, the dependent variables were expressed as the percent change (%) from the Baseline measurements. Statistical significance was set at $P \leq 0.05$.

RESULTS

Participants exhibited increased CMJ height in both TS (+4.1 ± 5.0%; P = 0.007) and CS (+8.7 ± 7.0%; P < 0.001) compared to Baseline, with CMJ height being higher in CS than TS (+4.4 ± 5.4%; P = 0.008) (Figure 2A; Table 1). Compared to Baseline, CMJ power output increased after CS (+3.6 ± 3.1%; P < 0.001), but not after TS (+0.4 ± 4.1%; P = 0.100). Additionally, CMJ power output was greater in CS than TS (+3.4 ± 4.4%; P = 0.040) (Figure 2B). Participants exhibited increased CMJ take-off velocity in both TS (+3.6 ± 3.7%; P = 0.004) and CS (+5.1 ± 3.8%; P < 0.001) compared to Baseline, with no significant differences between TS and CS (+1.5 ± 3.9%; P = 0.425) (Figure 2C). Regarding CMJ push-off impulse, both TS (+2.8 ± 3.1%; P = 0.006) and CS (+4.2 ± 2.7%; P < 0.001) resulted in improvements compared to Baseline, with no significant difference between TS and CS (+1.4 ± 2.7%; P = 0.128) (Figure 2D).

Both TS (+2.3 ± 2.5%; P = 0.007) and CS (+3.6 ± 2.2%; P < 0.001) resulted in faster sprint times compared to Baseline, with also faster sprint times in CS than TS (+1.3 ± 1.7%; P = 0.022) (Figure 3A; Table 1). Faster T-test times were observed after both TS (+4.5 ± 4.4%; P = 0.003) and CS (+5.5 ± 4.0%; P < 0.001) compared to Baseline, with no significant difference between TS and CS (+1.1 ± 3.3%; P = 0.585) (Figure 3B; Table 1).

DISCUSSION

Our intention was to compare the effects of two priming exercise protocols using low-volume back squats, with either a TS or CS configuration, on explosive performance after six hours of rest. Taken together, and in agreement with our hypothesis, a morning priming exercise improved jumping, sprinting, and agility performance in the afternoon. However, the CS configuration, with 30 seconds of rest between repetitions, was a better strategy to maximize neuromuscular performance compared to the TS arrangement, which had no rest within the sets.

A major finding of our study was the superior jumping and sprinting performance observed with the CS protocol. Arguably, the rest intervals incorporated in the CS configuration may have contributed to a better potentiation/fatigue balance [15], thus enabling greater performance benefits later in the day. This suggestion is consistent with previous research on post-activation performance enhancement, which has shown that CS with heavy loads (≥ 85% 1RM) results in better performance compared to TS arrangements [20, 23]. It is noteworthy that in these studies, performance evaluation was limited to only a few minutes after the intervention. For instance, Nickerson et al. [20] showed a significantly greater post-activation performance enhancement effect in the 20-meter sprint induced by CS compared to TS. From a neuromuscular perspective, high-frequency motor neuron activation, mechanical stiffness, and contractile properties are potential mechanisms for performance facilitation in the minutes after the intervention [24]. However, there is still uncertainty regarding the role of the neuromuscular system in priming that occurs six hours before performance assessment [7].

Another key finding was that CMJ peak power improved only in CS. Both TS and CS protocols also resulted in enhancements in CMJ height, take-off velocity, and push-off impulse six hours after the priming exercise. Additionally, participants sprinted faster following priming exercise protocols. These observations are consistent with several studies showing that high-intensity, low-volume priming exercise can induce positive effects for CMJ and/or 40-meter sprint performance due to enhanced neuromuscular efficacy [5, 6, 25, 26]. For

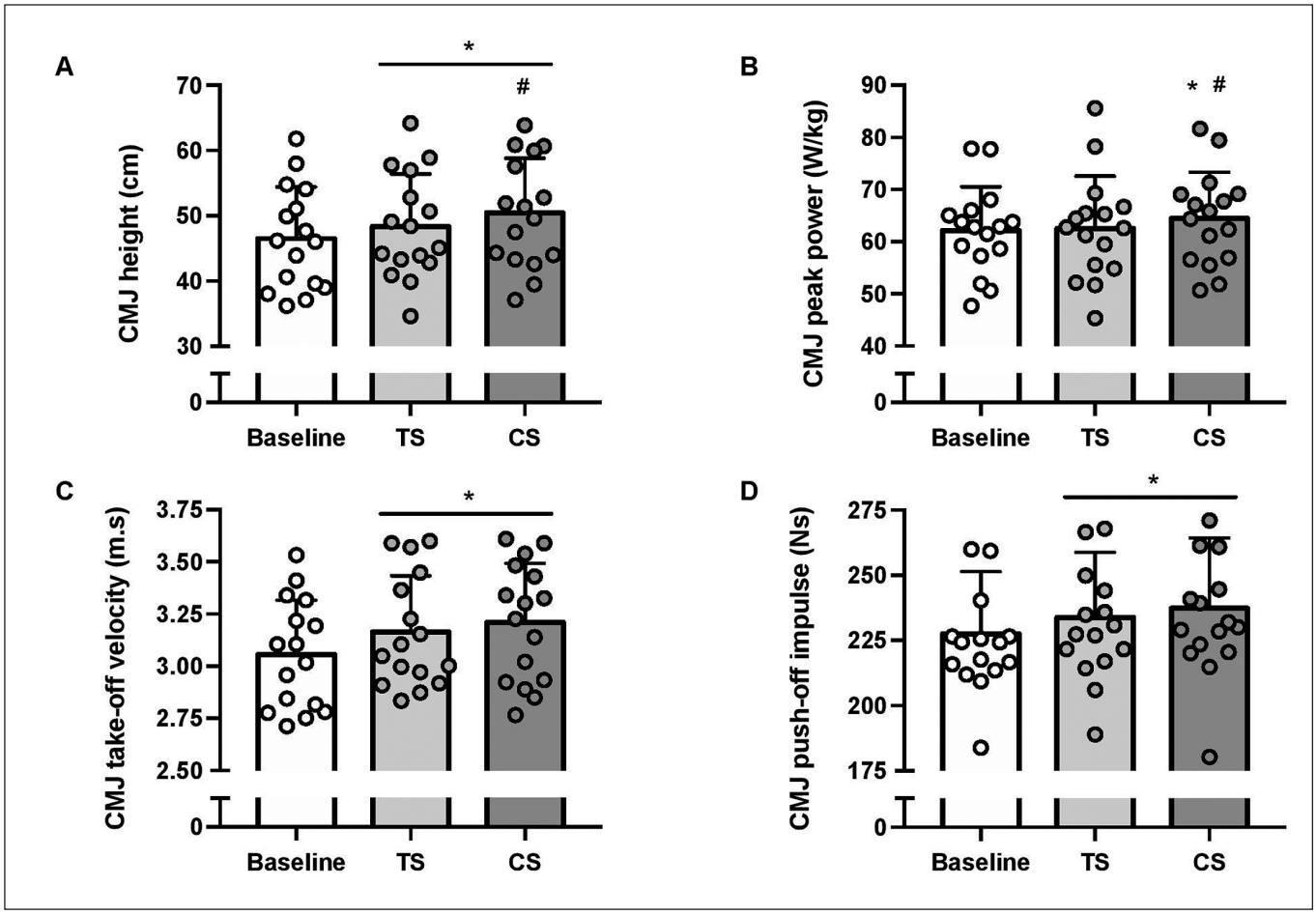


FIG. 2. Countermovement (CMJ) height (A), peak power (B), take-off velocity (C), and push-off impulse (D) at baseline and six hours after a morning priming exercise protocol using traditional (TS) or cluster sets (CS). Values are Mean ± SD (n = 16). * and # significantly different from Baseline and TS, respectively.

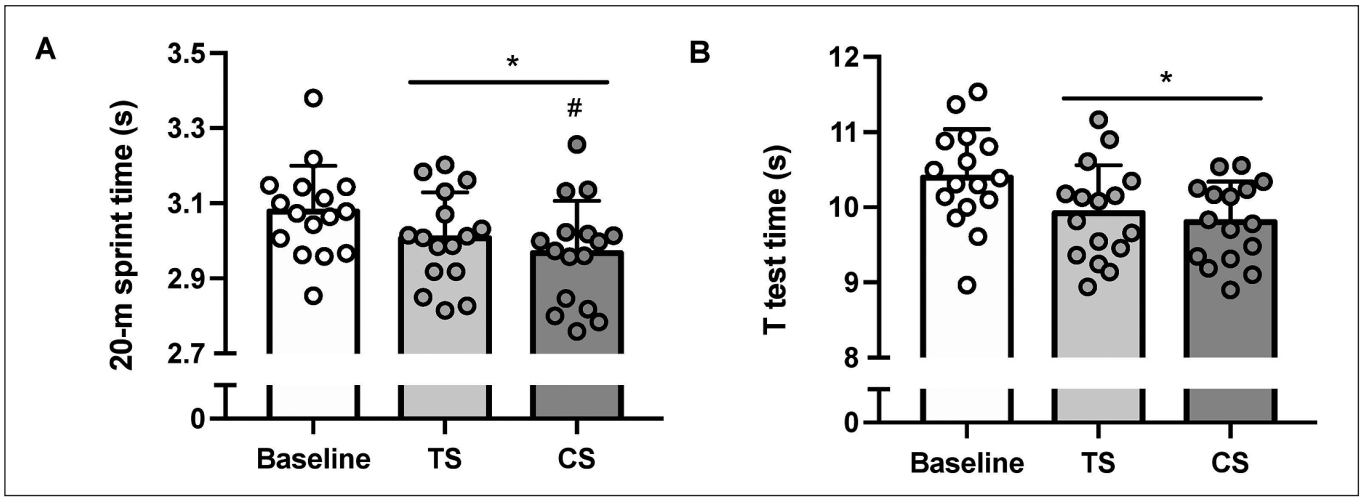


FIG. 3. Performance time for 20-meter sprint (A) and T-test (B) at baseline and six hours after a morning priming exercise protocol using traditional (TS) or cluster sets (CS). Values are Mean ± SD (n = 16). * and # significantly different from Baseline and TS, respectively.

example, semi-professional rugby players who engaged in priming exercise with an intensity ranging from 80–100% 1RM showed improvements in 3RM bench press, 3RM back squat, and CMJ peak power, as well as a decrease in 40-meter sprint time [5]. In our study, both TS and CS protocols led to comparable benefits (i.e., 4.5% *vs*. 5.5%, respectively) for agility performance relative to baseline. However, no previous studies were found that compared the afternoon performance changes induced by morning CS and TS priming exercises, limiting potential comparisons with the literature. Agility is largely determined by strength and power production capabilities [27], which probably explains why the improved T-test times were consistent with beneficial changes in CMJ and 20-meter sprint performance.

In this study, most athletes showed a positive response to moderate exercise volumes, while others did not. This raises the question of what the minimum effective dose should be for each athlete to achieve significant performance gains. It is argued that when heavy loads (≥ 80% 1RM) are used, an appropriate exercise volume (reps × sets × % 1RM) is necessary to induce beneficial effects [7]. In our study, both conditions had a total exercise volume of 765 a.u, with the same number of repetitions performed. This falls within the recommended dose range of 760–1190 a.u [7]. However, visual examination of Figures 2 and 3 indicates a wide range of inter-individual responses, which may be partly attributed to methodological factors. Firstly, the chronotype of participating athletes was not assessed, nor were their workout preferences in terms of their habitual pre-competition strategies (i.e., exercise selection and resistance loading methods) monitored. Secondly, the athletes tested may have been at different stages of their training cycles, ranging from periods of detraining and rest to their peak competitive state. This variation in training could have influenced their physical and mental approach to the testing process.

There are several methodological and logistical aspects that need to be emphasized. While the two different priming sessions were randomized, a primary limitation of this study is the lack of randomization regarding the order in which participants completed experimental protocols and baseline testing. Additionally, neurophysiological variables such as surface EMG indicators, as well as hormonal variables such as testosterone concentration, were not measured. Previously, both serum testosterone and cortisol levels were elevated six hours after a morning-based strength exercise session [5]. However, it remains to be investigated whether the morning CS workout condition resulted in higher blood testosterone levels later in the day compared to using TS arrangements.

An additional consideration is the assessment of athletes in the afternoon at a single time point. However, delayed performance benefits have been observed after various priming exercises performed up to 48 hours beforehand [1, 4, 7, 26]. Therefore, future studies should investigate the effects of our priming exercise protocols at different time points to determine the optimal recovery time for prescribing priming exercise. While there is growing interest in CS paradigms, it is still uncertain which method of CS application is more effective in enhancing neuromuscular performance. This includes the manipulation of rest periods between clusters of repetitions, as done in our study, or after each individual repetition within a set [15]. Investigation into different CS configurations could add further value for researchers and practitioners alike.

Practical applications

The majority of the sixty-nine practitioners (~84%) surveyed by Harrison et al. [2] believed that priming exercise in high performance sport is beneficial for enhancing performance. Our study results support this idea and add that including a barbell back squats session utilizing a CS configuration (30-second interval between repetitions, 4-minute interval between sets) six hours prior to testing can be an effective ergogenic strategy for improving explosive performance compared to a no morning exercise condition. The cost of using a CS configuration is negligible, especially considering performance improvements observed herein, and the fact that it only adds a few extra minutes to the completion time. When competitions are scheduled in the afternoon, strength and conditioning coaches could therefore prescribe a high-load, low-volume squat-based priming exercise (85% 1RM, three sets of three repetitions) in the morning to enhance jumping, sprinting, and agility in the afternoon.

CONCLUSIONS

The effects of two morning priming exercise protocols, both involving low-volume back squats, on explosive performance after six hours of rest were compared: one with a TS (nor rest between repetitions) configuration and the other with a CS (30 seconds of rest between repetitions) configuration. Compared to TS, employing a CS configuration further enhances performance benefits later in the day, resulting in improvements of 1–4.5%.

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Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. 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.
2. Harrison PW, James LP, McGuigan MR, Jenkins DG, Kelly VG. Prevalence and application of priming exercise in high performance sport. J Sci Med Sport. 2020; 23(3):297–303.
3. Saez Saez de Villarreal E, González-Badillo JJ, Izquierdo M. Optimal warm-up stimuli of muscle activation to enhance short and long-term acute jumping performance. Eur J Appl Physiol. 2007; 100(4):393–401.
4. Tsoukos A, Veligekas P, Brown LE, Terzis G, Bogdanis GC. Delayed effects of a low-volume, power-type resistance exercise session on explosive performance. J Strength Cond Res. 2018; 32(3):643–650.
5. Cook CJ, Kilduff LP, Crewther BT, Beaven M, West DJ. Morning-based strength training improves afternoon physical performance in rugby union players. J Sci Med Sport. 2014; 17(3):317–321.
6. Russel M, King A, Bracken RM, Cook CJ, Giroud T, Kilduff LP. A comparison of different modes of morning priming exercise on afternoon performance. Int J Sports Physiol Perform. 2016; 11(6):763–767.
7. 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.
8. McGowan CJ, Pyne DB, Thompson KG, Raglin JS, Rattray B. Morning exercise: enhancement of afternoon sprint-swimming performance. Int J Sports Physiol Perform. 2017; 12(5):605–611.
9. Ekstrand LG, Battaglini CL, McMurray RG, Shields EW. Assessing explosive power production using the backward overhead shot throw and the effects of morning resistance exercise on afternoon performance. J Strength Cond Res. 2013; 27(1):101–106.
10. Woolstenhulme MT, Bailey BK, Allsen PE. Vertical jump, anaerobic power, and shooting accuracy are not altered 6 hours after strength training in collegiate women basketball players. J Strength Cond Res. 2004; 18(3):422–425.
11. Haff GG, Hobbs RT, Haff EE, Sands WA, Pierce KC, Stone MH. Cluster Training: A novel method for introducing training program variation. Strength Cond J. 2008; 17(1):67–76.
12. Gorostiaga EM, Navarro-Amezqueta I, Calbet JA, et al. Blood ammonia and lactate as markers of muscle metabolites during leg press exercise. J Strength Cond Res. 2014; 28:2775–2785.
13. Benjanuvatra N, Bardbury D, Landers G, Goods P, Girard O. How does multi-set high-load resistance exercise impact neuromuscular function in normoxia and hypoxia? Eur J Sport Sci. 2022; 17(5):658–665.
14. Tufano JJ, Brown LE, Haff GG. (2017). Theoretical and practical aspects of different cluster set structures: a systematic review. J Strength Cond Res. 2017; 31(3):848–867.
15. Latella C, Teo WP, Drinkwater EJ, Kendall K, Haff GG. The acute neuromuscular responses to cluster set resistance training: a systematic review and meta-analysis. Sports Med. 2019; 49(12):1861–1877.
16. 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):885–892.
17. Dello Iacono A, Beato M, Halperin I. The effects of cluster-set and traditional-set postactivation potentiation protocols on vertical jump performance. Int J Sports Physiol Perform. 2019; 14(1):74–79.
18. 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):317–331.
19. 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):885–895.
20. Nickerson BS, Mangine GT, Williams TD, Martinez IA. Effect of cluster set warm-up configurations on sprint performance in collegiate male soccer players. Appl Physiol Nutr Metab. 2018; 43(6):625–630.
21. Dæhlin TE, Haugen OC, Haugerud S, Hollan I, Raastad T, Rønnestad BR. Improvement of ice hockey players' on-ice sprint with combined plyometric and strength training. Int J Sports Physiol Perform. 2017; 12(7):893–900.
22. Pauole K, Madole K, Garhammer J, Lacourse M, Rozenek R. Reliability and validity of the T-Test as a measure of agility, leg power, and leg speed in college-aged men and women. J Strength Cond Res. 2000; 14(4):443–450.
23. Boullosa DA, Abreu L, Beltrame LG, Behm DG. The acute effect of different half squat set configurations on jump potentiation. J Strength Cond Res. 2013; 27(8):2059–2066.
24. 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.
25. Fry AC, Stone MH, Thrush JT, Frazee SJ. Precompetition training sessions enhance competitive performance of high anxiety junior weightlifters. J Strength Cond Res. 1995; 9(1):37–42.
26. González-Badillo JJ, Rodríguez-Rosell D, Sánchez-Medina L, Ribas J, López-López C, Mora-Custodio R, Yañez-García JM, Pareja-Blanco F. Short-term recovery following resistance exercise leading or not to failure. Int J Sports Med. 2016; 37(4):295–304.

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Injury incidence and characteristics in adolescent female football players: A systematic review with meta-analysis of prospective studies

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ABSTRACT: To observe overall, training, and match injury incidence in female youth football. We also aimed to quantify the incidence of injuries by affected tissue and body location. The following databases were examined: PubMed, Web of Science, Scopus, SPORTDiscus, Cochrane and PEDro. Papers that reported overall injury incidence, training or match injury incidence were included. Additionally, studies had to be performed in adolescent female football players (13–19 years of age). The Newcastle-Ottawa Scale and the checklist of items that must be included in epidemiological football reports were used to assess methodological quality of the included articles. For the meta-analyses, a random effect model was used. A total of 13 studies were included. There were 2,333 injuries; incidence was higher during games (12.7/1000 h) compared to training sessions (2.3/1000 h). The injury match-to-training ratio was 5.8. The lower limbs were the region in which the greatest number of injuries occurred, with the ankle (1.2/1000 h) and knee (0.8/1000 h) having the most injuries. In relation to injured tissue, ligament injuries represented an incidence of 1.3/1000 h, followed by muscle injuries (0.9/1000 h). This study represents the first step towards the creation and implementation of preventative measures in female youth football. The results suggest that attention should be focused on ankle and knee injuries, since they are the most frequent and can lead to sport retirement in some cases depending on the severity.

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INTRODUCTION

Female participation in football is growing in popularity, especially supported by the influence of countries such as France, Sweden, or the United States [1–3]. Nevertheless, as sports participation grows, the incidence of injury increases [4, 5]. This can compromise future physical function and even lead to damage of the professional career [4, 6, 7] or abandonment of sports practice [8, 9].

Since the publication of the Consensus Statement on injury definition and data collection, interest in injury epidemiology in football has risen [10]. Researchers have focused attention on injuries in adult and young footballers, both professional and amateur [11–14]. However, this growth has been significantly biased towards male athletes. Only 21% of the papers included in a recent review reported data on injuries in female adolescent football players [14], highlighting the underrepresentation of women in research [15]. Another issue in exploring injuries around youth female football is the variability in methodological approaches used between studies. Differences in injury definition, follow-up time, and study design, among others, are some of the handicaps that prevent researchers drawing strong conclusions regarding this topic [16]. The previous points provide valuable information on what should be the focus when performing a meta-analysis, since the current state-of-the-art only serves to augment uncertainty around decision making.

The existence of anatomical and physiological differences between men and women make imperative the analysis of injuries separately, since this variability influences injury incidence and its characteristics [17, 18]. For example, males sustain more hamstring injuries than female players (0.8 vs. 0.6 injuries per 1000 h of exposure) [19, 20]. On the other hand, females have 2 to 3 times higher risk of sustaining an anterior cruciate ligament (ACL) injury, compared to their male counterparts [21]. Therefore, it seems inappropriate to extrapolate results from one population to another [22]. Regarding age differences, injury incidence in adolescent male football

players (5.7/1000 h [14]) is lower than that of male adult players (8.1/1000 h [11]). Main injured locations vary; adolescent injuries affect apophyses and growth plates the most [23], while adult players suffer muscle injuries principally [24].

Previous reviews on young female player injuries have included paediatric participants (inclusion criteria < 19 years of age without a lower threshold), which might confound the results [14]. Also, some criticism has arisen for methodological reasons (i.e. conclusions based on single-point estimates or modification of tools to assess study quality), which implies that results from these investigations must be interpreted with caution [25]. Medical teams prioritize enhancing sports safety by designing and implementing preventive measures, particularly crucial for youth populations. A structured approach, as proposed by van Mechelen, involves three key steps: (1) identifying and describing sport injuries, (2) analysis of risk factors and mechanisms underlying injuries, (3) introduction and effectiveness testing of prevention strategies [26]. We decided to conduct this systematic review with a clear age definition (13 to 19 years of age) and a rigid inclusion criterion due to the variability in injury incidence depending on participants' age, to address the first step in the "sequence of prevention" [26]. We aimed to summarize the overall information about the incidence, location, type, and severity of injuries in adolescent female football players.

MATERIALS AND METHODS

The study was registered in PROSPERO (code: CRD42020192263), was conducted in accordance with the methods outlined in the Cochrane Handbook, and is reported according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [27]. The PRISMA checklist is presented in Appendix A.

Study selection

The inclusion criteria for studies to be included in this systematic review were established according with the PICOS question

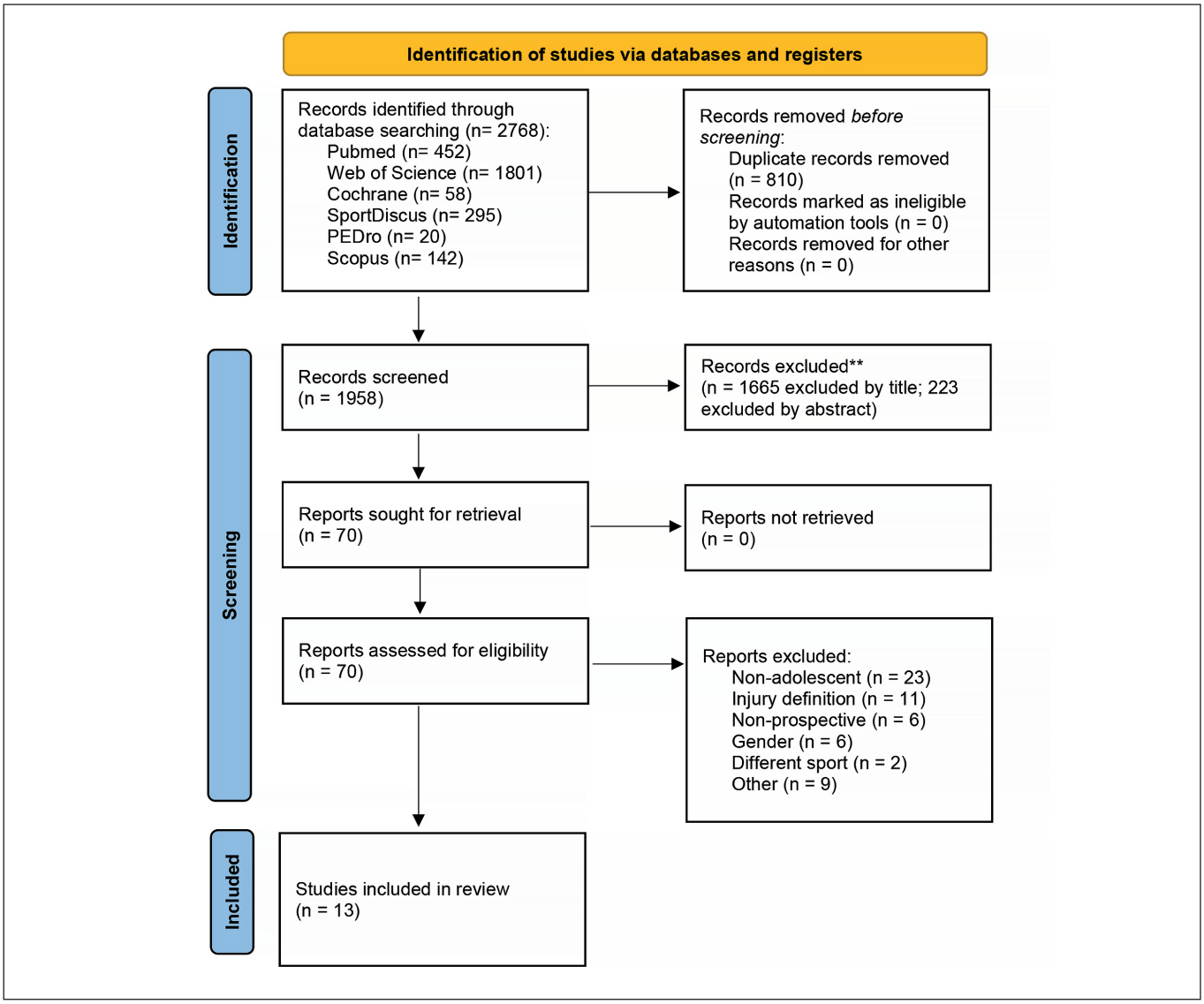


FIG. 1. Flowchart of the study selection for overall, training or match injury incidence.

(Population, Indicator, Control, Outcome, and Study design) [27]: (P) include adolescent female football players (i.e., players belonging to federated football teams regardless of category and aged 13–19 years), (I) injury definition in terms of time loss (injury that results in a player being unable to take full part in future football training or match play) [10], (C) interventional studies were included when there was a control group which had not undergone an intervention (control group data were utilized), (O) report either overall, training or match injury incidence rate among the surveyed players, (S) have a prospective design. Additionally, a minimum of 11 players (one team) had to be analysed, and articles were required to be written in English and published in a peer-reviewed journal to be included in the review. "Grey literature" (i.e., conference, abstracts, thesis, and unpublished reports) was not taken into account. Any article failing to meet one of the inclusion criteria was excluded.

Search strategy

All studies were identified through a systematic search on the electronic databases PubMed/MEDLINE, Web of Science, Scopus, SPORTDiscus, Cochrane and PEDro, from inception until October 3rd, 2022. A secondary database search was performed on August 28th 2023, yielding 90 additional records; no additional study was included since inclusion criteria were not met. Reference lists of the included articles were also searched for additional references. Details of the search strategy for PubMed/MEDLINE are shown in Appendix B. Two reviewers (I L-A and HO) independently screened the titles and abstracts of all studies. Duplicate articles were removed using Mendeley Reference Manager. Both reviewers assessed the full text of all potentially eligible articles identified in order to evaluate their possible inclusion in the review. Disagreements over article inclusion were settled through discussion with a third reviewer (MV) until a consensus was reached. The study selection process is presented in Figure 1.

Data extraction

Data were extracted independently by two reviewers (I L-A and HO) using an electronic data extraction form. The data extracted included the following: (1) General study descriptors (authors, year of publication, place, and study design), (2) characteristics of the subjects (sample size, age and team or place), (3) epidemiological data of injuries (incidence rate and exposure data and distribution by anatomical location). If necessary, the authors of included studies were contacted to provide clarifications or access to raw data. The purpose of the current meta-analysis was to determine the overall effects of: (1) adolescent female football/football-related injury incidence rate (number of injuries × 1000 hours of athletic exposure) [28], (2) location of injuries (lower extremity vs. trunk vs. upper extremity vs. head and neck) and (3) affected tissue (muscle vs. ligament).

Risk of bias and study quality assessment

Risk of bias of included studies was assessed by two reviewers (MQ and HO) independently using a modified version of the Newcastle-Ottawa Scale (NOS). The NOS is a quality assessment tool for cohort and case-control studies which contains eight items categorized into three domains (selection of study groups, comparability of groups and ascertainment exposure) and uses a star rating system to indicate the quality of a study. A description of the items used can be found in Appendix C. The higher the number of stars given to an article, the lower is the risk of bias; studies obtaining > 5 stars were classified as having low risk of bias [12].

The methodological quality of the included studies was evaluated using the "Checklist of items that must be included in epidemiological football reports" following the methodology proposed in a recent systematic review [10]. This checklist consists of 19 items of relevant information that any research in this field should contain; we removed two items (age range and gender of players), since these were part of the inclusion criteria and all the articles met both criteria; the description of each item is available in Appendix D. Any disagreement in the assessment of risk of bias or methodological quality was resolved by mutual consent in consultation with a third reviewer (MV).

Quality of the evidence

The quality of evidence (QoE) for the meta-analyses performed was graded using the GRADE (Grading of Recommendations Assessment, Development and Evaluation) approach [29]. Initially, it was assumed that the quality was high. Quality was downgraded to moderate, low, or very low when one of the following factors was rated as serious, or very serious: risk of bias, inconsistency, indirectness, or imprecision.

Statistical analyses

Data analysis was performed by a statistician (AF). Incidence rates (per 1000 hours of exposure) with the corresponding confidence intervals, and number of participants were extracted from the included studies to a Microsoft Excel (Microsoft Excel, Seattle, USA) sheet by one author (MQ). If data were not specifically reported, we calculated them from the available raw data (number of injuries, no. of games or sessions, exposure hours), using the following formulas:

(a) Incidence = (Σ Injuries / Σ Exposure) × 1000

(b) Incidence = no. of injuries / (no. of matches × 11 players × match duration*) × 1000

*Match duration, using the factor 1.5, based on standard 90 min match play [12].

Pooled inverse variance-weighted mean injury incidence rate (IR) estimates along with the 95% confidence interval (CI) for the outcomes were calculated using random effects models based on heterogeneity. The usage of random effects models was decided after applying the Cochran Q test ($p < 0.10$), which measures between-studies heterogeneity. Additionally, the variability between studies was estimated with the τ^2 statistic. Finally, the statistic I^2 was used to measure the percentage of total variation in the effect sizes due

to heterogeneity, with > 50% and > 75% representing moderate and high heterogeneity, respectively [30]. Sensitivity sub-analyses were performed to manage heterogeneity. Specifically, a leave-one-out influence analysis was chosen, and the estimation did not change meaningfully, supporting the usage of the random effects model. Forest plots were created to illustrate the effects of the different studies and the global estimation of the meta-analysis. The forest plot for each meta-analysis shows the incidence rates of each study and the pooled incidence rate (overall) for the random effect model, all with their 95% CI and on the logarithmic scale. Statistical analyses were performed using Stata 14.2 (Stata Corporation, College Station, TX, USA) and the mar package (V1.4.6.).

RESULTS

Study selection

The electronic searches retrieved 2768 references from the literature. After duplicates were removed, 1888 records were excluded during title and/or abstract analysis; 70 full-text copies of the remaining studies were obtained and subjected to further evaluation. At the end of the process, 13 publications met the eligibility criteria and were selected for qualitative and quantitative analysis [1, 2, 31–41].

Methodological quality assessment

With regards to the risk of bias of the included studies, the mean score obtained on the modified NOS scale was 6 (min: 4, max: 8). Eight studies scored > 5 stars and were considered of low risk of bias [1, 2, 31, 33, 36, 38–40] while the rest received lower scores. The main sources of bias were not reporting the proper methodology of exposure collection or estimating these data (item 4), and the lack of specification of whether the participants were healthy at the beginning of the study (item 5). The mean score for the methodological quality assessment was 16.4 out of 19 possible points [10].

TABLE 1. Characteristics of studies included in the meta-analyses.

Reference	Nº Players	Age	Study type	Exposure (hours)			Nº Injuries			Incidence			Risk of Bias (NOS)	Study Quality
				Overall	Training	Match	Overall	Training	Match	Overall	Training	Match		
Beech et al. 2022 [31]	375	U-16	Elite club season	52,834	46,461	6,374	111	52	59	2.1	1.1	9.3	**7**	19
Clausen et al. 2014 [32]	438	15 to 18	Club season	27,746	21,461	6,285	269	-	-	9.7	-	-	5	18
Hägglund et al. 2009 [33]	433	17.9 (0.8)	Elite international tournament	1,707	1,210	497	23	9	14	13.5	7.4	28.2	**6**	18
Le Gall et al. 2008 [1]	119	15 to 19	Elite club season	97,325	87,530	9,795	619	400	219	6.4	4.6	22.4	**7**	17
Lislevand et al. 2014 [34]	938	13 to 17	Club tournament	-	-	1,318	-	-	8	-	-	6.06	5	15
Schmidt-Olsen et al. 1985 [35]	964	13 to 19	Club tournament	-	-	3,913	-	-	69	-	-	17.6	5	13
Söderman et al. 2001 [2]	175	15.9 (1.2)	Club season	11,689	-	-	79	-	-	6	-	-	**7**	13
Soligard et al. 2008 [36]	837	15 (0.7)	Club season	45,428	31,086	14,342	212	74	138	4.73	2.38	9.62	**8**	18
Soligard et al. 2012 [37]	2357	13 to 19	Club season	-	-	18,376	-	-	101	-	-	4.62	5	14
Sprouse et al. 2020 [38]	5852	15 to 19	Elite international tournament	51,151	46,162	4,989	323	190	133	6.31	4.11	26.65	**7**	16
Steffen et al. 2007 [39]	2020	15.4 (0.8)	Club season	142,721	101,410	41,311	456	113	343	3.68	1.11	8.3	**6**	18
Steffen et al. 2008 [40]	943	15.4 (0.8)	Club season	65,725	45,869	19,856	241	-	-	3.66	-	-	**6**	19
Zebis et al. 2018 [41]	185	15 to 18	Club season	-	-	1,559	-	-	29	-	-	18.6	4	15

NOS = Newcastle-Ottawa Scale, U = Under. Age is presented as mean (SD) when possible or as range or category (i.e., U-16), NOS and Study Quality are measured on a 0–8 and 0–19 scale, NOS bold values indicate low risk of bias studies.

Individual study scores for risk of bias and methodological quality can be found in Table 1.

Characteristics of the included studies

Included studies had a prospective cohort design and recorded information on football injuries exclusively. They were published from 1985 [35] to 2022 [31], and the duration of follow-up ranged from 2 days [34] to 8 seasons [1, 38]. The participants' nationalities were varied; one study was conducted on a Kenyan population [34], one study included participants from international competitions [33], and the rest of the studies were performed in European players [1, 2, 31, 32, 35–40]. Regarding level of play, seven studies were performed on elite/sub-elite players [1, 31, 33, 35, 37, 38, 41], while the rest of the studies collected data on amateur populations. Nine studies reported the overall injury incidence [1, 2, 31–33, 36, 38–40]; six and ten studies reported training [1, 31, 33, 36, 38, 39] and match [1, 31, 33–39] injury incidence, respectively. Regarding secondary outcomes, five studies reported the aggregated lower limb injury incidence [2, 31, 32, 36, 40], two studies reported trunk and head/neck injury incidence [1, 31], six studies reported ankle, knee, thigh, and hip/groin injury incidence [1, 2, 31, 32, 36, 40], three studies reported muscle injury incidence [1, 31, 36], and four reported ligament injury incidence [1, 31, 36, 40].

Injury incidence

There were 2,333 injuries in total, of which 838 occurred during training sessions and 1,495 were sustained during games. Random effect models showed an overall injury incidence of 5.2 injuries per 1000 hours of exposure (95% CI: 4.2–6.3, Q = 1449.23, $p < 0.001$; $\tau^2 = 0.094$; $I^2 = 56\%$; low QoE), incidence for training injuries was 2.3/1000 h (95% CI: 1.3–4.2, Q = 878.61, $p < 0.001$; $\tau^2 = 0.48$; $I^2 = 0\%$; moderate QoE), and match injury incidence was 12.76/1000 h (95% CI: 8.78-18.53, Q = 1288.09, $p < 0.001$; $\tau^2 = 0.33$; $I^2 = 0\%$; moderate QoE). Injury match-to-training ratio was 5.8. Overall, training, and match injury incidence is displayed in forest plots and can be observed in Figure 2.

Injury location

Due to the low number of injuries reported in the studies affecting the upper body, trunk, and head/neck, meta-analyses were performed for lower limb injuries. Injury incidence affecting the lower limbs comprised 3.6 injuries per 1000 hours of exposure (95% CI: 2.1–6.4, Q = 1370.29, $p < 0.001$; $\tau^2 = 0.4$; $I^2 = 0\%$; low QoE), secondary analyses for specific body area showed an injury incidence of 0.5 (95% CI: 0.3–0.9, Q = 31.17, $p < 0.001$; $\tau^2 = 0.27$; $I^2 = 37.2\%$; low QoE) (hip/groin); 0.7 (95% CI: 0.5–1.1, Q = 72.6, $p < 0.001$; $\tau^2 = 0.23$; $I^2 = 30.6\%$; low QoE) (thigh); 0.9 (95% CI: 0.5–1.4, Q = 125.84, $p < 0.001$; $\tau^2 = 0.28$; $I^2 = 56.2\%$; very low QoE) (knee); and 1.2 (95% CI: 0.9–1.5, Q = 67.28, $p < 0.001$; $\tau^2 = 0.07$; $I^2 = 55.9\%$; very low QoE) (ankle). Forest plots with 95% confidence intervals for the different locations can be found in Appendix E.

Injuries affecting head/neck had the lowest injury incidence. Beech et al. [31] observed 0.1 injuries per 1000 exposure hours (95% CI: 0.1–0.3), while Le Gall et al. [1] reported an injury incidence of 0.03/1000 h (95% CI: 0–0.1). Injury incidence regarding the trunk rated between 0.04 (0–0.1) and 0.1 (0.1–0.3) injuries per 1000 hours of exposure [1, 31].

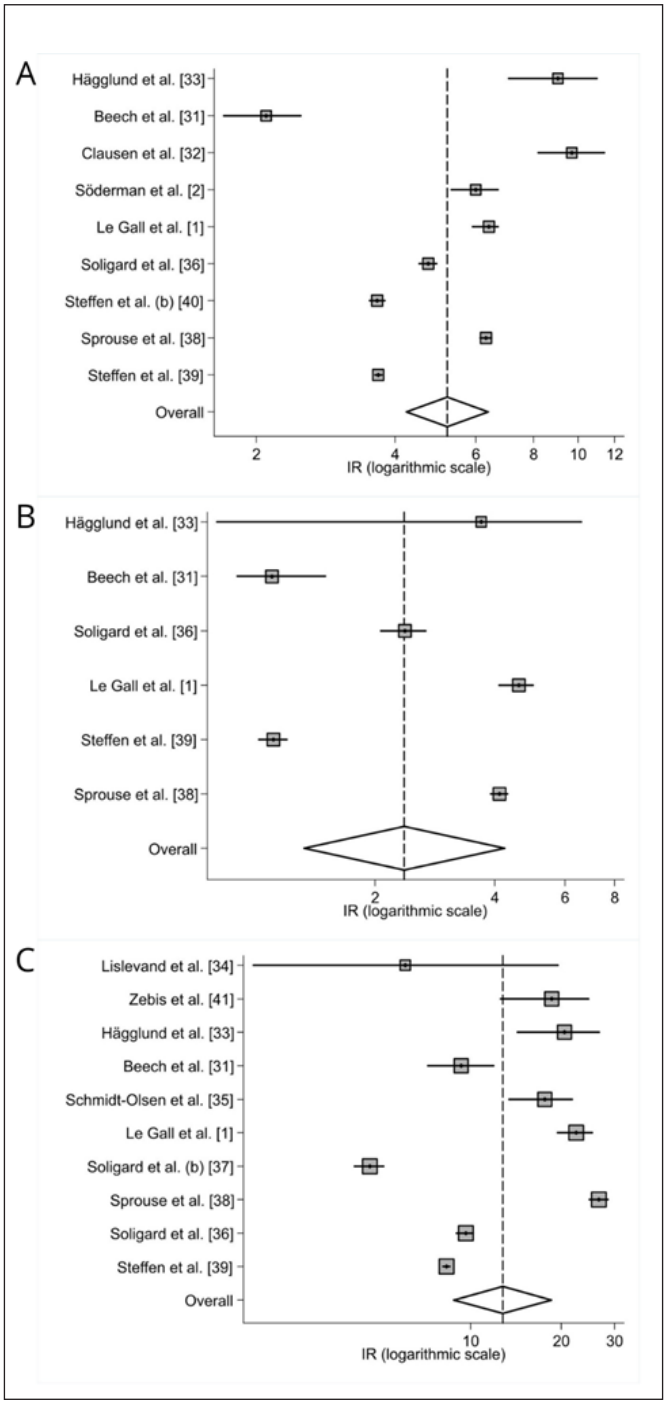


FIG. 2. Forest plot displaying overall (A), training (B), and match (C) injuries with the corresponding 95% confidence intervals.

Three studies reported upper limb injuries, resulting in a higher injury incidence compared to head/neck or trunk injuries. Steffen et al. [40] observed 0.6/1000 h injuries (95% CI: 0.4–0.7), followed by 0.3/1000 h (95% CI: 0.2–0.4) [1], and 0.2/1000 h (95% CI: 0.1–0.4) [31].

Injured tissue

Injuries were specified regarding ligament and muscle tissue. Injuries affecting ligamentous structures had an incidence of 1.3/ 1000 hours of exposure (95% CI: 1–1.6, Q = 54.67, $p < 0.001$; $\tau^2 = 0.05$; $I^2 = 67.1\%$; low QoE), while muscle injuries accounted for 0.9 injuries for every 1000 hours of exposure (95% CI: 0.4–1.8, Q = 101.24, $p < 0.001$; $\tau^2 = 0.36$; $I^2 = 0\%$; low QoE). Forest plots with 95% confidence intervals for the different injured tissues can be found in Appendix F.

DISCUSSION

This systematic review with meta-analysis aimed to quantify injury incidence rates in adolescent female football players. When aiming to mitigate the risk of suffering injuries, the first step is to define the extent of the problem [26]. Previous systematic reviews with meta-analysis have been performed in adults but recently some criticism has arisen due to methodological reasons [25]. This review focuses on this issue, and analyse the topic from a new perspective; included studies had a prospective design, which increases the reliability of the observed results.

Methodological quality assessment

It is vital to report information in accordance with consensus statements, aiding in the interpretation and analysis of data. We assessed methodological quality with the checklist from Fuller et al. since there is no tool for this purpose in observational studies [10]. In this regard, no threshold was set to determine high- or low-quality studies; it is the authors' opinion that scores above 15 points (80% of items met) could be categorized as of high quality. Using this threshold, we can be confident that our results are valid, since the mean score of the included papers was 16.4. Additionally, more than half of the included studies were rated as of low risk of bias. Many studies did not report how exposure time was collected; the recording of this value must be accurate since it can affect incidence rates (e.g. when two cohorts have the same number of injuries, the one with lower exposure will have had a higher injury incidence). To properly measure exposure, it is recommended to use weekly forms with individual training and match time.

Injury incidence

The main findings are that adolescent female football players sustain 5.2 injuries every 1000 hours of exposure, the incidence of match injuries (12.76/1000 h) being considerably higher than the incidence observed for training related injuries (2.37/1000 h). These results are in line with those reported by Horan et al. in female adult players, where overall, training and match injury incidence rates of 5.63/1000 h, 3.27/1000 h, and 19.07/1000 h, respectively, were observed [42]. Two hypotheses are proposed as to why injuries occur more often during matches: (1) Training sessions do not mimic match scenarios; it may be possible that players do not perform match-like actions with sufficient intensity during training. Many injuries happen during explosive actions (sprinting, accelerating, changing directions, or jumping) and players may not be well prepared to tolerate the load that these gestures impose on their muscles and joints [43]. In this regard, exposure to near maximal sprinting speed (> 95% of maximal speed) two days previous to a game can prevent hamstring strains; this effect may also be true for different lower limb injuries [44]. (2) Contact between players may be less common during training sessions; contacting situations can result in injuries that cause long absence from the sport [45]. To account for this point, education and promotion of fair play might be the answer to avoid injuries due to a contact mechanism [46].

Injury location

Most injuries affected the lower limbs; we observed an injury incidence rate of 3.65/1000 h in this area. Of these lower body injuries, the ankle was the most affected region (1.22/1000 h), followed by the knee (0.89/1000 h), thigh (0.76/1000 h), and hip/groin (0.50/1000 h). Differences were observed compared to male players, who suffer more injuries to the thigh (1.21/1000 h), followed by the ankle (0.91/1000 h) [14]. This can be explained after analysing injuries regarding affected tissue, where females had more ligamentous injuries while males sustained more muscle injuries. It seems therefore that the most common injury in female football is the ankle sprain. The fact that groin injuries had the lowest incidence (0.5/1000 h) is surprising since males have double the incidence of this condition (1/1000 h); these results need to be interpreted with caution, as injury prevalence is similar between genders when non-time-loss groin problems are also considered [47]. Still, anatomical differences in hip and pelvis morphology exist, which may produce differences in the force distribution around the pelvic ring and predispose males to more injuries [18]. However, no clear conclusions can be drawn to date that can explain these differences [48, 49].

Injured tissue

Our meta-analysis showed an overall time-loss injury incidence rate of 1.30/1000 h and 0.89/1000 h for ligament and muscle tissue, respectively. These results reflect the fact that adolescent players have fewer injuries than adult female elites, who have an injury incidence of 2.7 (muscle) and 2.62 (ligament) injuries per 1000 hours [42]. The difference might due to a constrained calendar in elite football with more games throughout the season and inadequate recovery, favouring the development of lesions [50]. Adolescents face an elevated risk of sustaining ligamentous tears, primarily attributed to the raised concentration of oestrogen during the postmenarchal period, which can affect the integrity of ligament structures, leading to

hyperlaxity and increased vulnerability, particularly in the ankle and knee ligaments [51, 52]. Additionally, adolescents undergo a period of significant biological changes, encompassing alterations in muscle-tendon junctions, ligaments, cartilage, and bone density. These changes may render them more susceptible to injuries due to their reduced capacity to tolerate mechanical loads [53]. Furthermore, during this developmental stage, motor skill performance can be impaired by rapid growth, placing additional stress on tissues beyond their typical limits [54, 55]. Lastly, it must be highlighted that youth players experience heightened exposure to football, characterized by increased session frequency, intensity, duration, diverse game formats, and variations in pitch size. This increased exposure may further augment their susceptibility to injuries [56].

Future directions

In order to reduce the risk of suffering a certain injury, the first step is to know the extent of the problem (incidence, prevalence, burden); this study aids in that direction but more research should focus on specific injuries such as ankle sprains, anterior cruciate ligament (ACL) tears, or hamstring strains. It is the authors' opinion that studies on this topic should meet the following criteria to be considered of sufficient quality to be reliable: prospective design, sufficient injury collection time (at least 1 season), diagnosis performed by either a physician or a physiotherapist, regular (weekly or bi-weekly) collection of football exposure, and data report within a clear age frame (i.e., 13–18 years old). Additionally, data on injury-inciting events should be collected using the Football Injury Inciting Circumstances Classification System, since this information adds further value in the prevention sequence and helps in proposing interventions focusing on the exact mechanisms that lead to injuries [57]. Another step could be to differentiate between hip and groin injuries; the last Consensus on football epidemiology suggested collecting these injuries separately [58]. The same principle could be applied to thigh injuries; it is advised to record anterior and posterior thigh injuries separately [19]. Only after we know the exact epidemiological data for these injuries will we be able to implement risk mitigation strategies using randomized controlled trials to test the effectiveness of these measures in reducing the risk of injury. It is of utmost importance to focus on youth populations since most injuries might be easier to sustain after a primer injury has happened already. Implementing programmes is challenging since these athletes tend to get bored or dislike doing extra exercises that demand more time and might lead to delayed onset muscle soreness [59]. Studies on the adoption of prevention programmes have observed that adherence is low [60, 61]; 17–31% of football clubs use hamstring prevention programmes despite its proven effectiveness, and the situation is similar for adductor preventative exercises [60–63]. In this regard, it is advised to educate stakeholders on the benefits of using prevention interventions since effectiveness directly depends on the adherence to the programme.

Limitations

Several methodological limitations must be acknowledged. Some studies were excluded since the injury reporting or definition was not in accordance with the gold standard proposed by the International Olympic Committee [28], which led to only thirteen studies meeting the eligibility criteria. The same problem arose when collecting certain types of injuries. We originally aimed to incorporate studies with a minimum duration of one season. However, due to the limited number of studies meeting our inclusion criteria, this approach was modified and papers with shorter durations were deemed eligible. This modification may have introduced some bias, as studies ranging from 2 days to 8 seasons were combined in our analysis. The checklist of items that must be included in epidemiological football reports was used, despite not being validated, which could have introduced bias in the quality assessment of the included studies. The quality of the evidence could only attain a moderate level in two of the meta-analyses (training and match injuries), and most results were of low quality due to methodological flaws (low number of studies, heterogeneity, or risk of bias), which downgraded the overall quality of the evidence. Some potentially relevant research may have been overlooked due to the absence of a search in the grey literature. It was not possible to perform quantitative analysis of bone injuries since some articles recorded fractures while others measured other types of bone injuries. Insufficient information on specific injuries could be observed, which inevitably led to reporting aggregated data. Lastly, it was not possible to calculate the injury burden due to the lack of data regarding lay-off days due to injury.

CONCLUSIONS

Adolescent female football players are exposed to a substantial risk of sustaining injuries. The anatomical region injured most commonly is the lower extremity (knee and ankle) and the most common types of injury are ligament and muscle/tendon. Future studies should focus on introducing and evaluating preventative and training measures that target the most common diagnoses and the results of this review, in order to reduce the number and severity of injuries within female adolescent football players.

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Conflict of interest

The authors declare no conflict of interest.

REFERENCES

1. Le Gall F, Carling C, Reilly T. Injuries in young elite female soccer players: an 8-season prospective study. Am J Sports Med. 2008 Feb; 36(2):276–84.
2. Söderman K, Adolphson J, Lorentzon R, Alfredson H. Injuries in adolescent female players in European football: a prospective study over one outdoor soccer season. Scand J Med Sci Sports. 2001 Oct; 11(5):299–304.
3. DiStefano LJ, Dann CL, Chang CJ, Putukian M, Pierpoint LA, Currie DW, Knowles SB, Wasserman EB, Dompier TP, Comstock RD, Marshall SW, Kerr ZY. The first decade of web-based sports injury surveillance: descriptive epidemiology of injuries in US high school girls' soccer (2005–2006 through 2013–2014) and national collegiate athletic association women's soccer (2004–2005 through 2013–2014). J Athl Train. 2018 Sep; 53(9):880–92.
4. Rauh MJ, Macera CA, Ji M, Wiksten DL. Subsequent injury patterns in girls' high school sports. J Athl Train. 2007 Dec; 42(4):486–94.
5. Yard EE, Schroeder MJ, Fields SK, Collins CL, Comstock RD. The epidemiology of United States high school soccer injuries, 2005–2007. Am J Sports Med. 2008 Oct; 36(10):1930–7.
6. de Loës M, Dahlstedt LJ, Thomée R. A 7-year study on risks and costs of knee injuries in male and female youth participants in 12 sports. Scand J Med Sci Sports. 2000 Apr; 10(2):90–7.
7. Emery CA, Meeuwisse WH, Hartmann SE. Evaluation of risk factors for injury in adolescent soccer: implementation and validation of an injury surveillance system. Am J Sports Med. 2005 Dec; 33(12):1882–91.
8. Garrick JG, Requa RK. Sports and fitness activities: the negative consequences. J Am Acad Orthop Surg. 2003 Dec; 11(6):439–43.
9. Price RJ, Hawkins RD, Hulse MA, Hodson A. The Football Association medical research programme: an audit of injuries in academy youth football. Br J Sports Med. 2004 Aug; 38(4):466–71.
10. Fuller CW, Ekstrand J, Junge A, Andersen TE, Bahr R, Dvorak J, Hägglund M, McCrory P, Meeuwisse WH. Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. Br J Sports Med. 2006 Mar; 40(3):193–201.
11. López-Valenciano A, Ruiz-Pérez I, Garcia-Gómez A, Vera-Garcia FJ, De Ste Croix M, Myer GD, Ayala F. Epidemiology of injuries in professional football: a systematic review and meta-analysis. Br J Sports Med. 2020 Jun; 54(12):711–8.
12. López-Valenciano A, Raya-González J, Garcia-Gómez JA, Aparicio-Sarmiento A, Sainz de Baranda P, De Ste Croix M, Ayala F. Injury profile in women's football: A systematic review and meta-analysis. Sports Med. 2021 Mar; 51(3):423–42.
13. Mayhew L, Johnson MI, Francis P, Lutter C, Alali A, Jones G. Incidence of injury in adult elite women's football: a systematic review and meta-analysis. BMJ Open Sport Exerc Med. 2021; 7(3):e001094.
14. Robles-Palazón FJ, López-Valenciano A, De Ste Croix M, Oliver JL, García-Gómez A, Sainz de Baranda P, Ayala F. Epidemiology of injuries in male and female youth football players: A systematic review and meta-analysis. J Sport Health Sci. 2022 Nov; 11(6):681–95.
15. Anderson N, Robinson DG, Verhagen E, Fagher K, Edouard P, Rojas-Valverde D, Ahmed OH, Jederström M, Usacka L, Benoit-Piau J, Foelix CG, Akinyi Okoth C, Tsiouti N, Moholdt T, Pinheiro L, Hendricks S, Hamilton B, Magnani R, Badenhorst M, Belavy DL. Under-representation of women is alive and well in sport and exercise medicine: what it looks like and what we can do about it. BMJ Open Sport Exerc Med. 2023 Apr; 9(2):e001606.
16. Mandorino M, J. Figueiredo A, Gjaka M, Tessitore A. Injury incidence and risk factors in youth soccer players:a systematic literature review. Part I: epidemiological analysis. Biol Sport. 2023; 40(1):3–25.
17. Powell JW, Barber-Foss KD. Sex-related injury patterns among selected high school sports. Am J Sports Med. 2000 Jun; 28(3):385–91.
18. Schache AG, Woodley SJ, Schilders E, Orchard JW, Crossley KM. Anatomical and morphological characteristics may explain why groin pain is more common in male than female athletes. Br J Sports Med. 2017 Apr; 51(7):554–5.
19. Mullins K, Mac Colgáin D, Carton P. Incidence and severity of hamstring injuries in female athletes who play field sports: A systematic review with meta-analysis of prospective studies. J Orthop Sports Phys Ther. 2022 Aug 5; 1–31.
20. Tabben M, Eirale C, Singh G, Al-Kuwari A, Ekstrand J, Chalabi H, Bahr R, Chamari K. Injury and illness epidemiology in professional Asian football: lower general incidence and burden but higher ACL and hamstring injury burden compared with Europe. Br J Sports Med. 2022 Jan; 56(1):18–23.
21. Lucarno S, Zago M, Buckthorpe M, Grassi A, Tosarelli F, Smith R, Della Villa F. Systematic video analysis of anterior cruciate ligament injuries in professional female soccer players. Am J Sports Med. 2021 Jun; 49(7):1794–802.
22. Faude O, Junge A, Kindermann W, Dvorak J. Injuries in female soccer players: a prospective study in the German national league. Am J Sports Med. 2005 Nov; 33(11):1694–700.
23. Materne O, Chamari K, Farooq A, Weir A, Hölmich P, Bahr R, Greig M, McNaughton LR. Injury incidence and burden in a youth elite football academy: a four-season prospective study of 551 players aged from under 9 to under 19 years. Br J Sports Med. 2021 May; 55(9):493–500.
24. Ekstrand J, Spreco A, Bengtsson H, Bahr R. Injury rates decreased in men's professional football: an 18-year prospective cohort study of almost 12 000 injuries sustained during 1.8 million hours of play. Br J Sports Med. 2021 Oct; 55(19):1084–91.
25. Mayhew L, Johnson MI, Jones G. Comment on: "Injury Profile in Women's Football: A Systematic Review and Meta-analysis." Sports Med. 2021 Dec 1; 51(12):2665–6.
26. van Mechelen W, Hlobil H, Kemper HC. Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. Sports Med. 1992 Aug; 14(2):82–99.
27. Moher D, Shamseer L, Clarke M, Ghersi D, Liberati A, Petticrew M, Shekelle P, Stewart LA. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev. 2015 Jan 1; 4(1):1.
28. Bahr R, Clarsen B, Derman W, Dvorak J, Emery CA, Finch CF, Hägglund M, Junge A, Kemp S, Khan KM, Marshall SW, Meeuwisse W, Mountjoy M, Orchard JW, Pluim B, Quarrie KL, Reider B, Schwellnus M, Soligard T, Stokes KA, Timpka T, Verhagen E, Bindra A, Budgett R, Engebretsen L, Erdener U, Chamari K. International Olympic Committee consensus statement: methods for recording and reporting of epidemiological data on injury and illness in sport 2020 (including STROBE Extension for Sport Injury and Illness Surveillance (STROBE-SIIS)). Br J Sports Med. 2020; 54(7):372–89.
29. Andrews J, Guyatt G, Oxman AD, Alderson P, Dahm P, Falck-Ytter Y, Nasser M, Meerpohl J, Post PN, Kunz R, Brozek J, Vist G, Rind D, Akl EA, Schünemann HJ. GRADE guidelines: 14. Going from evidence to recommendations: the significance and presentation of recommendations. J Clin Epidemiol. 2013 Jul; 66(7):719–25.
30. Higgins JPT, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses. BMJ. 2003 Sep 6; 327(7414):557–60.
31. Beech J, Jones B, King R, Bennett P, Young S, Williams S, Stokes K, Emmonds S. The incidence and burden of injuries in elite English youth female soccer players. Sci Med Footb. 2022 Dec 1; 6(5):605–15.
32. Clausen MB, Zebis MK, Møller M, Krustrup P, Hölmich P, Wedderkopp N, Andersen LL, Christensen KB, Thorborg K. High injury incidence in adolescent female soccer. Am J Sports Med. 2014 Oct; 42(10):2487–94.

33. Hägglund M, Waldén M, Ekstrand J. UEFA injury study--an injury audit of European Championships 2006 to 2008. Br J Sports Med. 2009 Jul; 43(7):483–9.
34. Lislevand M, Andersen TE, Junge A, Dvorak J, Steffen K. Injury surveillance during a 2-day national female youth football tournament in Kenya. Br J Sports Med. 2014 Jun; 48(11):924–8.
35. Schmidt-Olsen S, Bünemann LK, Lade V, Brassøe JO. Soccer injuries of youth. Br J Sports Med. 1985 Sep; 19(3):161–4.
36. Soligard T, Myklebust G, Steffen K, Holme I, Silvers H, Bizzini M, Junge A, Dvorak J, Bahr R, Andersen TE. Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. BMJ. 2008 Dec 9; 337:a2469.
37. Soligard T, Bahr R, Andersen TE. Injury risk on artificial turf and grass in youth tournament football. Scand J Med Sci Sports. 2012 Jun; 22(3):356–61.
38. Sprouse B, Alty J, Kemp S, Cowie C, Mehta R, Tang A, Morris J, Cooper S, Varley I. The football association injury and illness surveillance study: The incidence, burden and severity of injuries and illness in men's and women's international football. Sports Med. 2020 Dec 28; 1–20. doi: 10.1007/s40279-020-01411-8.
39. Steffen K, Andersen TE, Bahr R. Risk of injury on artificial turf and natural grass in young female football players. Br J Sports Med. 2007 Aug; 41 Suppl 1(Suppl 1):i33–37.
40. Steffen K, Myklebust G, Olsen OE, Holme I, Bahr R. Preventing injuries in female youth football--a cluster-randomized controlled trial. Scand J Med Sci Sports. 2008 Oct; 18(5):605–14.
41. Zebis MK, Thorborg K, Andersen LL, Møller M, Christensen KB, Clausen MB, Hölmich P, Wedderkopp N, Andersen TB, Krustrup P. Effects of a lighter, smaller football on acute match injuries in adolescent female football: a pilot cluster-randomized controlled trial. J Sports Med Phys Fitness. 2018 May; 58(5):644–50.
42. Horan D, Büttner F, Blake C, Hägglund M, Kelly S, Delahunt E. Injury incidence rates in women's football: a systematic review and meta-analysis of prospective injury surveillance studies. Br J Sports Med. 2022 Oct 13; bjsports-2021-105177.
43. Aiello F, Di Claudio C, Fanchini M, Impellizzeri FM, McCall A, Sharp C, Brown SJ. Do non-contact injuries occur during high-speed running in elite football? Preliminary results from a novel GPS and video-based method. J Sci Med Sport. 2023 Jul; S1440244023001809.
44. 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(4):1057–1067
45. Rekik R, Bahr R, Cruz F, Read P, Whiteley R, D'hooghe P, Tabben M, Chamari K. Mechanisms of ACL injuries in men's football: A systematic video analysis over six seasons in the Qatari professional league. Biol Sport. 2023; 40(2):575–86.
46. Bizzini M, Junge A, Dvorak J. Implementation of the FIFA 11+ football warm up program: How to approach and convince the Football associations to invest in prevention. Br J Sports Med. 2013 Aug; 47(12):803–6.
47. Langhout R, Weir A, Litjes W, Gozeling M, Stubbe JH, Kerkhoffs G, Tak I. Hip and groin injury is the most common non-time-loss injury in female amateur football. Knee Surg Sports Traumatol Arthrosc. 2019 Oct; 27(10):3133–41.
48. Mosler AB, Weir A, Eirale C, Farooq A, Thorborg K, Whiteley RJ, Hölmich P, Crossley KM. Epidemiology of time loss groin injuries in a men's professional football league: a 2-year prospective study of 17 clubs and 606 players. Br J Sports Med. 2018 Mar; 52(5):292–7.
49. Werner J, Hägglund M, Ekstrand J, Waldén M. Hip and groin time-loss injuries decreased slightly but injury burden remained constant in men's professional football: the 15-year prospective UEFA Elite Club Injury Study. Br J Sports Med. 2019 May; 53(9):539–46.
50. 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.
51. Parsons JL, Coen SE, Bekker S. Anterior cruciate ligament injury: towards a gendered environmental approach. Br J Sports Med. 2021 Sep; 55(17):984–90.
52. Wild CY, Steele JR, Munro BJ. Why do girls sustain more anterior cruciate ligament injuries than boys?: A review of the changes in estrogen and musculoskeletal structure and function during puberty. Sports Med. 2012 Sep; 42(9):733–49.
53. Johnson DM, Williams S, Bradley B, Sayer S, Murray Fisher J, Cumming S. Growing pains: Maturity associated variation in injury risk in academy football. Eur J Sport Sci. 2020 Apr 20; 20(4):544–52.
54. Lloyd RS, Oliver JL, Faigenbaum AD, Myer GD, De Ste Croix MBA. Chronological age vs. biological maturation: implications for exercise programming in youth. J Strength Cond Res. 2014 May; 28(5):1454–64.
55. Dupré T, Potthast W. Groin injury risk of pubertal soccer players increases during peak height velocity due to changes in movement techniques. J Sports Sci. 2020 Dec 1; 38(23):2661–9.
56. Light N, Johnson A, Williams S, Smith N, Hale B, Thorborg K. Injuries in youth football and the relationship to player maturation: An analysis of time-loss injuries during four seasons in an English elite male football academy. Scand J Med Sci Sports. 2021 Jun; 31(6):1324–34.
57. Aiello F, McCall A, Brown SJ, Serner A, Fortington LV, Huurman SAE, Lewin C, Nagao M, O'Brien J, Panossian A, Pruna R, Ramos GP, Whalan M, Impellizzeri FM. Development of a standardised system to classify injury-inciting circumstances in football: the Football Injury Inciting Circumstances Classification System (FIICCS). Sports Med. 2023 Sep; 53(9):1805–18.
58. Waldén M, Mountjoy M, McCall A, Serner A, Massey A, Tol JL, Bahr R, D'Hooghe M, Bittencourt N, Della Villa F, Dohi M, Dupont G, Fulcher M, Janse van Rensburg DCC, Lu D, Andersen TE. Football-specific extension of the IOC consensus statement: methods for recording and reporting of epidemiological data on injury and illness in sport 2020. Br J Sports Med. 2023 Jan 6. doi: 10.1136/bjsports-2022-106405. Epub ahead of print.
59. Lindblom H, Waldén M, Hägglund M. Adherence to injury prevention exercise programmes in amateur adolescent and adult football: A detailed description of programme use from a randomised study. Sports Med – Open. 2023 Jul 15; 9(1):57.
60. Horst N, Hoef S, Otterloo P, Klein M, Brink M, Backx F. Effective but not adhered to: How can we improve adherence to evidence-based hamstring injury prevention in amateur football? Clin J Sport Med. 2021; 31(1):42–8.
61. Stensø J, Andersen TE, Harøy J. Adductor Strengthening Programme is successfully adopted but frequently modified in Norwegian male professional football teams: a cross-sectional study. BMJ Open. 2022; 12(9).
62. Bahr R, Thorborg K, Ekstrand J. Evidence-based hamstring injury prevention is not adopted by the majority of Champions League or Norwegian Premier League football teams: The Nordic Hamstring survey. Br J Sports Med. 2015; 49(22):1466–71.
63. Ekstrand J, Hallén A, Gauffin H, Bengtsson H. Low adoption in women's professional football: teams that used the Nordic Hamstring Exercise in the team training had fewer match hamstring injuries. BMJ Open Sport Exerc Med. 2023 May; 9(2):e001523.

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APPENDIX A. PRISMA CHECKLIST

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Page where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	1
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Not applicable
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	3
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	4
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	4–6
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	5
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Appendix 2 (Pubmed)
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	5
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	7
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	7
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	7
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	7–8
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	8
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	8
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	8
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Not applicable
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	8
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	8
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	8
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	Not applicable
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	Not applicable

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	6
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Figure 1
Study characteristics	17	Cite each included study and present its characteristics.	Table 2
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	9, 11
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	12–13
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	12–13
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	14
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	8
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	Not applicable
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	Not applicable
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	13–15
	23b	Discuss any limitations of the evidence included in the review.	16
	23c	Discuss any limitations of the review processes used.	16
	23d	Discuss implications of the results for practice, policy, and future research.	15–16
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	4 (blinded)
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	4
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	14
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	None
Competing interests	26	Declare any competing interests of review authors.	None declared
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	None

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi:10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

APPENDIX B. SEARCH STRATEGY FOR PUBMED/MEDLINE

	PubMed/MEDLINE
#1	"Soccer"[Mesh] OR "football"[Mesh]
#2	"Soccer"[tiab] OR "football"[tiab] NOT "American football"[tiab] NOT "rugby"[tiab]
#3	#1 OR #2
#4	"Injuries"[Mesh] OR "Injury" [Mesh]
#5	"Injuries"[tiab] OR "Injury" [tiab]
#6	#4 OR #5
#7	"Prevalence"[Mesh] OR "Incidence"[Mesh]
#8	"Prevalence"[tiab] OR "Incidence"[tiab]
#9	#7 OR #8
#10	"Female"[Mesh] OR "Women"[Mesh]
#11	"Female"[tiab] OR "Women"[tiab]
#12	#10 OR #11
#13	#3 AND #6
#14	#9 AND #12
#15	#13 AND #14
#16	Filters: Adolescent: 13–18 years, Female

APPENDIX C. RISK OF BIAS ASSESSED WITH THE NEWCASTLE-OTAWA SCALE (NOS).

NOS	1	2	3	4	5	6	7	8	Total
Beech et al. 2022	*	*	*	*		*	*	*	7
Clausen et al. 2014	*	*	*				*	*	5
Hägglund et al.2009	*	*	*	*		*		*	6
Le Gall et al. 2008	*	*	*		*	*	*	*	7
Lislevand et al. 2014	*	*	*			*		*	5
Schmidt-Olsen et al. 1985	*	*	*			*		*	5
Söderman et al. 2001	*	*	*		*	*	*	*	7
Soligard et al. 2008	*	*	*	*	*	*	*	*	8
Soligard et al. 2012	*	*	*			*		*	5
Sprouse et al. 2020	*	*	*	*		*	*	*	7
Steffen et al. 2007	*	*	*		*		*	*	6
Steffen et al. 2008	*	*	*		*		*	*	6
Zebis et al. 2018	*	*	*				*		4

Modified Newcastle-Otawa Scale item description (extracted from López-Valenciano et al. 2021).

Item	Description
1. Description of Sport and participants	There are several types of football players (sub-elite vs. elite, males vs. females). Without the description regarding to the type of football players it is impossible to conclude which population the incidence rates refer to. Studies that reported a description of the football players or informed the type of football players receive a star for this criterion. Studies conducted in football tournaments (which may determine the type of football players; e.g., World Cup tournaments) and which describe the race characteristics receive a star for this criterion as well. Studies that did not describe the characteristics or the type of football players, and studies conducted in football tournaments that did not describe the characteristics of the tournament did not receive a star for this criterion.
2. Injury definition	Studies that aimed to investigate football-related injuries should present a definition of an injury informing what was considered as an injury in the study. Studies that present a definition of time-loss injury received a star for this criterion.
3. Representativeness of the exposed cohort	(a) Truly representative of the average football players in the community*; (b) somewhat representative of the average football players in the community*; (c) selected group of users; (d) no description of the derivation of the cohort.
4. Exposure time collection	(a) Secure record*; (b) structured interview*; (c) written self-report; (d) exposure was estimated, (e) no description
5. Demonstration that the outcome of interest was not present at the start of the study	(a) Yes*; (b) no. Studies that described that all football players included were injury-free at baseline received a star for this criterion.
6. Assessment of Outcome	(a) Independent blind assessment*; (b) record linkage*; (c) self-report; (d) no description.
7. Follow-up time for outcomes to occur	(a) Yes*; (b) no. Studies that carried out a follow-up period of at least 12 weeks received a star for this criterion.
8. Adequacy of cohorts follow-up	(a) Complete follow-up of all subjects accounted for*; (b) subjects lost to follow-up unlikely to introduce bias (up to 20% loss) or description provided of those lost*; (c) follow-up rate < 80% and no description of those lost; (d) no statement. A loss to follow–up greater than 20% may increase the risk of bias in prospective studies (Fewtrell et al., 2008).

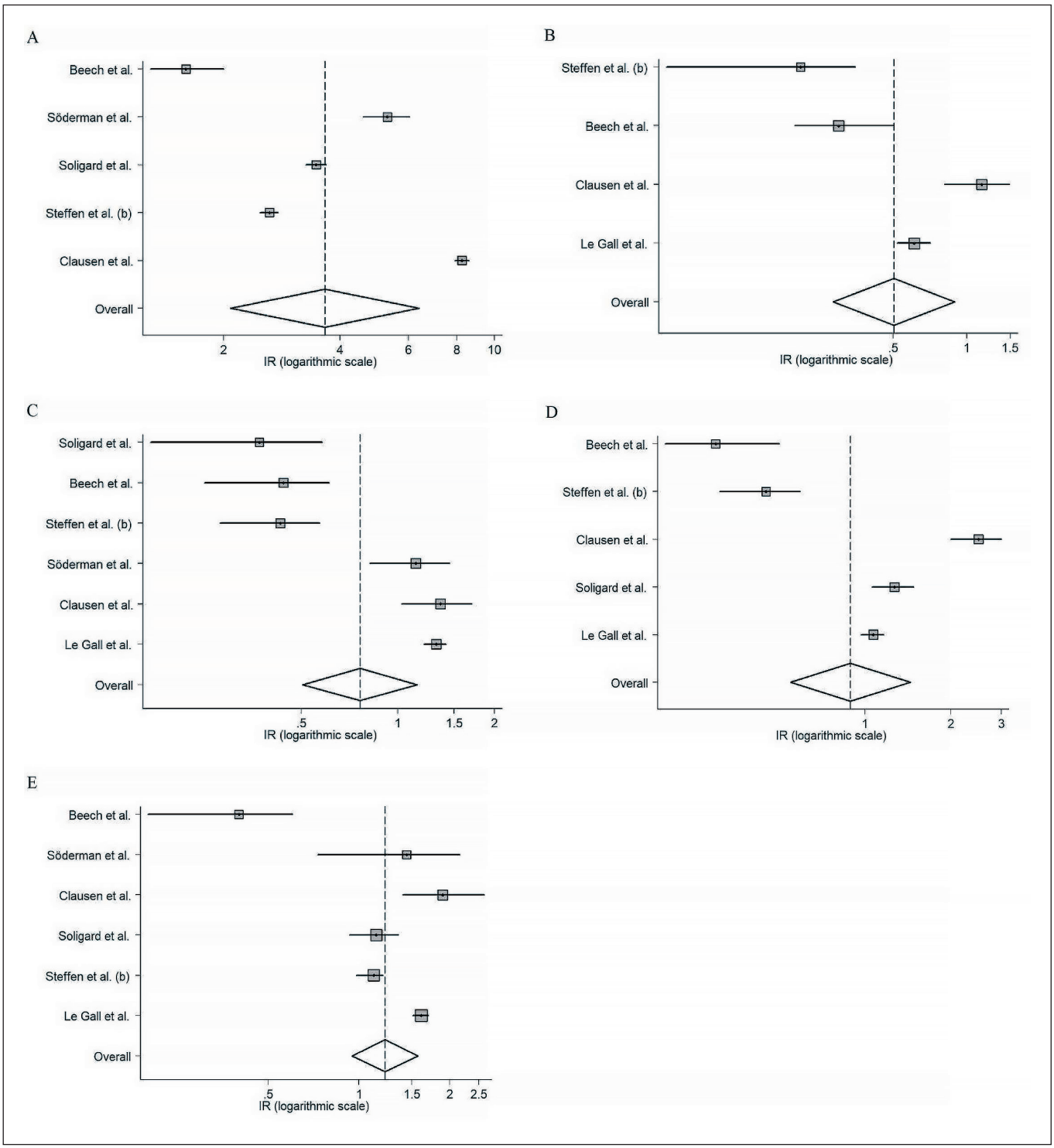
* Articles with this alternative received a star for this criterion.

APPENDIX D. CHECKLIST OF THE METHODOLOGICAL QUALITY ANALYSIS

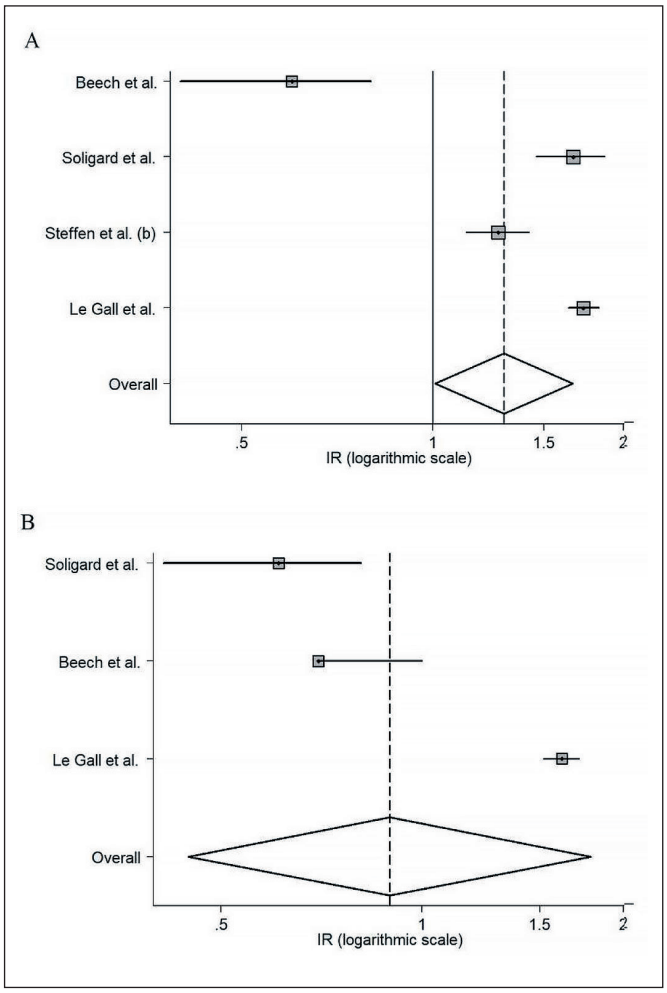
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Σ*
Beech et al 2022	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	19
Clausen et al 2014	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	18
Hägglund et al 2009	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	18
Le Gall et al 2008	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	17
Lislevand et al 2014	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓			15
Schmidt-Olsen et al 1985	✓	✓	✓	✓	✓	✓	✓	✓				✓		✓	✓			13
Söderman et al 2001	✓	✓	✓	✓	✓	✓		✓				✓	✓		✓		✓	13
Soligard et al 2008	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	18
Soligard et al 2012	✓	✓	✓	✓		✓	✓		✓		✓	✓	✓	✓	✓			14
Sprouse et al 2020	✓	✓	✓	✓	✓		✓	✓			✓	✓	✓	✓	✓	✓	✓	16
Steffen et al 2007	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	18
Steffen et al 2008	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	19
Zebis et al 2018	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓			15

Checklist: Study design (1)Duration (2) Organisational setting (3) Location (4) Nº Teams (5) Nº Players (6) Level of play (7) Medical personnel involved (8) Injury recording frequency (9) Exposure data recording frequency (10) Training to improve quality of data collection (11) Injury definition (12) Exposure definition (13) Nº of match exposures (14) Nº of match injuries (15) Nº of training exposures (16) Nº of training injuries (17). * All the included studies reported age and gender. Therefore, both items are summed to the final score.

APPENDIX E. FOREST PLOT DISPLAYING AGGREGATED LOWER LIMB (A), HIP/GROIN (B), THIGH (C), KNEE (D), AND ANKLE (E) INJURIES WITH THE CORRESPONDING 95% CONFIDENCE INTERVALS.



APPENDIX F. FOREST PLOT DISPLAYING LIGAMENT (A) AND MUSCLE (B) INJURIES WITH THE CORRESPONDING 95% CONFIDENCE INTERVALS.



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Acute effects of exercise-induced muscle damage on sprint and change of direction performance: A systematic review and meta-analysis

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ABSTRACT: The aim of this study is to determine the acute effects of resistance and plyometric training on sprint and change of direction (COD) performance in healthy adults and adolescents. A systematic literature search was conducted via Medline, Cinahl, Scopus and SportDiscus databases for studies that investigated: 1) healthy male, female adults, or adolescents; and 2) measured sprint or change of direction performance following resistance and plyometric exercises. Studies were excluded if: 1) resistance or plyometric exercises was not used to induce muscle damage; 2) conducted in animals, infants, elderly; 3) sprint performance and/or agility performance was not measured 24 h post muscle damaging protocol. Study appraisal was completed using the Kmet Quality Scoring for Quantitative Study tool. Forest plots were generated to quantitatively analyse data and report study statistics for statistical significance and heterogeneity. The included studies ($n = 20$) revealed sprint and COD performance was significantly impaired up to 72 hr following resistance and plyometric exercises; both protocols significantly increased creatine kinase (CK), delayed-onset muscle soreness (DOMS) and decreased countermovement jump (CMJ) up to 72 hr. The systematic review of 20 studies indicated that resistance and plyometric training significantly impaired sprint and COD performance up to 72 hours post-exercise. Both training protocols elevated exercise-induced muscle damage (EIMD) markers (CK, DOMS) and decreased CMJ performance within the same timeframe.

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Resistance Training

INTRODUCTION

The health benefits of physical exercise are irrefutable [1, 2]. However, strenuous exercise was shown to cause immediate and delayed alterations in cardiovascular function [3, 4]. Furthermore, strenuous exercise may also result in high levels of exercise-induced muscle damage (EIMD), particularly for untrained people [5]. EIMD symptoms can occur due to unfamiliar eccentric contractions which are known to cause significant structural damage [5]. The resulting structural damage is commonly measured by outcomes that encapsulate EIMD, such as creatine kinase (CK), delayed-onset muscle soreness (DOMS), and muscular contractility [6–13]. Blood biomarkers, such as CK, can be used as indicators of muscle damage [14]. It has been speculated that the disruption of the intermediate filaments reportedly activates Groups III and IV afferents, which cause an individual to experience DOMS [15]. Despite the clear impairment in muscle function, classical studies since the 1980's focused on muscle function using mono-articular isometric or isokinetic contractions, which may not be applicable to sporting populations.

Incorporating 'multi-articular' activities as both EIMD protocols and motor performance measures in EIMD research would improve the application of findings to real-world practice in sports. Multi-articular exercises commonly practiced by athletes known to cause EIMD include resistance (squats, bench press, latpull down) [16-19], and plyometric exercises (various jump protocols, explosvie push-ups) [20-24]. To date, several studies [18, 20, 22–25] have reported impairment in both sprint and COD performance for several days post-exercise with a concomitant increase in CK and DOMS. Conversely, numerous studies have reported no differences in sprint [19, 21, 26–29] and COD [16, 21, 22] performance following a bout of resistance or plyometric training. The discrepancy between these findings could be attributed to variations in exercise prescription (i.e., resistance or plyometric), the type of sprint and COD protocols, athletes' training histories and skill level of the participants between studies. These factors are known to influence the effects of EIMD [30], thus a systematic review evaluating the variation in study design will provide a comprehensive overview of prior research as well as highlight the methodological limitations to improve the quality of future research.

Since 2018, several systematic reviews have investigated the impact of EIMD on various performance measures. For example, a series of meta-analyses conducted by Doma and colleagues [31–33]

demonstrated that EIMD impaired vertical jump, isometric contractions, and isokinetic contractions, with concomitant increases in CK and DOMS for up to 48 hours after a variety of muscle-damaging protocols, including isokinetic eccentric contractions and downhill running. Whilst the meta-analyses by Doma et al [31–33] clearly shows that EIMD impaired muscle function for up to 48 hours, the studies included involved a variety of muscle-damaging protocols (e.g., isokinetic contractions and downhill running) and muscle performance measures (isokinetic and isometric contractions) that does not reflect real-world training practice. Silva et al [34] conducted a systematic review and meta-analysis and reported that vertical jump and sprint performance was impaired following competitive and simulated soccer matches. Whilst the use of soccer matches as a muscle-damaging protocol may replicate real-world exercise conditions, workloads may vary between positions, and the intensity is unable to be controlled due to the different team-specific tactics. Furthermore, a meta-analysis which concentrates on exercises widely used for athletic development, such as resistance and plyometric training, which assess their acute effects on performance outcomes observed in sport, like sprint and COD, would be of value. Thus, the purpose of this systematic review and meta-analysis was to determine the acute effects of resistance and plyometric training on sprint and COD performance in healthy adults or adolescents. We hypothesise that both muscle damaging protocols will significantly impair sprint and COD performance for up to 48 hours post-exercise.

MATERIALS AND METHODS

The current systematic review was conducted in accordance with the PRISMA guidelines [35] and followed a population, intervention/exposure, comparison, and outcome (PICO) approach.

1) *Population:* healthy adults or adolescents.
2) *Intervention:* resistance or plyometric exercises.
3) *Comparison:* the outcome measures were compared at 24-, 48-, and 72-hours after the muscle damaging protocols.
4) *Outcome:* the outcome measures included fundamental movement patterns (i.e., sprint and COD), muscle damage biomarkers (i.e., creatine kinase), and subjective measures of muscle soreness (i.e., visual analogue scale).

Studies were excluded if: (1) they did not use resistance or plyometric exercises to induce muscle damage; (2) were conducted in animals, infants, elderly; (3) outcome measures were examined for chronic adaptation; (4) outcome measures were not compared 24 h post muscle damaging protocol; (5) sprint performance and/or agility performance was not measured; (6) they were published in non-English language; (7) results were published as a conference abstract, review, or case report.

Search strategy

A search of scientific literature was conducted on October 10th , 2022, via four major electronic databases (Medline, Cinahl, Scopus and SportDiscus). MeSH terms and free text searches were combined. The subject headings were categorised into three strings, including: (1) humans; (2) motor performance (sprint or jump or COD); (3) biomarkers of muscle damage (Creatine Kinase/blood OR Myalgia). The following free text search terms were used: (eccentric or resistance training or exercise) and ("muscle damage" or "creatine kinase" or soreness).

Selection process

Two authors (JC and DH) independently screened and processed the literature search. First, all abstracts were highlighted as either 'green' (definitively meeting the criteria), 'yellow' (possibly meeting the criteria) or 'red' (not meeting the criteria). After independent screening, the inter-rater reliability of the two reviewer's inclusions was assessed using 40% of the screened abstracts. A Weighted Kappa statistic of 0.78 revealed the inter-rater reliability was acceptable (95% confidence interval: 0.69-0.88) [36]. Full text was then extracted from the selected articles and subjected to further screening for additional relevant publications in accordance with the inclusion/exclusion criteria.

Data extraction, assessment of quality and risk of bias

An excel spreadsheet was used to extract descriptive information involving (1) study; (2) research design (i.e., randomised, placebo control or cross-over); (3) sample size; (4) physical characteristics; (5) training background; (6) EIMD protocol; (7) exercise type; (8) outcome measures; and (9) post-exercise time points of when outcome measures were collected (i.e., 24-, 48-, 72-hours after the muscle damaging protocol). Means ± standard deviations from pre- and post-exercise outcome measures were extracted in preparation for the current meta-analyses. Any outcome measures reported as standard error or confidence intervals, or median quartiles were converted using appropriate methods [37]. Each study was critically appraised using a modified Kmet rating scale [38]. The Kmet quality ratings were classified as either excellent (1.00–0.8), good (0.79–0.60), fair (0.59–0.50), and poor (0–0.049). Additional criteria were incorporated to the original 14-point scoring system to assess methodological characteristics of each study, including: (1) adequate description of EIMD protocol (i.e., load, volume, rest); (2) sufficient detail of participants' training history; (3) participants being instructed to abstain from supplementation or recovery protocols. Studies were given a score of "2" if the specific criteria were met, a "1" if partially met and "0" if not met. Studies with non-applicable items were denoted with "n/a" and excluded from the final score. Two authors completed the critical appraisal of each study independently to establish an inter-rater reliability of the Kmet scoring procedure.

Statistical analysis

A meta-analysis was conducted using RevMan. To account for inter-study heterogeneity, forest plots were generated via a random effects model. All data points from post-exercise time points (i.e., 24–72-hours

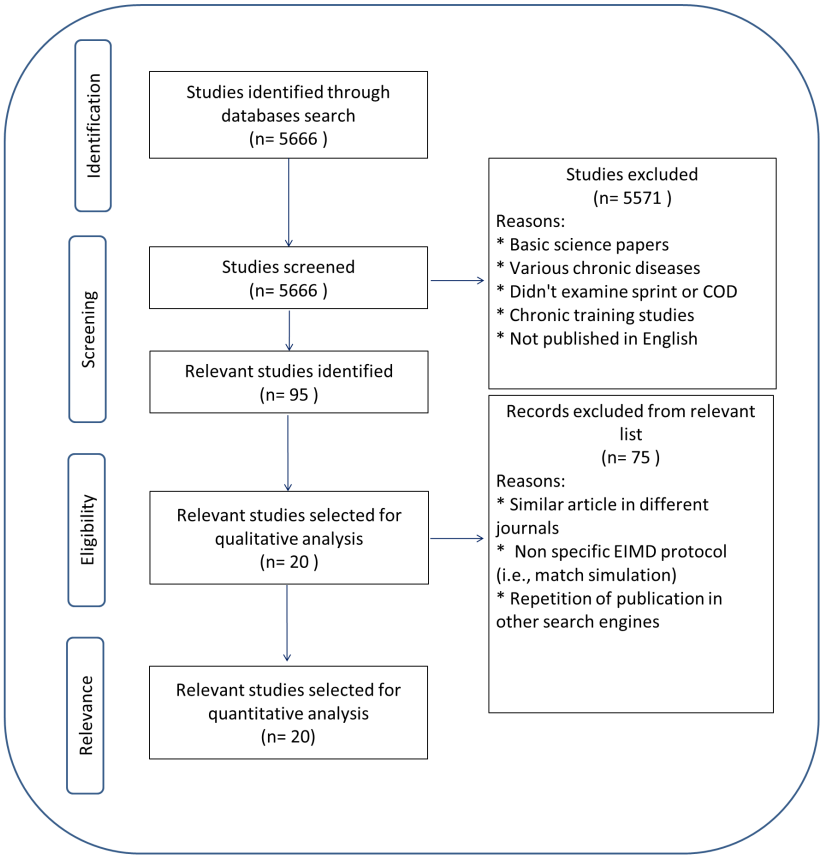


FIG 1. Schematic of the PRISMA flowchart.

post muscle-damaging protocol) were collected to calculate the magnitude of differences when compared to baseline values. Small, medium, and large (0.2, 0.5, 0.8) were values used to denote magnitude of change based upon the standardised mean differences (SMD). The level of statistical significance of the repeated measures was determined from p-values (0.05). Differences in study design was controlled using separate equations to estimate effect of SMD and standard errors [39].

RESULTS

Systematic literature search

The scientific literature search of Medline, Cinahl, Scopus and SportDiscus databases yielded 9232 abstracts. Duplicates were removed (n = 3565) and a total of 5667 abstracts were screened according to the inclusion criteria (Fig 1). After screening was completed, another 5647 abstracts were excluded, leaving 20 full text articles for inclusion (Table 2).

Participants

Table 1 displays participant physical characteristics, sample size and outcome distribution at baseline for the placebo (PLA) conditions for each study. There was a total of 208 participants which had a collective mean ± standard deviation for age, height, and body mass of 21.4 ± 2.6 years, 1.78 ± 0.8 m, and 75.3 ± 7.8 kg.

Methodological descriptions

The most frequently utilized sprint performance protocol was 30 m sprint (4 studies), followed by 20 m sprint (3 studies), 15 m sprint (3 studies), 10 m sprint (2 studies), 40 m, 50 m, 100 m sprint with one study each. Only two studies investigated repeated sprint ability over 10 m and 35 m distances, respectively. The most common agility performance protocol was the T-test agility (5 studies), followed by the Illinois agility test (2 studies), Square test (1 study), Y-test (1 study) and M-test (1 study). The most reported biomarker of muscle damage was CK (12 studies), whilst only two studies reported myoglobin and six studies reported no blood biomarkers. CMJ was the most reported jump performance measure (14 studies) whilst only four studies assessed drop jump (DJ) performance. The most reported DOMS measure was VAS 0–10 (13 studies), other measures included 5-point Likert scale (1 study), 10-point Likert scale (1 study), Total quality recovery (2 studies), 10 cm pain scale (2 studies), Navigate pain application (1 study) and a 6-point acute recovery and stress scale (ARSS).

Methodological quality

The Kmet scaling scores ranged from 0 to 2 quality (Table 3.). All included studies met the following criteria: appropriate objective and study design; participant characteristics and pre-exercise variables; and defined performance outcome measures. The Kmet items that were reported least included: resistance training history; control of

TABLE 1. Participant characteristics and baseline comparisons of outcome measures

Study	Sample Size	Physical Characteristics	Training background
AkdenİZ et al. [20]	n = 11	Age 21.6 ± 1.9 years; height 1.76 ± 0.05 m; body mass 70.4 ± 3.7 kg; BMI 23.5 ± 3.6 kg/m^2	Male, Detrained
Cockburn et al. [40]	EXP: n = 7 CON: n = 7	Age 24 ± 4 years; height 1.83 ± 0.07 m; body mass 70.4 ± 3.7 kg	Male, Trained
Cook and Beaven [41]	n = 12	Age 23.3 ± 1.4 years; height 1.85 ± 0.04 m; body mass 96.7 ± 10.8 kg	Male, RT trained
de Freitas et al. [16]	EXP: n = 6 CON: n = 6	Age 24.8 ± 4.7 years; height 1.94 ± 0.07 m; body mass 92.5 ± 9.8 kg	Male, RT trained
de Oliveira et al. [21]	EXP: n = 11 CON: n = 10	Age 17 ± 0.3 years; height 1.77 m; body mass 67.1 ± 2.3 kg	Male, RT trained
Doma et al. [22]	n = 9	Age 25 ± 5 years; height 1.77 ± 0.06 m; body mass 75 ± 8 kg	Female (1) Male (8), RT untrained
Doma et al. [18]	n = 8	Age 15 ± 1.7 years; height 1.80 ± 0.1 m; body mass 67.9 ± 7.9 kg	Male, RT untrained
Doma et al. [17]	n = 16	Age 21 ± 1 years; height 1.71 ± 0.05 m; body mass 77.8 ± 12.6 kg	Female, RT trained
French et al. [42]	EXP: n = 20 CON: n = 6	Age 21.5 ± 2 years; height 1.87 ± 0.08 m; body mass 79.4 ± 12.1 kg	Male, RT trained
Getto and Golden [26]	EXP: n = 15 CON: n = 8	M = Age not stated; height 1.88 ± 0.1 m; body mass 113.2 ± 20.2 kg F = Age not stated; height 1.77 ± 0.11 m; body mass 74.1 ± 14.3 kg	Female (10) Male (13), RT trained
Goulart et al. [27]	n = 10	Age 22.2 ± 5.3 years; height 1.65 ± 0.06 m; body mass 59.8 ± 6.1 kg	Female, RT trained
Harrison et al. [19]	n = 10	Age 18 ± 2 years; height 1.78 ± 5.3 m; body mass 71.2 ± 4.2 kg; BMI 23.2 ± 5.0 kg/m^2	Male, RT untrained
Highton et al. [23]	EXP: n = 7 CON: n = 5	Age 21 ± 1.2 years; height 1.77 ± 0.11 m; body mass 70.8 ± 8.2 kg	Not stated, RT untrained
Kargarfard et al. [25]	EXP: n = 15 CON: n = 15	Age 28.1 ± 3.3 years; height 1.74 ± 0.08 m; body mass 79.3 ± 10.8 kg; BMI 26.2 ± 1.9 kg/m^2	Male, RT trained
Rankin et al. [43]	n = 18	Age 21.6 ± 3.4 years; height 1.62 ± 0.09 m; body mass 64.3 ± 6.1 kg	Female, Trained
Santos-Mariano et al. [28]	n = 11	Age 18.7 ± 2.7 years; height 1.81 ± 0.08 m; body mass 69.9 ± 6.4 kg	Male, RT Trained
Semark et al. [29]	EXP: n = 13 CON: n = 12	Age 19 ± 3 years; height 1.77 ± 8 m; body mass 70 ± 8 kg	Male, Trained
Twist and Eston [24]	n = 10	Age 22.4 ± 3.2 years; height 1.79 ± 0.05 m; body mass 80.6 ± 10.7 kg	Male, Trained
VanHeest et al. [44]	EXP: n = 24 CON: n = 12	Age 20 ± 0.01 years; height 1.78 ± 0.03 m; body mass 78.7 ± 3.9 kg	Male, Trained
Zinner et al. [45]	n = 12	Age 22 ± 4 years; height 1.87 ± 0.07 m; body mass 89.7 ± 12.7 kg	Not specified, Trained

M – male; F – female.

TABLE 2. Methodological description for muscle damaging protocol, type of outcome measure and study timeline.

Study	EIMD Protocol	Fundamental Biomarker DOMS	Time Points
AkdenİZ et al. [20]	Drop jumps 5 sets × 20 repetitions, 60 cm, 2 minutes rest between sets and 10 second intervals between jumps	30 m sprint and Illinois agility None VAS 0–10	Baseline, 1-hr, 24-hr, 48-hr, 72-hr, 96-hr
Cockburn et al. [40]	Unilateral eccentric-concentric knee flexions 6 sets × 10 repetitions at 1.05 rad·s-1	15 m sprint, T-test agility, CMJ and DJ CK VAS 0–10	Baseline, 24 hr, 48 hr, 72 hr post
Cook and Beaven [41]	Gym and track-based conditioning session 60 minute, high intensity	40 m RSA None None	24 hr post
de Freitas et al. [16]	Bench press, incline bench press, decline bench press, barbell shoulder press, leg press, dumbbell squat; leg extension machine, cable pull down—pro lat bar, wide grip seated row, dumbbell bent over row, barbell curl, leg press, seated leg curl and seated hip adduction machine, 3 3 × 8–10 maximal repetitions, with 1.5–2 minutes recovery.	Square agility, SJ, CMJ CK VAS 0–10	Baseline, 24 hr post
de Oliveira et al. [21]	Box jumps 5 sets × 20 repetitions, 60 cm, 2 minutes rest between sets. Squatting leg extensions and leg curls 4 sets of 8 repetition maximum (RM), 2 minutes rest between sets.	35 m RSA, T-test agility and CMJ CK VAS 0–10	Baseline, 24 hr, 48 hr, 72 hr post
Doma et al. [22]	Split squat jumps 3 sets × 12 repetitions, 1.5 minutes rest between sets. Weighted squat jumps 3 sets × 7 repetitions with 35% body mass (BM), 2 minutes rest between sets. Depth jumps 3 sets × 7 repetitions, 1.5 minutes rest between sets. Tuck jumps 3 sets × 12 repetitions, 2 minutes rest between sets. Walking lunges 3 sets × 12 repetitions with 35% BM, 3 minutes rest between sets. Single-leg dumbbell Romanian deadlifts 3 sets × 15 repetitions with 50% BM, 2 minutes rest between sets. Sit-ups 3 sets × AMRAP with 10% BM, 2 minutes rest between sets.	20 m sprint and DJ CK VAS 0–10	Baseline, 24 hr, 48 hr
Doma et al. [18]	Incline leg press, chest press, single-leg horizontal leg press, seated row and triceps extensions 3 sets × 10 repetitions each exercise at 70% of 1 or 6 RM, 1.5 minutes rest between sets. Walking lunges 3 sets × 20 m with 30% BM, 1.5 minute between sets.	15 m sprint, CMJ and DJ CK VAS 1–10	Baseline, 24 hr, 48 hr post
Doma et al. [17]	Power cleans 3 sets × 5 repetitions at 80% 1RM. Deadlift 5 sets × 5 repetitions at 80% 1 RM. Dumbbell shoulder press 3 sets × 10 repetitions at 70% 1RM. Back squats 5 sets of 5 repetitions at 80% 1RM. Dumbbell lunges 4 sets × 10 repetitions at 40% BM. 2 minutes rest between each set and exercise.	T-test agility and CMJ None Vas 1–10	Baseline, 24 hr, 48 hr post
French et al. [42]	Squats 6 sets × 10 repetitions at 100% BM	10, 30 m sprint, Multiplanar agility and CMJ CK VAS 100 mm	Baseline, 1 hr, 24 hr, 48 hr
Getto and Golden [26]	Sprints 8 reps × 70 yrd and various plyometric exercises	20 m sprint and CMJ None VAS 1–10	Baseline, 24 hr post
Goulart et al. [27]	Half-squat, jump squat, deadlift and lunge 3 sets of 6 repetitions at 50% 1RM	20 m sprint and CMJ None VAS 0–10	Baseline, 24 hr, 48 hr post

TABLE 2. Continue.

Study	EIMD Protocol	Fundamental Biomarker DOMS	Time Points
Harrison et al. [19]	Incline leg press, chest press, single-leg horizontal leg press, seated row and triceps extensions 3 sets × 10 repetitions each exercise at 70% of 1 or 6 RM, 2 minutes rest between sets. Walking lunges 3 sets × 20 m with 10–30% BM, 2 minutes between sets.	15 m sprint, CMJ CK VAS 1–10	Baseline, 24 hr, 48 hr post
Highton et al. [23]	Maximal vertical jumps 10 sets × 10 repetitions, 1 minute rest between sets.	10 m sprint, 505–agility and CMJ None VAS 1–10	Baseline, 24 hr, 48 hr, 168 hr post
Kargarfard et al. [25]	Squats and leg press AMRAP at 75–77% 1RM	T-test agility and CMJ CK VAS 100 mm	Baseline, 24 hr, 48 hr, 72 hr post
Rankin et al. [43]	Sprints with decelerations and plyometric jumps 8 sets × 10 repetitions	20 m sprint, CMJ and DJ CK VAS 0–10	Baseline, 24 hr, 48 hr, 72 hr
Santos-Mariano et al. [28]	Eccentric half-squat 4 sets × 12 repetitions at 70% 1RM, 2 minutes rest between each set	30 m sprint and CMJ CK VAS 0–10	Baseline, 24 hr, 48 hr, 72 hr post
Semark et al. [29]	Drop jumps 7 sets × 10 repetitions, 50 cm, 1 minute rest between sets	30 m sprint CK VAS 0–10	Baseline, 12 hr, 24 hr, 48 hr, 72 hr
Twist and Eston [24]	Maximal vertical jumps 10 sets × 10 repetitions, 1 minute rest between sets.	10 m sprint CK VAS 0–10	Baseline, 0.5 hr, 24 hr, 48 hr, 72 hr post
VanHeest et al. [44]	Seated knee flexion 100 repetitions at 120% 1RM	T-test agility CK VAS 100 mm	24 hr, 48 hr, 72 hr, 96 hr, 120 hr post
Zinner et al. [45]	Sprints 30 repetitions × 30 m and CMJ 2 repetitions	30 m RSA and CMJ CK Likert-type 0–6	Baseline, 48 hr post

VAS- Visual analog scale; CK- creatine kinase; RM- repetition maximum; AMRAP – as many repetitions as possible

TABLE 3. Kmet scores of all included studies

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Ratings	Quality
AkdenİZ et al. [20]	2	2	2	2	2	1	2	2	2	2	2	2	2	2	27/28	Excellent
Cockburn et al. [40]	2	2	2	2	2	1	2	2	1	1	2	2	2	1	24/28	Excellent
Cook and Beaven [41]	2	2	2	2	0	2	2	2	1	1	2	0	2	1	21/28	Good
de Freitas et al. [16]	2	2	2	2	2	2	2	2	2	2	2	1	2	2	27/28	Excellent
de Oliveira et al. [21]	2	2	2	2	2	2	2	2	2	2	2	2	2	2	28/28	Excellent
Doma et al. [22]	2	2	2	2	2	2	2	2	2	2	2	2	2	2	28/28	Excellent
Doma et al. [17]	2	2	2	2	2	2	1	2	2	2	2	2	2	2	27/28	Excellent
Doma et al. [18]	2	2	2	2	2	2	0	2	1	2	2	2	2	2	25/28	Excellent
French et al. [42]	2	2	1	2	2	2	2	2	2	2	2	2	2	2	27/28	Excellent
Getto and Golden [26]	2	2	2	2	2	1	1	2	1	2	2	1	2	2	24/28	Excellent
Goulart et al. [27]	2	2	2	2	2	2	1	2	1	2	2	2	2	2	26/28	Excellent
Harrison et al. [19]	2	2	1	2	2	2	2	2	2	2	2	2	2	2	27/28	Excellent
Highton et al. [23]	2	2	2	2	2	2	0	2	2	2	2	1	2	2	25/28	Excellent
Kargarfard et al. [25]	2	2	2	2	2	2	2	2	1	2	2	1	2	1	25/28	Excellent
Rankin et al. [43]	2	2	2	2	2	0	2	2	2	1	2	2	2	2	25/28	Excellent
Santos-Mariano et al. [28]	2	2	2	2	2	2	1	2	2	2	2	2	2	2	27/28	Excellent
Semark et al. [29]	2	2	1	2	2	1	1	2	2	2	2	2	2	2	25/28	Excellent
Twist and Eston [24]	2	2	1	2	2	1	2	2	2	2	2	2	2	2	26/28	Excellent
VanHeest et al. [44]	2	2	1	2	2	2	1	2	0	2	2	2	0	0	20/28	Good
Zinner et al. [45]	2	2	2	2	2	1	2	2	2	2	1	2	2	1	25/28	Excellent

factors that may bias the results (i.e., supplements, recovery interventions, familiarisation); and sample size appropriation.

Quantitative analyses

The meta-analysis revealed that EIMD protocols significantly decreased sprint performance at 24-hours ($Z = 13.71$; $p = \leq 0.01$; SMD = 1.43; Figure 2a), 48-hours ($Z = 12.19$; $p = \leq 0.01$; SMD = 1.37; Figure 2b) and 72-hours ($Z = 10.15$; $p = \leq 0.01$; SMD = 1.22; Figure 2c) post-exercise, with low-to-high interstudy heterogeneity ($I^2 = 0\%$, 26% and 0%, respectively). The COD performance measures were also significantly decreased by EIMD at 24-hours ($Z = 8.37$; $p = \leq 0.01$; SMD = 1.17; Figure 3a), 48-hours ($Z = 6.98$; $p = \leq 0.01$; SMD = 1.48; Figure 3b) and 72-hours ($Z = 7.70$; $p = \leq 0.01$; SMD = 1.01; Figure 3c) post-exercise, with low-to-moderate interstudy heterogeneity ($I^2 = 30\%$, 61% and 0%, respectively). The EIMD protocols also significantly increased CK, at 24-hours ($Z = 7.52$; $p = \leq 0.01$; SMD = 2.16; Figure 4a), 48-hours ($Z = 7.06$; $p = \leq 0.01$; SMD = 2.12; Figure 4b) and 72-hours ($Z = 4.32$; $p = \leq 0.01$; SMD = 1.91; Figure 4c) post-exercise, with moderate-to- high interstudy heterogeneity ($I^2 = 66\%$, 67% and 76%, respectively). For DOMS, perceived measures were significantly increased at 24-hours ($Z = 7.28$; $p = \leq 0.01$; SMD = 3.07; Figure 5a), 48-hours ($Z = 6.89$; $p = \leq 0.01$; SMD = 3.29; Figure 5b) and 72-hours ($Z = 5.06$; $p = \leq 0.01$; SMD = 3.29; Figure 5c) post-exercise, with moderate-to-high interstudy heterogeneity ($I^2 = 77\%$, 78%, 65%, respectively). Finally, CMJ measures were significantly decreased at 24-hours ($Z = 11.53$; $p = \leq 0.01$; SMD = 1.20; Figure 6a), 48-hours ($Z = 12.19$; $p = \leq 0.01$; SMD = 1.24; Figure 6b) and 72-hours ($Z = 8.59$; $p = \leq 0.01$; SMD = 1.26; Figure 6c) post-exercise, with low interstudy heterogeneity ($I^2 = 0\%$).

Sensitivity Analysis

When studies that investigated resistance untrained participants were excluded, the primary outcome measures (Sprint $p = \leq 0.01$; SMD = 1.46, 1.37, 1.27; COD $p = \leq 0.01$; SMD = 1.30, 1.57, 1.18) and secondary outcome measures (CK $p = \leq 0.01$; SMD = 3.47, 3.90, 3.60; DOMS $p = \leq 0.01$; SMD = 3.08, 4.25, 3.91; CMJ $p = \leq 0.01$; SMD = 1.30, 1.36, 1.32) did not significantly change the results across all respective timepoints. When studies utilising plyometric exercises were removed, no significant change was apparent amongst the primary and secondary outcome measures throughout 72-hours (Sprint $p = \leq 0.01$; SMD = 1.48, 1.49, 1.46; COD $p = \leq 0.01$; SMD = 1.18, 1.62, 1.02; CK $p = \leq 0.01$; SMD = 2.89, 2.52, 3.03; DOMS $p = \leq 0.01$; SMD = 2.34, 2.31, 2.15; CMJ $p = \leq 0.01$; SMD = 1.19, 1.28, 1.38). Inversely, when studies utilising resistance exercises were removed, no significant change was apparent amongst

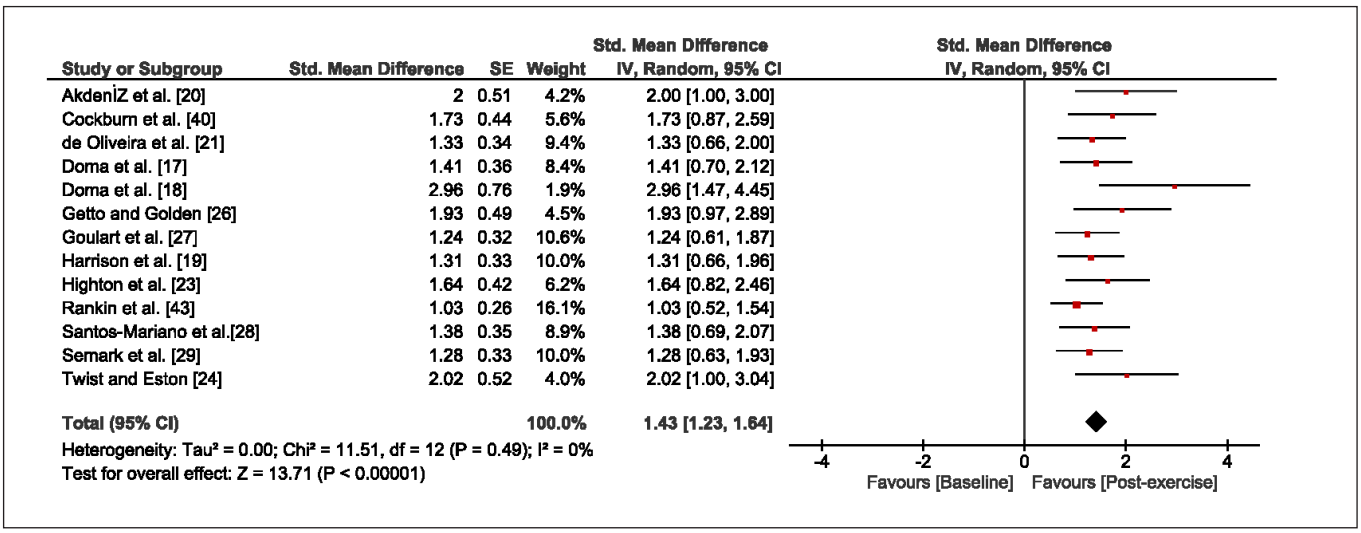


FIG. 2a. Forest plot for sprint performance at 24-hours after the muscle damaging protocol

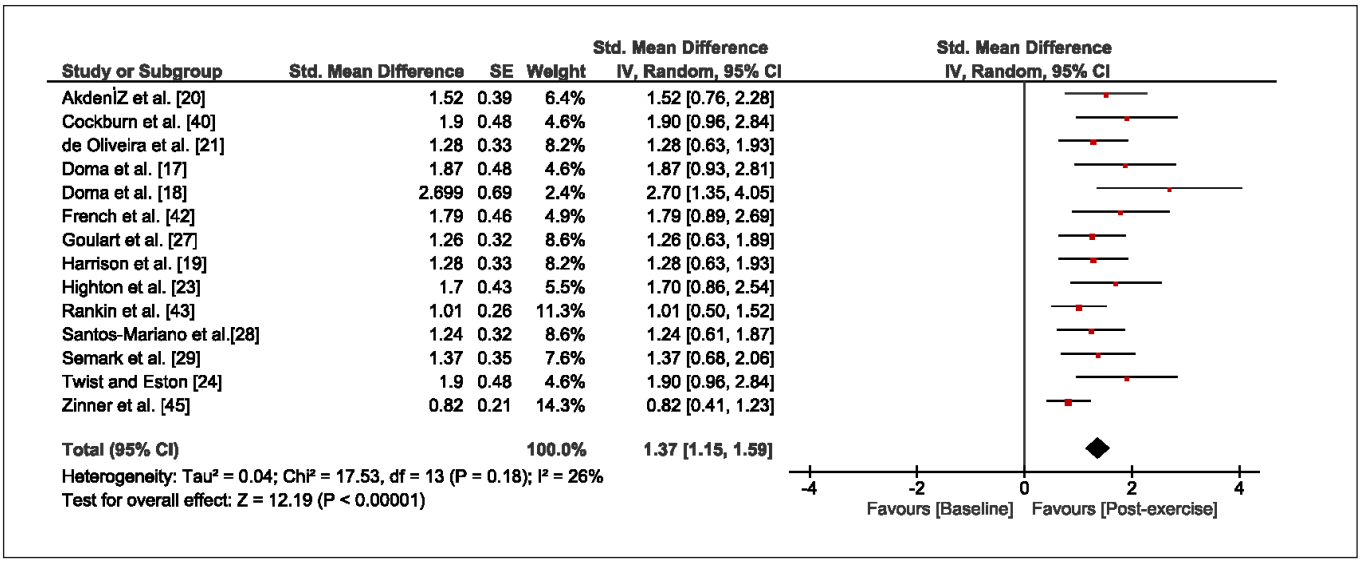


FIG. 2b. Forest plot for sprint performance at 48-hours after the muscle damaging protocol

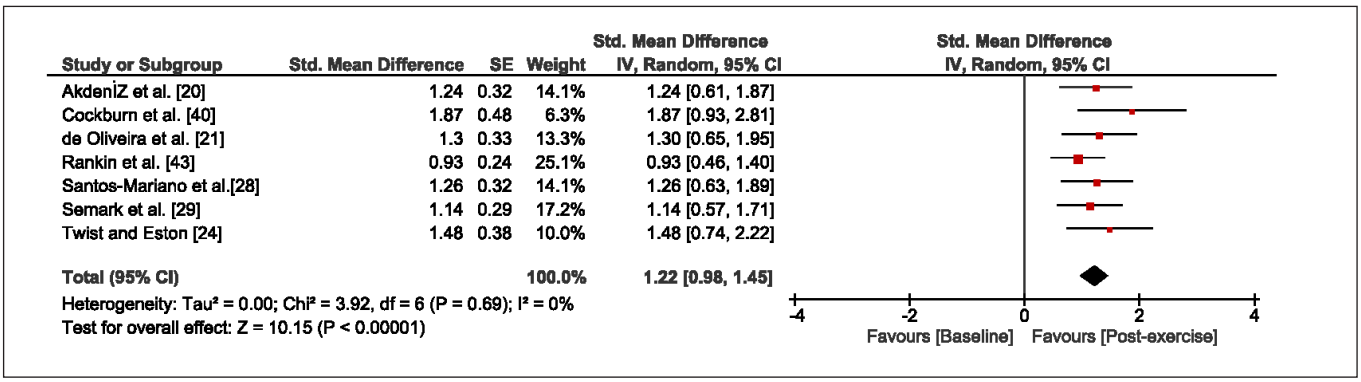


FIG. 2c. Forest plot for sprint performance at 72-hours after the muscle damaging protocol

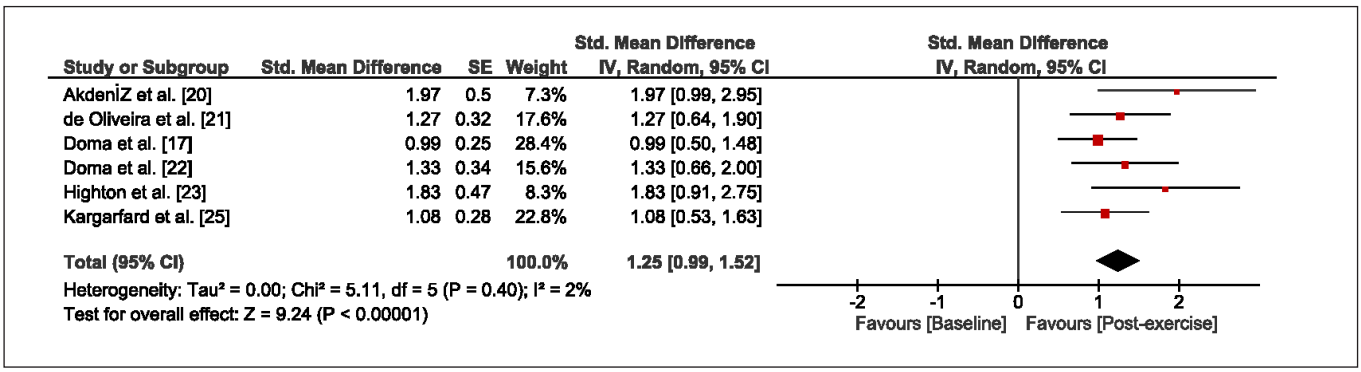


FIG. 3a. Forest plot for COD performance at 24-hours after the muscle damaging protocol

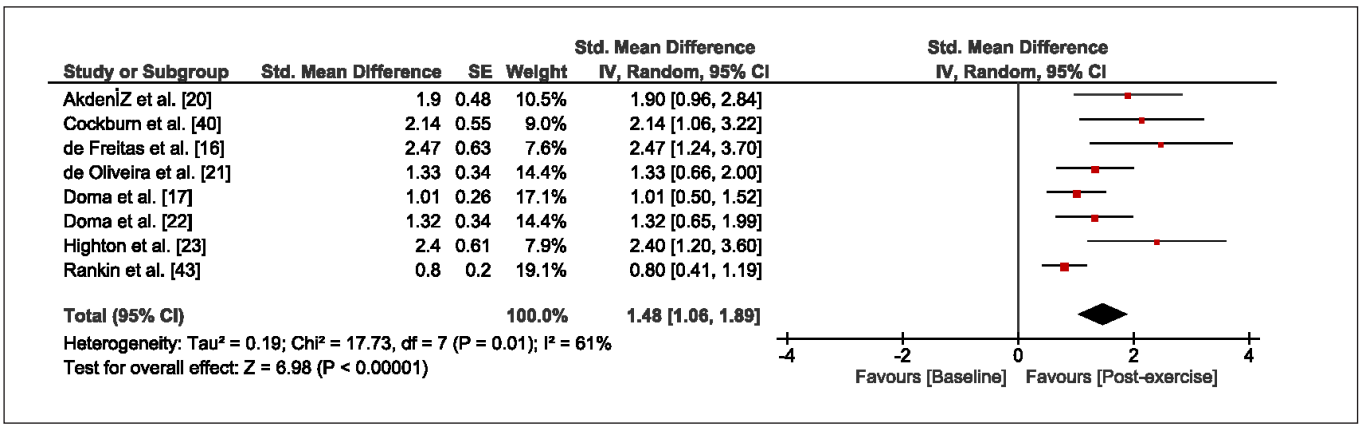


FIG. 3b. Forest plot for COD performance at 48-hours after the muscle damaging protocol

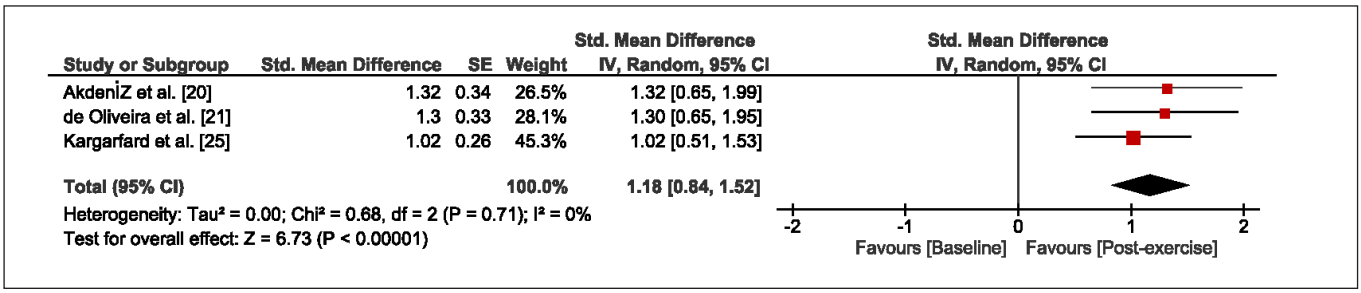


FIG. 3c. Forest plot for COD performance at 72-hours after the muscle damaging protocol

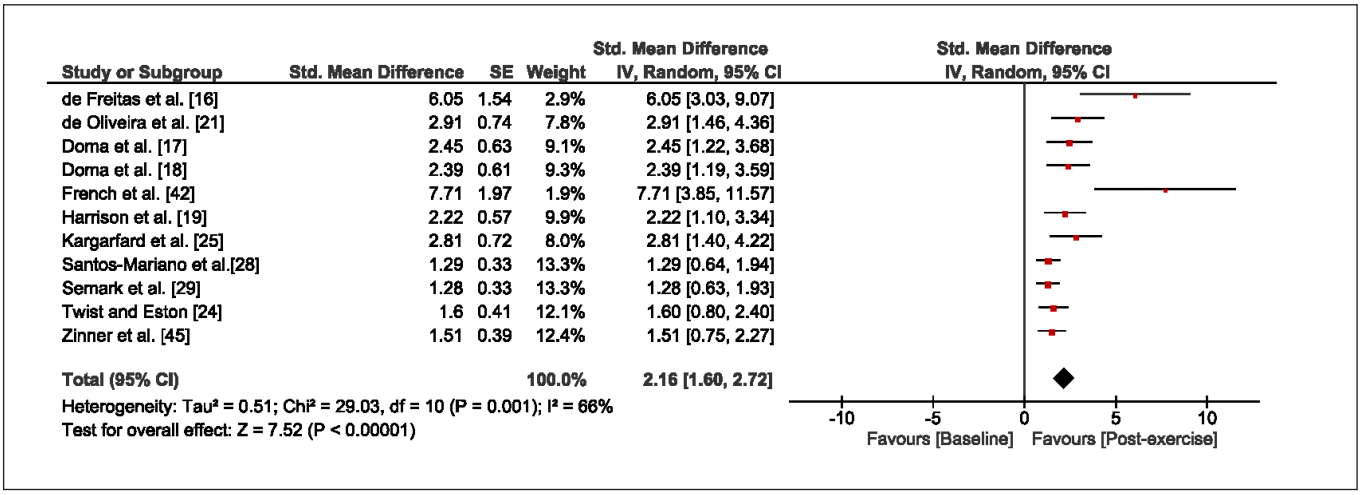


FIG. 4a. Forest plot for CK at 24-hours after the muscle damaging protocol

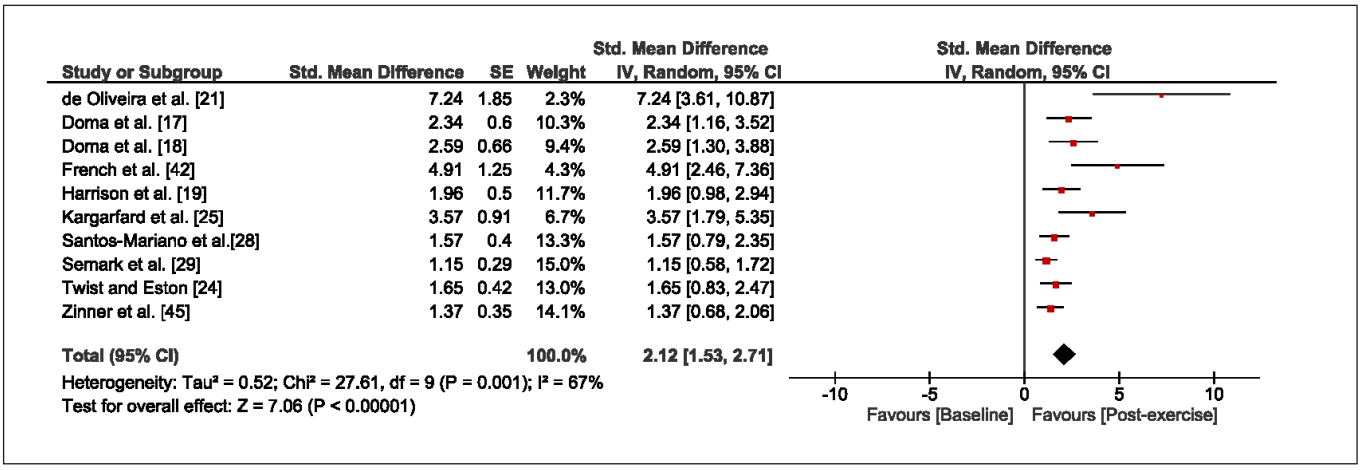


FIG. 4b. Forest plot for CK at 48-hours after the muscle damaging protocol

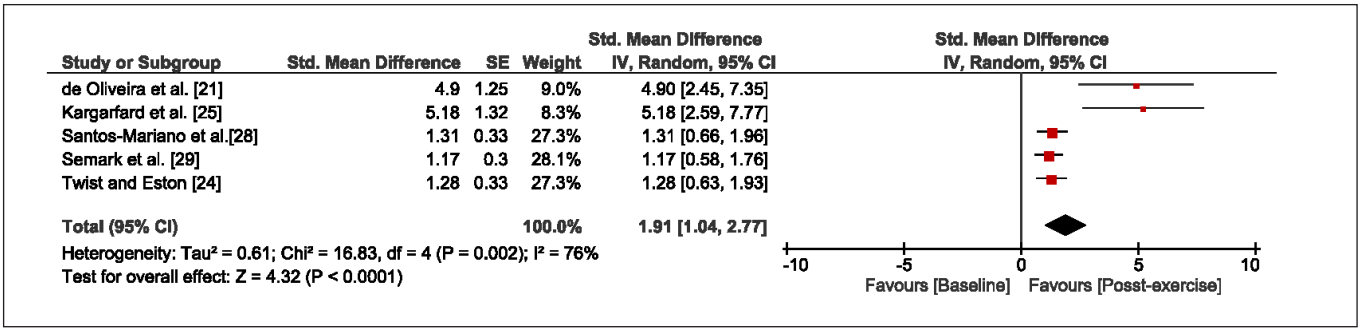


FIG. 4c. Forest plot for CK at 72-hours after the muscle damaging protocol

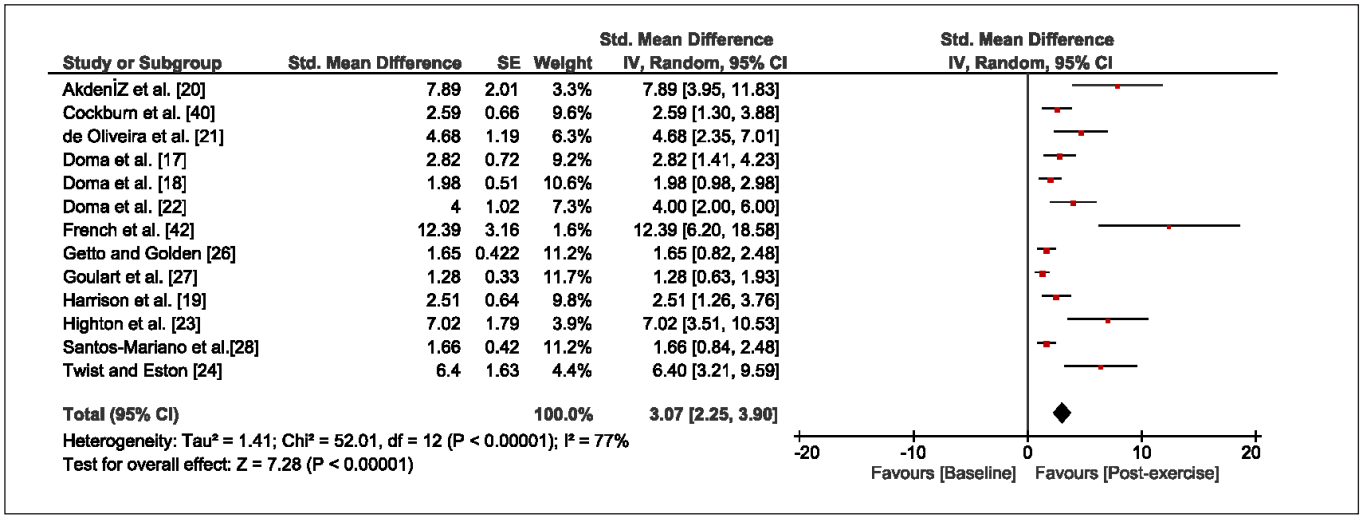


FIG. 5a. Forest plot for perceived muscle soreness at 24-hours after the muscle damaging protocol

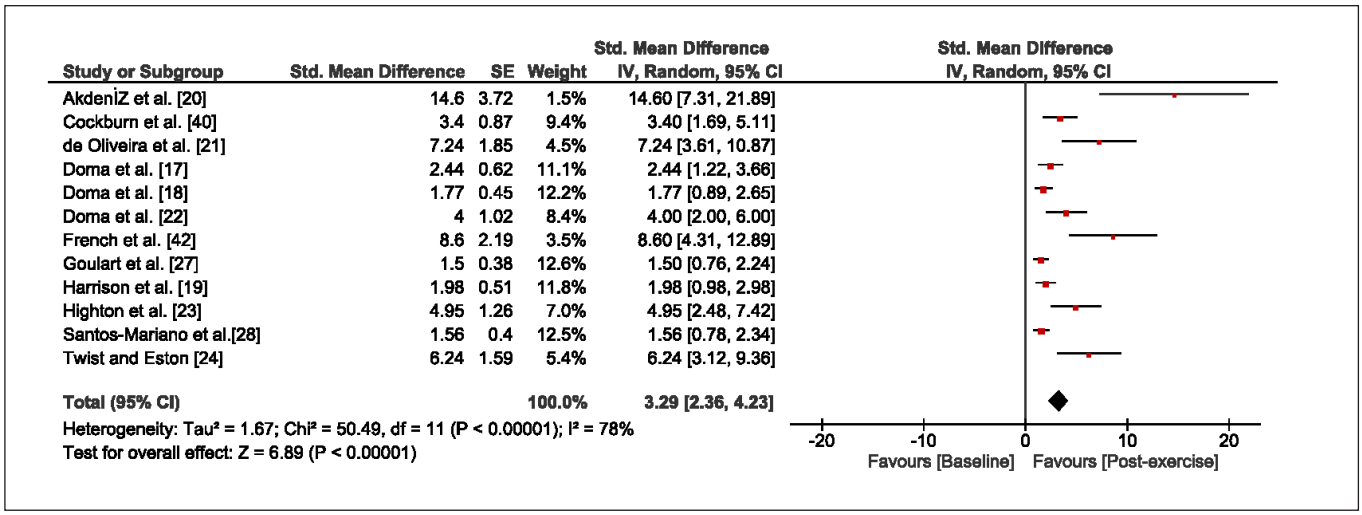


FIG. 5b. Forest plot for perceived muscle soreness at 48-hours after the muscle damaging protocol

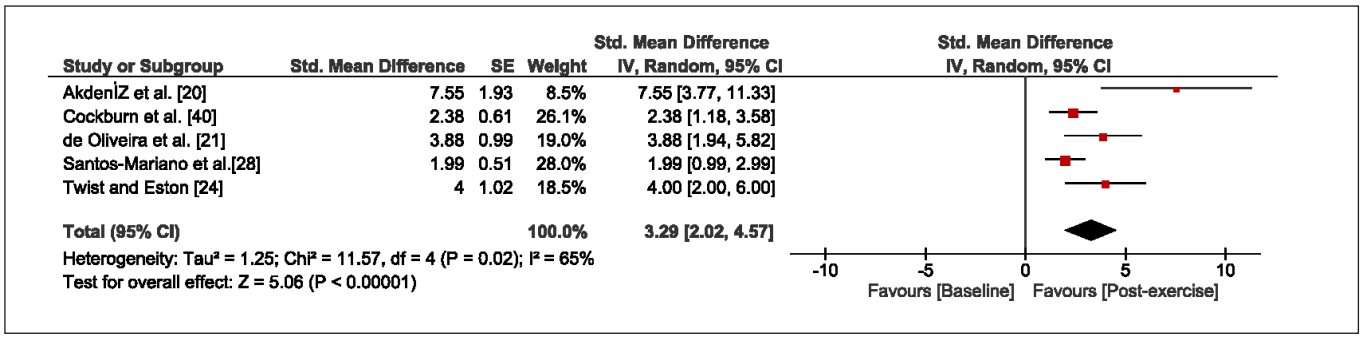


FIG. 5c. Forest plot for perceived muscle soreness at 72-hours after the muscle damaging protocol

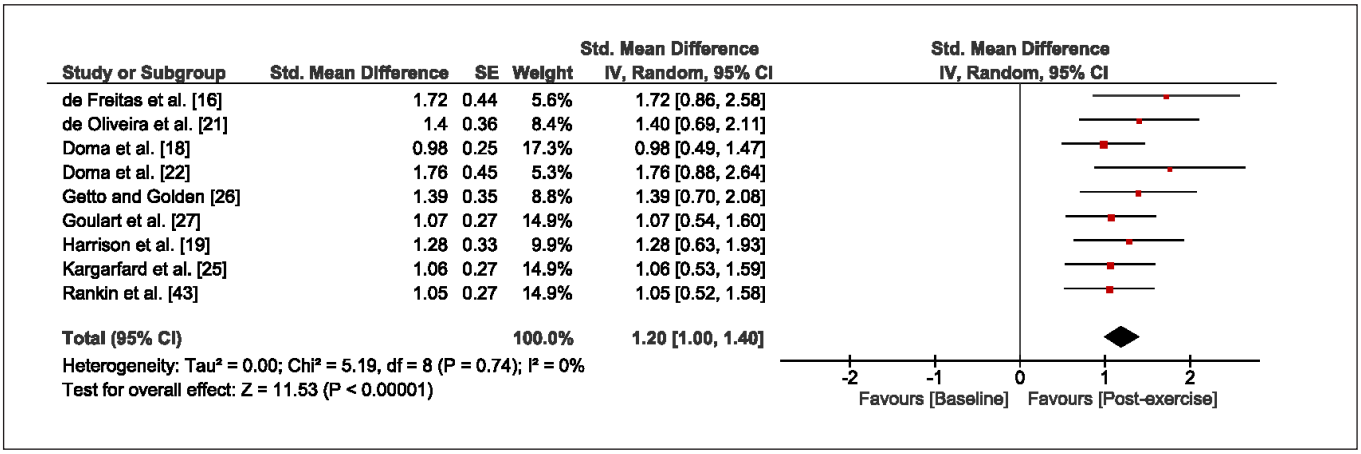


FIG. 6a. Forest plot for jump performance at 24-hours after the muscle damaging protocol

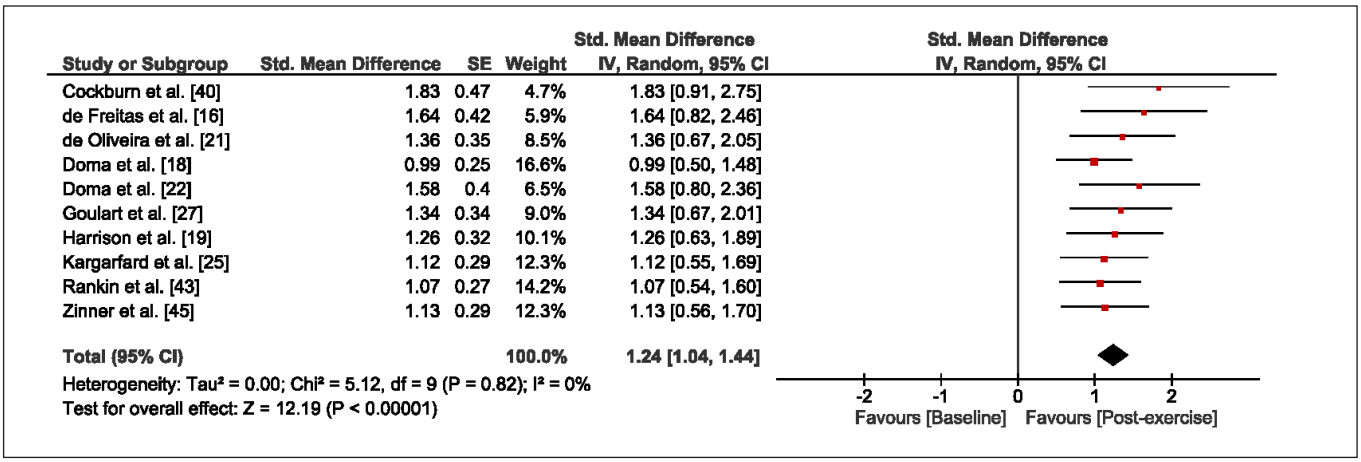


FIG. 6b. Forest plot for jump performance at 48-hours after the muscle damaging protocol

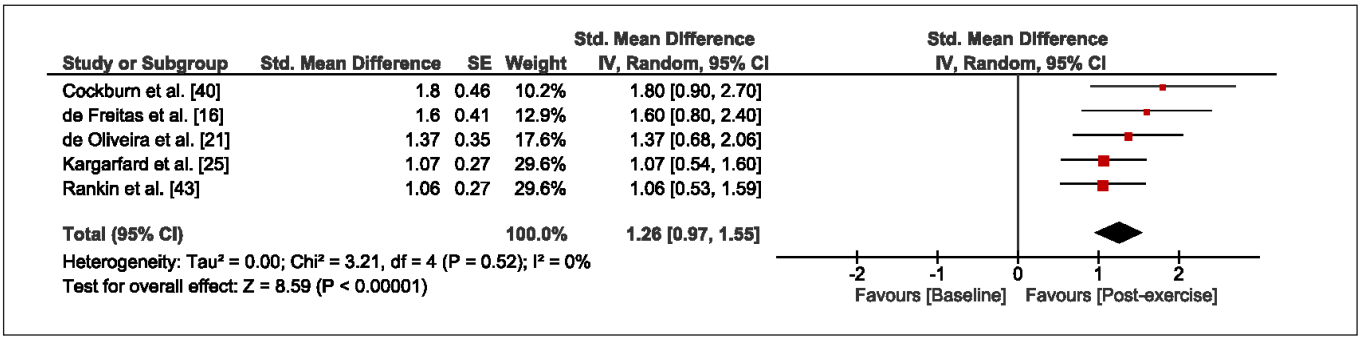


FIG. 6c. Forest plot for jump performance at 72-hours after the muscle damaging protocol

the primary and secondary outcome measures across all timepoints (Sprint p = ≤ 0.01; SMD = 1.58, 1.57, 1.46; COD p = ≤ 0.01; SMD = 1.18, 1.62, 1.02; CK p = ≤ 0.01; SMD = 2.68, 2.84, 3.03; DOMS p = ≤ 0.01; SMD = 2.35, 2.47, 2.15; CMJ p = ≤ 0.01; SMD = 1.12, 1.24, 1.38). When studies that scored 25 or lower on the Kmet scores were excluded, the results were unaffected for all primary and secondary outcome measures and all timepoints (Sprint p = ≤ 0.01; SMD = 1.46, 1.46, 1.27; COD p = ≤ 0.01; SMD = 1.25, 1.42, 1.31; CK p = ≤ 0.01; SMD = 2.72, 2.65, 1.8; DOMS p = ≤ 0.01; SMD = 3.86, 4.03, 4.54; CMJ p = ≤ 0.01; SMD = 1.37, 1.46, 1.47). In some instances, authors did not report standard deviations for some outcome measures and as a result standard deviations were averaged. When such studies were excluded from the analysis, the significance of the results were unaffected for all primary and secondary outcome measures (Sprint p = ≤ 0.01; SMD = 1.44, 1.33, 1.18; COD p = ≤ 0.01; SMD = 1.25, 1.40, 1.18; CK p = ≤ 0.01; SMD = 2.72, 2.65, 1.8; DOMS p = ≤ 0.01; SMD = 3.86, 4.03, 4.54; CMJ p = ≤ 0.01; SMD = 1.25, 1.23, 1.27).

DISCUSSION

The current systematic review and meta-analysis examined the acute effects of EIMD typically performed in a training context (i.e., resistance and/or plyometric exercises) on fundamental movement patterns, including sprints, COD, and CMJ performance. The inclusion criteria yielded 20 articles which: 1) utilised resistance or plyometric exercises; 2) compared post-exercise time points 24-hours onwards; 3) included sprint and COD performance. The meta-analysis revealed that, resistance training and plyometric exercises induced significant increase in muscle damage which impaired sprint and COD performance up to 72-hours post-exercise. In addition, EIMD was confirmed by changes in CK, DOMS, and CMJ for up to 72-hours post exercise.

Sprint and COD performances are impaired up to 72-hours following plyometric and resistance training. Our findings disagree with Silva et al [34] who found that sprint and COD performances recovered faster (48-hours) after an 11v11 football match. These athletes may have experienced lower match-induced stress given the physical demands are known to be inconsistent between playing positions, which may have reduced their pooled effect estimate of EIMD. For example, Bradley et al [46] found large positional differences in high intensity running in elite football players. Therefore, based on our findings, greater recovery may be required for more structured exercise sessions involving strenuous eccentric contractions (i.e., resistance training and plyometrics) when compared to team sport matches.

In the current meta-analysis, comparing RT and plyometric exercises showed a consistent acute impairment in sprint and COD performance, despite fundamental differences between the training modalities. Eccentric contractions are a significant component of plyometric and resistance exercise that are known to exacerbate the signs and symptoms of EIMD [47]. Several mechanisms may contribute to the symptom exacerbation such as increased mechanical stress, calcium homeostasis disruption and inflammation [48]. The mechanical stress sustained has shown to impair excitation-contraction coupling mechanism which in turn results in a later reduction of muscle strength [15]. Our meta-analysis supports these findings, demonstrating significant decreases in CMJ performance for up to 72-hours post-exercise. Sprinting and plyometric performance is performed optimally when morphological and neural components act in unison [49]. However, EIMD may disrupt these components (i.e., muscle architecture, tendon properties, motor unit recruitment and synchronicity) by increasing the displacement of the muscle fibres during stretch-shortening cycle movements causing slower running actions (e.g., acceleration) involved with the respective sprinting and COD tasks, as evidenced in this meta-analysis.

The current meta-analysis suggested that resistance and plyometric exercise impaired sprint and COD performance up to 72 hours post-exercise. However, when inspecting the papers individually, several studies reported non-significant differences at 24 [16, 17, 19, 26–29], 48 [16, 19, 21, 27–29, 42], and 72-hours [20, 21, 24, 25, 28, 29] post-exercise, which may be attributed to previous training experience of the participants involved in these studies. For example, the paper by Goulart et al [27] found no significant difference in 20 m sprint time over the 48-hour period in professional, resistance trained, female soccer players. Additionally, de Oliveira et al [21] found that COD performance did not change up to 72-hours post-exercise in under 19 male football players who participated in strength training 3 days per week. This trend may be explained by the repeated bout effect phenomenon, which is known to reduce EIMD symptomology via neural, mechanical, and cellular pathways with greater familiarity to eccentric contractions [50]. Thus, the detrimental effect of resistance or plyometric exercises has on sprint and COD performance appears to be attenuated in those who are previously exposed to strenuous exercises involving eccentric contractions (due to lower levels of EIMD).

Eccentric exercise is known to increase perception of DOMS and CK secretion. Both indirect muscle damage markers increase due to sarcomere trauma which activates the inflammatory response to repair intracellular damage [48]. Our meta-analysis showed that DOMS and CK were significantly increased at 24, 48, and 72 hours after resistance and plyometric exercise. These findings are in line with traditional research that has employed isokinetic contractions [14, 51, 52], suggesting similar soreness trends between monoarticular and multiarticular exercises. However, these findings should be considered with caution as receptor types and perception of soreness vary between individuals [53], resulting in high inter-study heterogeneity which is common among DOMS and CK values in meta-analyses [31–33]. Nonetheless, our findings confirm that resistance and plyometric exercises are muscle-damaging exercises, and athlete discomfort should be considered when planning subsequent training sessions (particularly those involving sprint and COD exercises).

According to the critical appraisal analyses, we found several methodological concerns from previous studies that should be

addressed in future research. Firstly, whilst most studies reported key training variables for the muscle-damaging protocols, such as load, repetitions, sets, rest and exercise order, some studies did not provide sufficient methodological description to replicate the muscle-damaging protocol [24, 29, 40, 43–45]. Future research must clearly outline the muscle damaging protocols [30, 54, 55]. Secondly, limited number of studies provided replicable information on participants' training history. This information is important as previous resistance training exposure can significantly reduce the level of muscle damage due to the repeated bout effect phenomenon [56]. Third, only few studies [17, 19–21] controlled for dietary and supplementation habits and implemented familiarisation sessions during the testing period. Future research should consider restricting foods known to reduce the signs and symptoms of EIMD [31–33] and incorporate familiarisation sessions to limit the learning effect. There are limitations that exist within the current systematic review and meta-analysis which should be noted. Firstly, the I^2 values for CK and DOMS ranged between 65%–81%, indicating high inter-study heterogeneity. Secondly, articles not published in English were excluded, possibly biasing our meta-analysis from a cultural and linguistic standpoint. Thirdly, we combined studies with participants from various training backgrounds, which may have influenced the results due to the repeated bout effect. However, the sensitivity analyses indicated that removal of trained participants exhibited minimal impact on the overall meta-analyses. Fourth, whilst COD and sprint performance are representative of movements observed in sports, the findings from this meta-analysis may not translate to movement or sport-specific skills, such as throwing or kicking accuracy. Finally, whilst the inclusion criteria strictly included studies that utilised either plyometrics, resistance exercises or the combination as muscle-damaging protocols, the subtle differences in the type of exercises may have influenced our results. However, the sensitivity analyses showed that when studies with plyometric exercises were removed, the overall meta-analyses did not change.

CONCLUSIONS

Our systematic review and meta-analysis demonstrated a significant impairment of sprint and COD performances for 24–72-hours following resistance and plyometric exercises. Therefore, coaches should monitor each athlete's individual response to these training methods, adapting their exercise prescription and integrating appropriate time for recovery when EIMD is observed.

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REFERENCES

1. Reiner M, Niermann C, Jekauc D, Woll A. Long-term health benefits of physical activity–a systematic review of longitudinal studies. BMC Public Health. 2013; 13(1):1–9. https://doi.org/10 .1186/1471-2458-13-813.
2. Warburton DE, Nicol CW, Bredin SS. Health benefits of physical activity: the evidence. CMAJ. 2006; 174(6):801–9. https://doi.org/10.1503/cmaj.051351.
3. 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 2022/12/01; 52(12):2821–36. https://doi.org/10 .1016/j. lfs.2021.120109.
4. Souissi A, Haddad M, Dergaa I, Ben Saad H, Chamari K. A new perspective on cardiovascular drift during prolonged exercise. Life Sci. 2021 2021/12/15/; 287:120109. https://doi .org/10.1007/ s40279-022-01734-8.
5. Newton MJ, Morgan GT, Sacco P, Chapman DW, Nosaka K. Comparison of responses to strenuous eccentric exercise of the elbow flexors between resistance-trained and untrained men. J Strength Cond Res. 2008; 22(2):597–607. https://doi.org /10.1519/ JSC.0b013e3181660003.
6. Bar DPR. Exercise-induced muscle damage : recent development. Basic Appl Myol. 1994 1994; 4:5–16.
7. Friden J. Muscle soreness after exercise: implications of morphological changes. Int J Sports Med. 1984; 5(02):57–66.
8. Friden J, Kjörell U, Thornell L-E. Delayed muscle soreness and cytoskeletal alterations: an immunocytological study in man. Int J Sports Med. 1984; 5(01):15–8.
9. Friden J, Sjöström M, Ekblom B. Myofibrillar damage following intense eccentric exercise in man. Int J Sports Med. 1983; 4(03):170–6.
10. Fritz VK, Stauber WT. Characterization of muscles injured by forced lengthening. II. Proteoglycans. Med Sci Sports Exerc. 1988; 20(4):354–61. https://doi. org/10.1249 / 00005768-198808000-00005.
11. Jones D, Newham D, Round J, Tolfree S. Experimental human muscle damage: morphological changes in relation to other indices of damage. J Physiol. 1986; 375(1):435–48. https://doi. org/10.1113/jphysiol.1986 .sp016126.
12. Newham D, McPhail G, Mills K, Edwards R. Ultrastructural changes after concentric and eccentric contractions of human muscle. J Neurol Sci. 1983; 61(1):109–22. https://doi.org/10.1016 /0022-510X(83)90058-8.
13. Stauber W, Clarkson P, Fritz V, Evans W. Extracellular matrix disruption and pain after eccentric muscle action. J Appl Physiol. 1990; 69(3):868–74. https:// doi.org/10.1152 /jappl.1990.69.3.868.
14. Clarkson PM, Ebbeling C. Investigation of serum creatine kinase variability after muscle-damaging exercise. Clin Sci (Lond). 1988 Sep; 75(3):257–61. https:// doi.org/10.1042/cs0750257.
15. Ebbeling CB, Clarkson PM. Exercise-induced muscle damage and adaptation. Sports Med. 1989; 7(4):207–34. https:// doi.org/10.2165/00007256 -198907040-00001.
16. de Freitas VH, Ramos SP, Bara-Filho MG, Freitas DGS, Coimbra DR, Cecchini R, et al. Effect of cold water immersion performed on successive days on physical performance, muscle damage, and inflammatory, hormonal, and oxidative stress markers in volleyball players. J Strength Cond Res. 2019 Feb; 33(2):502–13. https://doi.org/10.1519 / JSC.0000000000001884.
17. Doma K, Connor J, Gahreman D, Boullosa D, Ahtiainen JP, Nagata A. Resistance training acutely impairs agility and spike-specific performance measures in collegiate female volleyball players returning from the off-season. Int J Environ Res Public Health. 2020 Sep 4; 17(18). https://doi.org/10.3390 /ijerph17186448.
18. Doma K, Leicht A, Woods C, Harrison D, McGuckin T, Connor J. Effect of exercise-induced muscle damage on bowling-specific motor skills in male adolescent cricketers. Sports (Basel). 2021 Jul 19; 9(7). https://doi.org /10.3390/sports9070103.

19. Harrison DC, Doma K, Leicht AS, McGuckin TA, Woods CT, Connor JD. Repeated Bout Effect of Two Resistance Training Bouts on Bowling-Specific Performance in Male Cricketers. Sports. 2022; https://doi.org/10.3390/sports 10090126.
20. AkdenİZ Ş, Karli Ü, DaŞDemİR T, Yarar H, Yilmaz B. Impact of exercise induced muscle damage on sprint and agility performance. J Phys Educ Sport. 2012; 6(2):152–60.
21. de Oliveira DCX, Rosa FT, Simões-Ambrósio L, Jordao AA, Deminice R. Antioxidant vitamin supplementation prevents oxidative stress but does not enhance performance in young football athletes. Nutrition. 2019 Jul-Aug; 63–64:29–35.
22. Doma K, Burt D, Connor JD. The acute effect of a multi-modal plyometric training session on field-specific performance measures. J Sports Med Phys Fitness. 2021 Jul; 61(7):899–906. https://doi.org/10.23736/S0022-4707 .20.11603-7.
23. Highton JM, Twist C, Eston RG. The Effects of Exercise-Induced Muscle Damage on Agility and Sprint Running Performance. J Exerc Sci Fit. 2009; 7(1):24–30. https:// doi.org/10.1016/ S1728-869X(09)6 0004-6.
24. Twist C, Eston R. The effects of exercise-induced muscle damage on maximal intensity intermittent exercise performance. Eur J Appl Physiol. 2005 Aug; 94(5–6):652–8. https://doi.org /10.1007/s00421-005-1357-9.
25. Kargarfard M, Lam ETC, Shariat A, Shaw I, Shaw BS, Tamrin SBM. Efficacy of massage on muscle soreness, perceived recovery, physiological restoration and physical performance in male bodybuilders. J Sports Sci. 2016; 34(10):959–65. https://doi. org/10.1080/02640414 .2015.1081264.
26. Getto CN, Golden G. Comparison of active recovery in water and cold-water immersion after exhaustive exercise. Athl Train Sports Health Care. 2013; 5(4):169–76. https://doi. org/10.3928/19425864-2013 0702-03.
27. Goulart KNDO, Duffield R, Junior GOC, Passos Ramos G, Pimenta EM, Couto BP. Recovery timeline following resistance training in professional female soccer players. Sci Med Footb. 2020; 4(3):233–9. https://doi.org/10 .1080/24733938.2020.1737724.
28. Santos-Mariano AC, Tomazini F, Felippe LC, Boari D, Bertuzzi R, De-Oliveira FR, et al. Effect of caffeine on neuromuscular function following eccentric-based exercise. PLoS One. 2019; 14(11):e0224794. https://doi. org/10.1371/journal.pone .0230470.
29. Semark A, Noakes TD, Gibson ASC, Lambert MI. The effect of a prophylactic dose of flurbiprofen on muscle soreness and sprinting performance in trained subjects. J Sports Sci. 1999; 17(3):197–203. https://doi. org/10.1080/026404199366091.
30. Markus I, Constantini K, Hoffman J, Bartolomei S, Gepner Y. Exercise-induced muscle damage: Mechanism, assessment and nutritional factors to accelerate recovery. Eur J Appl Physiol. 2021; 121(4):969–92. https://doi. org/10.1007/s00421-020 -04566-4.
31. Doma K, Devantier-Thomas B, Gahreman D, Connor J. Selected root plant supplementation reduces indices of exercise-induced muscle damage: a systematic review and meta-analysis. Int J Vitam Nutr Res. 2020; 1(1):1–21. https://doi.org/10.1024/0300-9831 / a000689.
32. Doma K, Gahreman D, Ramachandran AK, Singh U, Connor J. The effect of leaf extract supplementation on exercise-induced muscle damage and muscular performance: A systematic review and meta-analysis. J Sports Sci. 2021; 39(17):1952–68. https://doi.org /10.10 80/02640414.2021.1911050.
33. Doma K, Ramachandran AK, Boullosa D, Connor J. The Paradoxical Effect of Creatine Monohydrate on Muscle Damage Markers: A Systematic Review and Meta-Analysis. Sports Med. 2022:1–23. https://doi.org/10.1007 / s40279-022-01640-z.
34. Silva J, Rumpf M, Hertzog M, Castagna C, Farooq A, Girard O, et al. Acute and residual soccer match-related fatigue: a systematic review and meta-analysis. Sports Med. 2018; 48(3):539–83. https://doi.org/10.1007 /s40279-017-0798-8.
35. Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group* t. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Annals Inter Med. 2009; 151(4):264–9. https://doi.org /10.1093/ ptj/89.9.873.
36. Pierce DR, Doma K, Leicht AS. Acute effects of exercise mode on arterial stiffness and wave reflection in healthy young adults: a systematic review and meta-analysis. Front Physiol. 2018; 9:73. https://doi.org/10.3389 / fphys.2018.00073.
37. Wan X, Wang W, Liu J, Tong T. Estimating the sample mean and standard deviation from the sample size, median, range and/ or interquartile range. BMC Med Res Methodol. 2014; 14:1–13. https://doi . org/10.1186/1471-2288-14-135.
38. Kmet LM, Cook LS, Lee RC. Standard quality assessment criteria for evaluating primary research papers from a variety of fields. 2004.
39. Deeks JJ. Systematic reviews of evaluations of diagnostic and screening tests. BMJ. 2001; 323(7305):157–62. https://doi.org/10.1136/bmj.323.7305 .157.
40. Cockburn E, Bell PG, Stevenson E. Effect of milk on team sport performance after exercise-induced muscle damage. Med Sci Sports Exerc. 2013 Aug; 45(8):1585–92. https://doi.org/10 .1249/MSS.0b013e31828b7dd0.
41. Cook CJ, Beaven CM. Individual perception of recovery is related to subsequent sprint performance. Br J Sports Med. 2013; 47(11):705–9. https://doi.org/10.1136 / bjsports-2012-091647.
42. French DN, Thompson KG, Garland SW, Barnes CA, Portas MD, Hood PE, et al. The effects of contrast bathing and compression therapy on muscular performance. Med Sci Sports Exerc. 2008 Jul; 40(7):1297–306. https://doi. org/10.1249/MSS.0b013e 31816b10d5.
43. Rankin P, Landy A, Stevenson E, Cockburn E. Milk: An effective recovery drink for female athletes. Nutrients. 2018 Feb 17; 10(2). https://doi.org/10 .3390/nu10020228.
44. VanHeest JL, Stoppani J, Scheett TP, Collins V, Roti M, Anderson J, et al. Effects of ibuprofen and VICOPROFENR on physical performance after exercise-induced muscle damage. J Sport Rehabil. 2002; 11(3):224–34. https:// doi.org/10.1123 /jsr.11.3.224.
45. Zinner C, Pelka M, Ferrauti A, Meyer T, Pfeiffer M, Sperlich B. Responses of low and high compression during recovery after repeated sprint training in well-trained handball players. Eur J Sport Sci. 2017 Nov; 17(10):1304–10. https://doi.org/10.1080/17461391 .2017.1380707.
46. 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):159–68. https:// doi. org/10.1080/0264041080251 2775.
47. Clarkson P, Byrnes W, McCormick K, Turcotte L, White J. Muscle soreness and serum creatine kinase activity following isometric, eccentric, and concentric exercise. Int J Sports Med. 1986; 7(03):152–5. DOI: 10.1055/s-2008-1025753.
48. Clarkson PM, Sayers SP. Etiology of exercise-induced muscle damage. Can J Appl Physiol. 1999; 24(3):234–48.
49. Debenham J, Travers M, Gibson W, Campbell A, Allison G. Eccentric fatigue modulates stretch-shortening cycle effectiveness–a possible role in lower limb overuse injuries. Int J Sports Med. 2016; 37(01):50–5. https://doi. org/10.1139 /h99-020.

50. Hyldahl RD, Hubal MJ. Lengthening our perspective: morphological, cellular, and molecular responses to eccentric exercise. Muscle & nerve. 2014; 49(2):155–70. https://doi.org/10.1002 / mus.24077.
51. Nosaka K, Clarkson PM. Variability in serum creatine kinase response after eccentric exercise of the elbow flexors. Int J Sports Med. 1996 Feb; 17(2):120–7. DOI: 10.1055/s-2007-972819.
52. Prou E, Guevel A, Benezet P, Marini JF. Exercise-induced muscle damage: absence of adaptive effect after a single session of eccentric isokinetic heavy resistance exercise. J Sports Med Phys Fitness. 1999 Sep; 39(3):226–32.
53. Byrnes WC, Clarkson PM. Delayed onset muscle soreness and training. Clin Sports Med. 1986; 5(3):605–14.
54. Douglas J, Pearson S, Ross A, McGuigan M. Eccentric exercise: physiological characteristics and acute responses. Sports Med. 2017; 47:663–75.
55. Guilhem G, Cornu C, Guével A. Neuromuscular and muscle-tendon system adaptations to isotonic and isokinetic eccentric exercise. Ann Phys Rehabil Med. 2010; 53(5):319–41. https://doi.org /10.1007/s40279-016-0624-8.
56. Doma K, Schumann M, Sinclair WH, Leicht AS, Deakin GB, Häkkinen K. The repeated bout effect of typical lower body strength training sessions on sub-maximal running performance and hormonal response. Eur J Appl Physiol. 2015; 115(8):1789–99. https://doi.org/10 .1007/s00421-015-3159-z.

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Gut microbiota and physical activity level: characterization from sedentary to soccer players

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ABSTRACT: Evidence of the relationship between physical activity and gut microbiota composition is steadily increasing. The purpose of the study is to compare the gut microbiota composition of a group of elite male soccer players with a group of subjects with different physical activity levels. Cross-sectional studies were performed on 91 healthy young males, in detail: 17 elite soccer players (23.7 ± 4.2 yrs, BMI 23.2 ± 1.2 kg/m^2); 14 with high levels of physical training (24.5 ± 5.6 yrs, BMI 22.7 ± 0.8 kg/m^2); 23 with moderate levels of physical training (29.3 ± 3.9 yrs, BMI 22.5 ± 0.8 kg/m^2); and 37 healthy men without exercise habits (28.1 ± 5.9 yrs, BMI 22.4 ± 1.0 kg/m^2). Relative microbiota composition was determined by analyzing DNA extracted from stool samples. The quality and quantity of extracted DNA were assessed using a Qubit Fluorometer. Differences between subjects' populations were analyzed using a one-way ANOVA, and Bonferroni's post-hoc test was employed to identify localized effects. Elite soccer players and subjects with high physical activity levels showed a significantly higher prevalence of the nine microbiota populations analyzed than subjects with moderate physical training or who were sedentary. No differences were found in the Firmicutes to Bacteroidetes ratio among the different study populations. This study reports the gut microbiota parameters of elite footballers for the first time. In addition, it brings new insights into the effects of different levels of physical activity on the composition of the gut microbiota.

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INTRODUCTION

The gut microbiota is a broad term for the billions of microorganisms within the gastrointestinal tract, including bacteria, fungi, and viruses [1]. Investigation of the gut microbiota is a field of research that is attracting growing interest because of its potential role in health and disease [2]. These microorganisms inhabit the human intestine, forming a complex community that interacts within itself and with the host; however, its composition depends on the host's genetics and numerous environmental factors [3], and the latter plays a dominant role in its continuous modification.

Among the environmental factors that have been determined to have a role in modifying the gut microbiota are lifestyle, in terms of eating habits and weight status [4], levels of physical activity [5], tobacco smoking habits, and sleep habits [6].

Physical activity is associated with changes in gut microbial composition and an increase in butyrate-producing bacteria. It increases fecal butyrate concentrations in humans independent of diet, an essential mechanism for improving intestinal and cardiometabolic health with exercise [7]. Athletes are considered a specific population to study exercise's chronic effects on the human body. Athletes' nutrition follows specific recommendations, and each sport has characteristics that affect eating habits [8]. Therefore, it is difficult to establish the impact of different dietary patterns in studying the gut microbiota in elite athletes since sport has been shown to induce modifications to the gut microbiota per se [9]. For example, elite rugby players have been shown to have greater gut microbiota diversity than non-sporting controls. However, this difference is also attributable to a higher intake of whey protein as a supplement [10]. Higher-level martial arts athletes have an increased diversity and higher metabolic capacity of the gut microbiota than lower-level martial arts athletes [11]. Unlike rugby and martial arts, cycling [12] is a sport with higher endurance effort levels; transitioning from amateur to professional cycling induces increased levels of microorganisms such as

Prevotella and Methanobrevibacter. Other endurance sports include the marathon [13] and cross-country skiing: these athletes have a reduced abundance of the principal genus of intestinal microbiota, Bacteroidetes, and a higher level of Prevotella. Compared to resistance training, it has been shown that endurance training is the metabolic process that involves the most significant changes in the composition of the gut microbiota through physical exercise [14]. In confirmation, subjects with higher cardiorespiratory fitness showed high diversity in their gut microbiota and a relative abundance of butyrate-producing bacteria, essential to gut microbiota homeostasis [15]. Therefore, the changes in the gut microbiota following physical exercise have yet to be definitively determined and fully understood but could depend on how the activity is practiced in terms of type, duration, intensity, and weekly frequency [16]. In addition, although the available evidence suggests that physical exercise alters the gut microbial composition, the metrics (e.g., abundance, evenness, richness, and diversity) have yet to be consistently reported [17]. Therefore, examining the microbiota in athletes fails to differentiate specific training regimens, as most situational sports involve mixed alternating aerobic and anaerobic training [18]. In particular, the gut microbiota of elite soccer players has yet to be reported in any study.

The present study hypothesized that the type, level, and quantity of exposure to exercise could influence the gut microbiota. To investigate the effects of levels of exercise on gut microbiota, the present study aimed to describe the differences and compare the gut microbiota characteristics of a group of elite male soccer players with a group of healthy sedentary men, a group of healthy males who practiced regular exercise and a group of healthy males who were exposed to a high amount of exercise.

MATERIALS AND METHODS

Participants recruitment

This cross-sectional study enrolled subjects with different physical activity habits during the previous two months to evaluate their gut microbiota composition differences. In particular, the inclusion criteria were: 1) male, 2) aged between 18 and 35 years, 3) normal weight condition, 4) absence of any metabolic disease, 5) non-smokers, 6) white ethnicity, and 7) ≥ 9.5 points of adherence to the Mediterranean Diet (MedQ-Sus questionnaire) [19]. The exclusion criteria were: 1) treatment with antibiotics or probiotics during the previous two months, 2) acute gastrointestinal infections one month before the enrolment, and 3) chronic inflammatory bowel diseases (Crohn's disease and ulcerative colitis).

Ninety-one subjects were enrolled for this study:

- 17 elite soccer players belonging to Italian Serie A (23.7 ± 4.2 yrs) with more than 6 hours of training per week, consisting of 5 sessions of about 90 minutes of mixed endurance and anaerobic exercise.
- 14 healthy men with high levels of physical training (24.5 ± 5.6 yrs) with 6 hours of training per week, consisting of about three sessions of about 2 hours of mixed endurance and resistance exercise.
- 23 healthy men with moderate levels of physical training (29.3 ± 3.9 yrs) with up to 3 hours of training per week, consisting of about 3–4 sessions of about 30–45 minutes each of endurance exercise.
- 37 healthy men without exercise habits (28.1 ± 5.9 yrs).

All subjects provided written informed consent before beginning the study. The Anti-Doping Lab Institutional Review Board (Qatar), which conforms to the recommendations of the Declaration of Helsinki, approved the present study (IRB number: E201300004).

Mediterranean Diet assessment

Before the start of the study, each subject underwent a nutritional assessment to assess their eating habits. Eligible participants were those who had adhered to a Mediterranean diet in the previous two months; those who did not follow these eating habits were not included in the study. Given the retrospective nature of the dietary assessment, the MedQ-Sus questionnaire [19] was chosen because this tool demonstrated both reliability in assessing adherence to the Mediterranean diet and the nutritional sustainability of food choices.

Microbiome sample collection and DNA Extraction

Fecal samples were collected using the eNAT® kit (608CS01R, COPAN, Italy), stored at room temperature, and delivered within five days to the laboratory (NEXT Genomics, Sesto Fiorentino, Italy) to perform the analysis. Total DNA was isolated using a Microbiome DNA Isolation Kit (Norgen Biotek Corp. Thorold, ON, Canada) from the microbial pellets following the manufacturer's protocol. The quality and quantity of extracted DNA were assessed using a Qubit Fluorometer (Thermo Fisher Scientific, Waltham, Massachusetts, USA), and sample purity was confirmed spectrophotometrically by measuring the A260/A280 ratio.

Sequencing and Bioinformatics Analysis

Amplicons of the variable V3–V4 region of the bacterial 16S rRNA gene, delimited through primers 341F and 805R, were sequenced in paired-end (2 × 250 cycles) on the Illumina MiSeq platform, according to the Illumina 16S Metagenomic Sequencing Library Preparation protocol. Raw sequences were processed with the DADA2 pipeline in R, which assigns taxonomy using the SILVA 138 database [20] as a reference with a 0.99 identity threshold. After pre-processing in R, the data were imported into QIIME 2 version 2021.4 for further analysis [21]. Sequence depth ranged from 12,334 to 435,143 with a mean of 232,129 ± 57,543 per sample.

DNA Sequencing for Species Assignment

Species identified by NGS technology were then verified by sequencing 16S rRNA gene full-length amplicons (1550 bp) in end-point PCR using universal primer pair P0 (5' GAAGAGTTTGATCCTGGCTCAG forward) and P6 (5' CTACGGCTACCTTGTTACGA reverse). PCR was performed in 96-well detection plates in ABI prism 7000 (Applied

TABLE 1. Anthropometrics parameters and the MedQ-Sus questionnaire score in sedentary, moderately active, very active, and elite soccer players. Data are expressed as mean and standard deviation.

	No Physical Activity	Moderate Level of Physical Activity (< 3 hours × week)	High Level of Physical Activity (> 6 hours × week)	Elite Soccer Players
Height (cm)	175.7 ± 4.7	177.0 ± 6.7	179.8 ± 9.3	182.6 ± 6.7
Weight (kg)	69.4 ± 4.9	70.6 ± 6.3	73.7 ± 8.5	77.6 ± 6.9
BMI (kg/m^2)	22.4 ± 1.0	22.5 ± 0.8	22.7 ± 0.8	23.2 ± 1.2
Cereals & cereal products	1.7 ± 0.5	1.5 ± 0.6	1.7 ± 0.6	1.5 ± 0.6
Legumes	1.3 ± 0.5	1.2 ± 0.9	1.5 ± 0.8	1.3 ± 0.8
Fresh vegetables	1.5 ± 0.6	1.2 ± 0.7	1.5 ± 0.6	1.5 ± 0.5
Fresh fruit	1.0 ± 0.9	1.5 ± 0.8	1.7 ± 0.5	1.5 ± 0.8
Dairy products	1.5 ± 0.8	1.5 ± 0.8	1.2 ± 0.7	1.3 ± 0.8
Fish and fish products	1.0 ± 0.6	1.3 ± 0.5	1.7 ± 0.5	1.3 ± 0.7
Meat and meat products	1.8 ± 0.4	1.5 ± 0.5	1.5 ± 0.5	1.5 ± 0.5
Olive oil	1.3 ± 0.5	1.2 ± 0.9	1.2 ± 0.7	1.5 ± 0.5
Total score	11.2 ± 1.5	10.8 ± 1.2	11.8 ± 1.6	11.5 ± 0.8

Legend. BMI: Body Mass Index.

Biosystems, Stockholm, Sweden) by amplifying the total DNA extracted from the same stool sample. The reaction was carried out using a Thermo Scientific PCR Master Mix (Thermo Fisher Scientific Inc., CA, USA) according to the manufacturer's protocol. The amplicons obtained were sent to Eurofins Genomics (Eurofins Genomics Italy, Milano, Italy) for sequencing. Raw data were then analysed with BLASTN to verify the species assigned.

Statistical Analysis

All statistical analyses were completed with SPSSS (Version 18.0, SPSS Inc., IL, USA). Data are presented as mean ± SD with significance at $p \leq 0.05$. Descriptive statistics were computed on each variable, and the Shapiro-Wilk test was used to verify normality. Where statistical significance was shown, 95% confidence intervals (CI) were indicated to estimate the mean difference. Differences between populations were analyzed using a one-way ANOVA. Bonferroni's post-hoc test was employed to identify any localized effects in the event of a significant difference. The standardized differences of effect size (ES, [95%CI]) in the selected variables were calculated. Threshold values for assessing magnitudes of the ES were > 0.20, 0.20, 0.60, 1.2, and 2.0 for trivial, small, moderate, large, and very large, respectively [22]. The z score was calculated to elaborate Figure 4.

RESULTS

The anthropometric parameters and adherence to the Mediterranean Diet through the MedQ-Sus questionnaire, relating to the inclusion criteria of the different study populations, are presented in Table 1.

Descriptive statistics of the gut microbiota parameters of the different study populations are presented in Table 2.

Elite soccer players showed a significantly higher prevalence of Genus Phascolarctobacterium, species Lactobacillus iners, Phascolarctobacterium succinatutens, Prevotella albensis, and Streptococcus itis than the group without physical activity ($p < 0.05$). However, Genus Roseburia showed a significantly lower prevalence than the group with a high level of physical activity (Figure 1, $p < 0.05$).

The population with high physical activity showed a significantly higher prevalence of Bacteroides fluxus and Roseburia feces than those with moderate physical activity levels ($p < 0.05$). The population with a high level of physical activity showed a significantly higher prevalence of Roseburia feces, Bacteroides fluxus, and Genus Roseburia than the group with no physical activity ($p < 0.05$). The population with high physical activity showed a significantly lower prevalence of Prevotella copri compared to the group with a moderate level of physical activity (Figure 2, $p < 0.05$).

The pie chart (Figure 3) and the heatmap (Figure 4) present the previously stated results. Each pie chart shows the percentage distribution of the most representative bacterial species within each group of subjects (SED (the group with no physical activity), MLE (moderate level of physical activity), HLE (high physical activity), SOC (elite soccer players)), the heatmap allows a comparison between the different populations in the different parameters analyzed. The results showed a significantly higher prevalence of Prevotella copri in subjects with moderate physical activity, followed by elite soccer players and, finally, sedentary subjects. In contrast, subjects with

TABLE 2. Differences in gut microbiota parameters in sedentary, moderately active, very active and elite soccer players.

	No Physical Activity	Moderate Level of Physical Activity (< 3 hours × week)	High Level of Physical Activity (> 6 hours × week)	Elite Soccer Players	ANOVA
Genus Phascolarctobacterium (%)	0.7390 ± 0.9401 [a]	0.6666 ± 0.88242 [a]	1.1295 ± 1.26701	2.1373 ± 2.51849	F 4.581 p 0.005
Genus Roseburia (%)	2.9828 ± 2.40412 [b]	4.0301 ± 3.04254	6.0291 ± 5.36580	2.3905 ± 2.29816 [b]	F 4.191 p 0.008
Species Bacteroides fluxus (%)	0.0009 ± 0.0018 [b]	0.0008 ± 0.0017 [b]	0.0028 ± 0.0038	0.0011 ± 0.0016	F 3.191 p 0.028
Species Lactobacillus iners (%)	0.0000 ± 0.0 [a]	0.0000 ± 0.0	0.0000 ± 0.0	0.0001 ± 0.00027	F 2.936 p 0.038
Species Phascolarctobacterium succinatutens (%)	0.1735 ± 0.36710 [a]	0.2307 ± 0.53093	0.1211 ± 0.19593	0.8535 ± 1.63961	F 3.377 p 0.022
Species Prevotella albensis (%)	0.0065 ± 0.01242 [a]	0.0073 ± 0.00811 [a]	0.0028 ± 0.00542 [a]	0.0302 ± 0.05215	F 4.696 p 0.004
Species Prevotella copri (%)	5.3773 ± 9.47572[c]	13.6948 ± 13.51410	3.6473 ± 9.38986[c]	10.8339 ± 13.64028	F 3.563 p 0.017
Species Roseburia faecis (%)	1.5666 ± 1.58516[b]	1.1463 ± 0.92128[b]	3.1095 ± 3.36707	1.3045 ± 1.94235	F 3.472 p 0.019
Species Streptococcus mitis (%)	0.0000 ± 0.0000 [a]	0.000 ± 0.000	0.000 ± 0.000	0.0002 ± 0.00051	F 3.008 p 0.035
F/B	1.37 ± 0.79	1.23 ± 0.60	1.61 ± 1.15	0.96 ± 0.62	F 1.946 p 0.127

Legend. F/B: Firmicutes to Bacteroidetes ratio. [a] Differences with elite soccer players; [b] Differences with high levels of physical activity; [c] Differences with moderate levels of physical training.

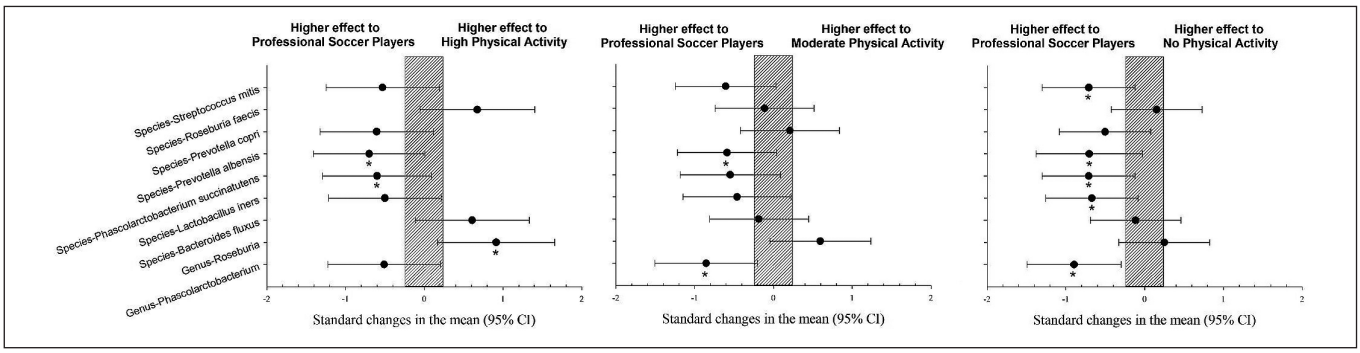


FIG. 1. Differences in gut microbiota parameters between professional soccer players vs. population with high, moderate and no physical activity. CI: confidence interval.

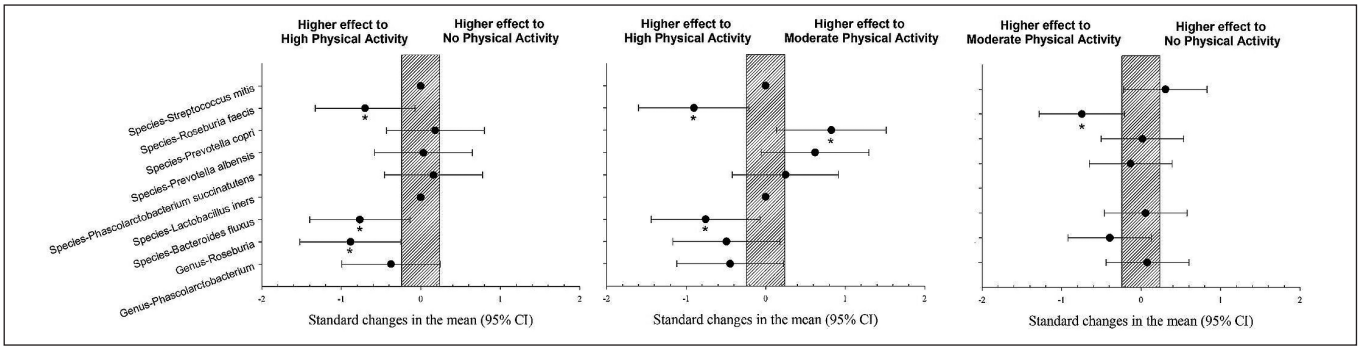


FIG. 2. Differences in gut microbiota parameters between populations with high, moderate and no physical activity. CI: confidence interval.

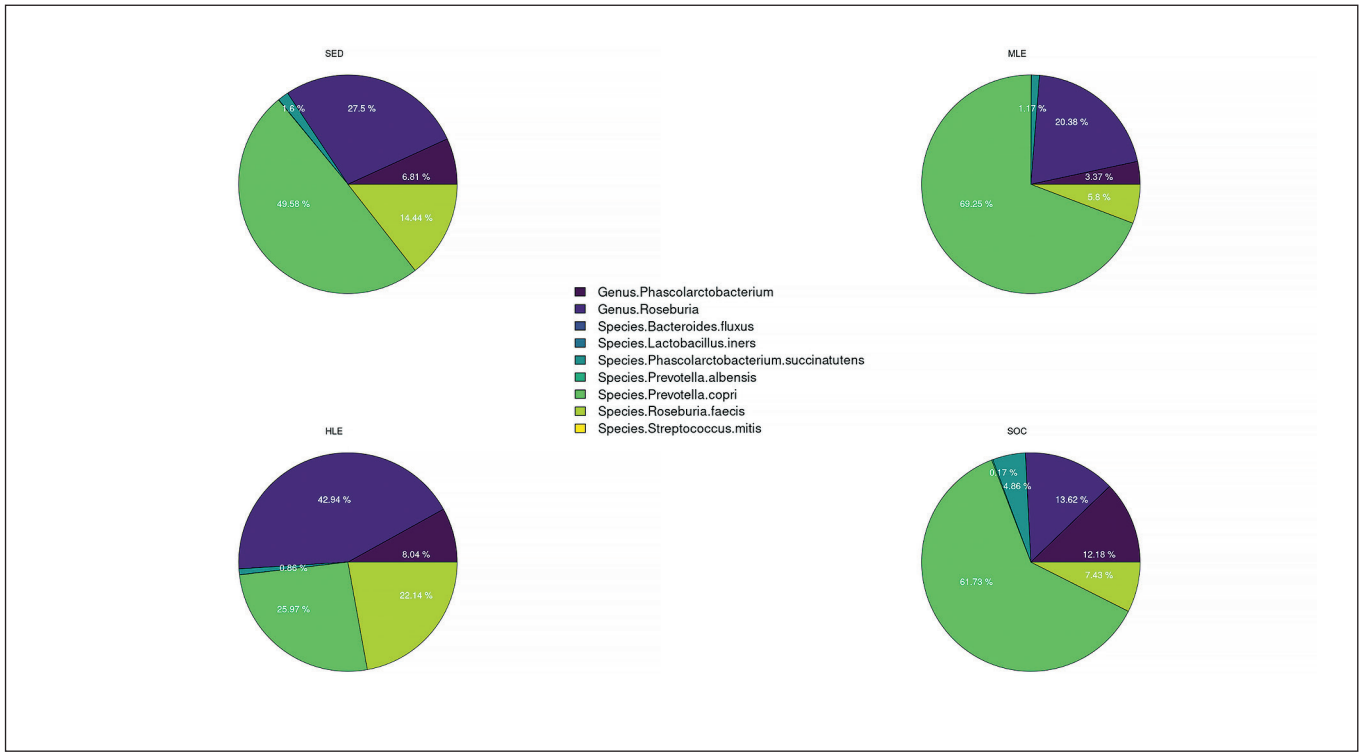


FIG. 3. Percentage distribution of bacterial species. Furthermore, based on the prevalence of the various bacterial species in the different subject groups, the heatmap generated two clusters contrasting the bacterial species found in elite footballers and subjects with moderate physical activity vs. sedentary subjects and subjects with high physical activity.

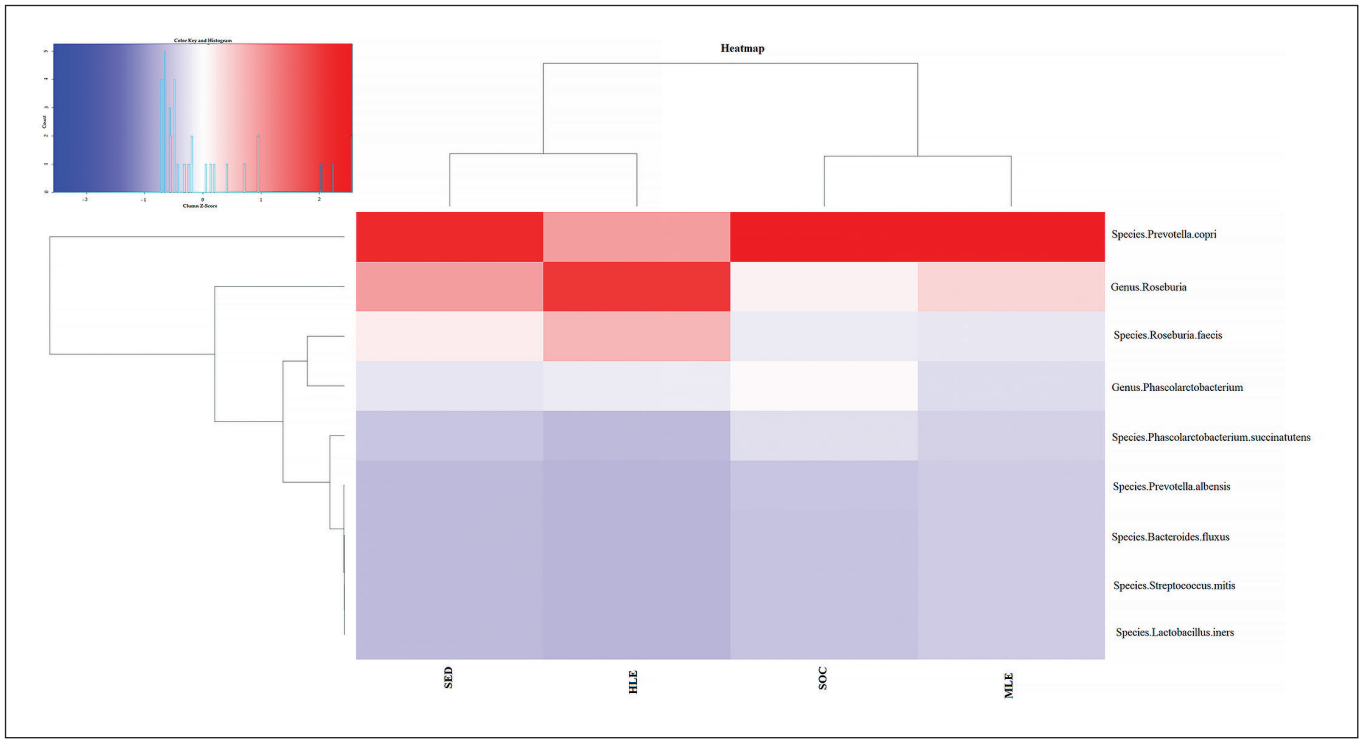


FIG. 4. Figure 4. Distribution of bacterial species in the heatmap. The heatmap (constructed with R studio's heatmap.2 function) depicts the distribution of the various bacterial species with different colors ranging from red to blue through intermediate colors. The red color represents a higher z score (>1.5), while the blue color represents a lower z score (<0.2).

a high level of physical activity showed a significantly higher prevalence of Genus Roseburia and Species Roseburia feces than the other subject groups.

DISCUSSION

The gut microbiota comprises billions of bacteria, viruses, fungi, and protozoa. The present study showed nine gut microbiota parameters differences between the four sample groups studied. Five parameters were significantly greater in elite soccer players, three in the group with a high level of physical activity and one in the group with a moderate level of physical activity (Table 2, Figures 1 and 2). Some findings in the present study confirm earlier results, which describe how exercise appears to be associated with changes in gut microbial composition, an increase in butyrate-producing bacteria (e.g., Roseburia hominis, Faecalibacterium pausnitzii, and Ruminococcaceae) and increases in butyrate concentrations in faeces in rodent models [23] and in humans [24] regardless of diet.

In more detail, the results of our study about Genus Phascolarctobacterium and Species Phascolarctobacterium succinatutens are in line with a previous study [25] where higher levels of physical activity were associated with a greater abundance of this gut microbiota species. Phascolarctobacterium is a propionate producer, an SCFA that inhibits pro-inflammatory cascades by suppressing the activity of pro-inflammatory regulator nuclear factor kappa-B (NFκB) [26]. Our results showed that moderate physical activity is not enough to promote an increase in this gut microbiota species; a higher level of physical activity is probably needed.

The higher presence of Prevotella albensis and P. copri in soccer players also confirmed the results obtained in previous studies with cyclists and marathon runners compared to a sedentary population [12, 13].

In the present study, our results showed a gradual increase in Streptococcus mitis, Lactobacillus iners, and Roseburia species based on physical activity, excluding soccer players. The typology of competition and training in terms of high-intensity actions, type of specific/intermittent endurance, and muscle damage are probably responsible for this and are parameters for further study.

Bacteroides fluxus is a Gram-negative anaerobic bacillus associated with sarcopenia [27]. However, our results do not align with previous findings on the non-sporting adult population. The Firmicutes to Bacteroidetes ratio obtained from the present study is not in line with a previous study, which showed a direct relationship between this species and VO_2 max [28]. While our soccer players' values were comparable to those of healthy young adults in the Durk et al. study [28], although not significantly different, the sedentary subjects in our study showed higher F/B values.

The exercise-induced shifts in SCFA-producing taxa (Genus Phascolarctobacterium, species Prevotella copri, and Roseburia faecis) observed in this study corroborate data presented in rodent models [29] and in a previous cross-sectional study in humans relating fecal butyrate concentrations to aerobic physical performance and muscle turnover [30]. However, intense physical exercise probably induces a relatively low abundance of short-chain fatty acids (SCFA) and lactic acid-producing bacteria [30]

Previous studies have shown that BMI can influence gut microbiota compositions [7]. However, our study included only normal weight subjects; therefore, the differences could relate to the quantity of physical exercise.

The participants in this study, particularly the athletes, differed from numerous studies that have evaluated the gut microbiota in sports populations, as our sample followed the Mediterranean diet, which provided a lower protein intake and higher levels of fiber than the diets of the sportspeople in the previous studies [31]. Higher protein intake leads to differences in the composition of the gut microbiota because excessive protein ingestion leads to excess nitrogen substrates in the intestinal microbes, producing putrefactive fermentation products such as ammonia, hydrogen sulfide, amines, phenols, thiols, and indoles [32]. Conversely, low dietary fiber may decrease bowel movements and reduce gut microbiota diversity [32]. A variable that is difficult to control is the carbohydrate load, especially if the sample includes elite athletes. Carbohydrate load strictly depends on the physical training load required; in some cases, various carbohydrates can be used to maximize sports performance. However, our athletes preferred to eat resistant starch rather than monosaccharides. Proteins and carbohydrates are linked in intestinal digestion, as when the carbohydrate content decreases, putrefactive fermentation becomes more harmful [33]. It has been reported that high protein intake leads to DNA damage in the colon mucosa when the dietary intake of fermentable carbohydrates is low [34].

Strength and limitations

This study has some strengths. This was the first study of the gut microbiota in elite soccer players. Secondly, the sample was homogeneous regarding body mass index, age, and eating habits. Therefore, the variable that differed between the four study groups in the sample was the level of physical activity. Furthermore, the sample size aligned with other studies investigating the human gut microbiota. Finally, subjects from the same territory were evaluated with the same conditions, place, and by the same operators.

However, limitations must be highlighted. The first limitation was the study's cross-sectional design, with an inherent inability to generalize the cause-effect relationship. Secondly, according to the study design, the nutritional assessment was carried out retrospectively, therefore with an intrinsic limit to generalizability. However, a recently validated assessment method was used. Thirdly, although the total sample size is in line with other current studies, the sequencing method used, 16s RNA, may lose reliability in the subgroup analysis of the present study. Finally, this study did not analyze the biodiversity of the microbiota. However, this aspect was not in line with the aim of the study; furthermore, the sample size would not have allowed to obtain statistically significant results and consequently less reliable conclusions.

CONCLUSIONS

The study of gut microbiota as related to the host's health is a recent field of research, and there are currently numerous study directions. The relationship with physical activity, regardless of eating habits, is one of these new study directions. The results obtained from the present study, involving elite soccer players, expanded current knowledge and confirmed that increased levels of physical activity promote greater bioavailability of the gut microbiota. Our study described how exercise appears to be associated with changes in gut microbial composition, with an increase in butyrate-producing bacteria. To conclude, we have shown that high levels of physical activity positively contribute to health as they indirectly produce SCFA, which inhibits pro-inflammatory cascades.

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Conflict of interest declaration

The authors declare that they have no competing interests.

REFERENCES

1. Thursby E, Juge N. Introduction to the human gut microbiota. Biochem J. 2017 May 16; 474(11):1823–1836. doi: 10.1042/BCJ20160510.
2. Matijašić M, Meštrović T, Paljetak HČ, Perić M, Barešić A, Verbanac D. Gut Microbiota beyond Bacteria-Mycobiome, Virome, Archaeome, and Eukaryotic Parasites in IBD. Int J Mol Sci. 2020 Apr 11; 21(8):2668. doi: 10.3390/ijms21082668.
3. Seed PC. The human mycobiome. Cold Spring Harb. Perspect. Med. 2014; 5:a019810. doi: 10.1101/cshperspect.a019810.
4. Pinart M, Dötsch A, Schlicht K, Laudes M, Bouwman J, Forslund SK, Pischon T, Nimptsch K. Gut Microbiome Composition in Obese and Non-Obese Persons: A Systematic Review and Meta-Analysis. Nutrients. 2021 Dec 21; 14(1):12. doi: 10.3390/nu14010012.
5. Aya V, Flórez A, Perez L, Ramírez JD. Association between physical activity and changes in intestinal microbiota composition: A systematic review. PLoS One. 2021 Feb 25; 16(2):e0247039. doi: 10.1371/journal.pone.0247039.
6. Matenchuk BA, Mandhane PJ, Kozyrskyj AL. Sleep, circadian rhythm, and gut microbiota. Sleep Med Rev. 2020 May 13; 53:101340 doi: 10.1016/j.smrv.2020.101340.
7. Allen JM, Mailing LJ, Niemiro GM, et al. Exercise alters gut microbiota composition and function in lean and obese humans. Med Sci Sports Exerc. 2018; 50(4):747–57. doi: 10.1249/MSS.0000000000001495.
8. Ritson AJ, Hearris MA, Bannock LG. Bridging the gap: Evidence-based practice guidelines for sports nutritionists. Front Nutr. 2023 Mar 29; 10:1118547. doi: 10.3389/fnut.2023.1118547.
9. Jang LG, Choi G, Kim SW, Kim BY, Lee S, Park H. The combination of sport and sport-specific diet is associated with characteristics of gut microbiota: an observational study. J Int Soc Sports Nutr. 2019 May 3; 16(1):21. doi: 10.1186/s12970-019-0290-y.
10. Clarke SF, Murphy EF, O'Sullivan O, Lucey AJ, Humphreys M, Hogan A, Hayes P, O'Reilly M, Jeffery IB, Wood-Martin R, Kerins DM, Quigley E, Ross RP, O'Toole PW, Molloy MG, Falvey E, Shanahan F, Cotter PD. Exercise and associated dietary extremes impact on gut microbial diversity. Gut. 2014 Dec; 63(12):1913–20. doi: 10.1136/gutjnl-2013-306541.
11. Liang R, Zhang S, Peng X, Yang W, Xu Y, Wu P, Chen J, Cai Y, Zhou J. Characteristics of the gut microbiota in professional martial arts athletes: A comparison between different competition levels. PLoS One. 2019 Dec 27; 14(12):e0226240. doi: 10.1371/journal.pone.0226240.
12. Petersen LM, Bautista EJ, Nguyen H, Hanson BM, Chen L, Lek SH, Sodergren E, Weinstock GM. Community characteristics of the gut microbiomes of competitive cyclists. Microbiome. 2017 Aug 10; 5(1):98. doi: 10.1186/s40168-017-0320-4.
13. Kulecka M, Fraczek B, Mikula M, Zeber-Lubecka N, Karczmarski J, Paziewska A, Ambrozkiewicz F, Jagusztyn-Krynicka K, Cieszczyk P, Ostrowski J. The composition and richness of the gut microbiota differentiate the top Polish endurance athletes from sedentary controls. Gut Microbes. 2020 Sep 2; 11(5):1374–1384. doi: 10.1080/19490976.2020.1758009.
14. Bycura D, Santos AC, Shiffer A, Kyman S, Winfree K, Sutliffe J, Pearson T, Sonderegger D, Cope E, Caporaso JG. Impact of Different Exercise Modalities on the Human Gut Microbiome. Sports (Basel). 2021 Jan 21; 9(2):14. doi: 10.3390/sports9020014.
15. Estaki M, Pither J, Baumeister P, Little JP, Gill SK, Ghosh S, et al. Cardiorespiratory fitness as a predictor of intestinal microbial diversity and distinct metagenomic functions. Microbiome. 2016; 4(1):42. doi: 10.1186/s40168-016-0189-7.
16. Cataldi S, Bonavolontà V, Poli L, Clemente FM, De Candia M, Carvutto R, Silva AF, Badicu G, Greco G, Fischetti F. The Relationship between Physical Activity, Physical Exercise, and Human Gut Microbiota in Healthy and Unhealthy Subjects: A Systematic Review. Biology (Basel). 2022 Mar 21; 11(3):479. doi: 10.3390/biology11030479.
17. Dorelli B, Gallè F, De Vito C, Duranti G, Iachini M, Zaccarin M, Preziosi Standoli J, Ceci R, Romano F, Liguori G, Romano Spica V, Sabatini S, Valeriani F, Cattaruzza MS. Can Physical Activity Influence Human Gut Microbiota Composition Independently of Diet? A Systematic Review. Nutrients. 2021 May 31; 13(6):1890. doi: 10.3390/nu13061890.
18. Harper DJ, 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 Dec; 49(12):1923–1947. doi: 10.1007/s40279-019-01170-1.
19. Ruggeri S, Buonocore P, Amoriello T. New Validated Short Questionnaire for the Evaluation of the Adherence of Mediterranean Diet and Nutritional Sustainability in All Adult Population Groups. Nutrients. 2022 Dec 5; 14(23):5177. doi: 10.3390/nu14235177.
20. Callahan BJ, McMurdie PJ, Rosen MJ, Han AW, Johnson AJA, Holmes SP. DADA2: High-resolution sample inference from Illumina amplicon data. Nat. Methods 2016, 13, 581–583. doi: 10.1038/nmeth.3869.
21. Bolyen E, Rideout JR, Dillon MR, Bokulich NA, Abnet CC, Al-Ghalith GA,

Alexander H, Alm EJ, Arumugam M, Asnicar F, et al. Reproducible, interactive, scalable and extensible microbiome data science using QIIME 2. Nat. Biotechnol. 2019, 37, 852–857. doi: 10.1038/s41587-019-0209-9.
22. 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: 10.1249/MSS.0b013e31818cb278.
23. Matsumoto M, Inoue R, Tsukahara T, et al. Voluntary running exercise alters microbiota composition and increases n-butyrate concentration in the rat cecum. Biosci, Biotechnol, and Biochem. 2008; 72(2):572–6. doi: 10.1271/bbb.70474.
24. Barton W, Penney NC, Cronin O, Garcia-Perez I, Molloy MG, Holmes E, et al. The microbiome of professional athletes differs from that of more sedentary subjects in composition and particularly at the functional metabolic level. Gut. 2018; 67(4):625–33. doi: 10.1136/gutjnl-2016-313627.
25. Holzhausen EA, Malecki KC, Sethi AK, Gangnon R, Cadmus-Bertram L, Deblois CL, Suen G, Safdar N, Peppard PE. Assessing the relationship between physical activity and the gut microbiome in a large, population-based sample of Wisconsin adults. PLoS One. 2022 Oct 26; 17(10):e0276684. doi: 10.1371/journal.pone.0276684.
26. Al Bander Z, Nitert MD, Mousa A, Naderpoor N. The Gut Microbiota and Inflammation: An Overview. Int J Environ Res Public Health. 2020 Oct 19; 17(20):7618. doi: 10.3390/ijerph17207618.
27. Wang Y, Zhang Y, Lane NE, Wu J, Yang T, Li J, He H, Wei J, Zeng C, Lei G. Population-based metagenomics analysis reveals altered gut microbiome in sarcopenia: data from the Xiangya Sarcopenia Study. J Cachexia Sarcopenia Muscle. 2022 Oct; 13(5):2340–2351. doi: 10.1002/jcsm.13037.
28. Durk RP, Castillo E, Márquez-Magaña L, Grosicki GJ, Bolter ND, Lee CM, Bagley JR. Gut Microbiota Composition Is Related to Cardiorespiratory Fitness in Healthy Young Adults. Int J Sport Nutr Exerc Metab. 2019 May 1; 29(3):249–253. doi: 10.1123/ijsnem.2018-0024.
29. Matsumoto M, Inoue R, Tsukahara T, Ushida K, Chiji H, Matsubara N, et al. Voluntary running exercise alters microbiota composition and increases n-butyrate concentration in the rat cecum. Biosci Biotechnol Biochem. 2008; 72(2):572–6. doi: 10.1271/bbb.70474.
30. Estaki M, Pither J, Baumeister P, Little JP, Gill SK, Ghosh S, et al. Cardiorespiratory fitness as a predictor of intestinal microbial diversity and distinct metagenomic functions. Microbiome. 2016; 4(1):42. doi: 10.1186/s40168-016-0189-7.
31. Dziewiecka H, Buttar HS, Kasperska A. et al. Physical activity induced alterations of gut microbiota in humans: a systematic review. BMC Sports Sci Med Rehabil. 2022; 14(1):122. doi: 10.1186/s13102-022-00513-2.
32. Clark A, Mach N. Exercise-induced stress behavior, gut-microbiota-brain axis and diet: a systematic review for athletes. J Int Soc Sports Nutr. 2016; 13(1):43. doi: 10.1186/s12970-016-0155-6.
33. Toden S, Bird AR, Topping DL, Conlon MA. Resistant starch attenuates colonic DNA damage induced by higher dietary protein in rats. Nutr Cancer. 2005; 51(1):45–51. doi: 10.1207/s15327914nc5101_7.
34. Russell WR, Gratz SW, Duncan SH, Holtrop G, Ince J, Scobbie L, et al. Highprotein, reduced-carbohydrate weight-loss diets promote metabolite profiles likely to be detrimental to colonic health. Am J Clin Nutr. 2011; 93(5): 1062–72. doi: 10.3945/ajcn.110.002188.

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A small switch in perspective: Comparing weight loss by nutrient balance versus caloric balance

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ABSTRACT: The establishment of a Caloric balance has been classically discussed as the means to induce weight loss. Recently, the idea of nutrient balance as opposed to Caloric balance has emerged as a better means to induce weight loss. This investigation compared differences in weight loss between a diet based on a nutrient balanced diet compared to a Caloric balance diet. 53 (27M/26F) active overfat individuals (30.7+/- 7.1 years) were randomly (matched for age, gender, training history) assigned within an 8-week intervention to follow either a self-selected diet (control) or a diet based on following a Caloric balance (%Cal/day) or a nutrient balance (g/kg/day) in conjunction with a periodized exercise regimen to determine effectiveness for each diet to induce weight loss. Nutrient balance group had significantly different changes ($p < 0.05$) in fat-free mass (2.26 (2.02, 2.49) kg versus 0.42 (-0.40, 1.24) kg) and fat mass (-5.96 (-5.34, -6.58) kg versus -4.08 (-3.92, -5.92) kg) relative to the Caloric balance group and was more effective at meeting nutritional requirements for protein (ES = 0.65 (0.48, 0.85)) and lipids (ES = 0.24 (-0.09, 0.98)) than the Caloric balance group. Nutrient balance was subjectively scored as easier to follow and more likely to be self-selected. Using a nutrient balance diet may be more effective at inducing beneficial body compositional changes and shows being a more self-selected dietary method when compared to a Caloric balance diet. Therefore, it may be a better choice for advice when offering treatments to those who are attempting to lose weight or maintain weight loss.

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INTRODUCTION

We have come to understand the relationship of fatness with the onset of non-communicable diseases [1, 2]. Especially for those individuals expressing overfatness (metabolic dysfunction associated with excessive fatness regardless of designation of obesity) [2]. Moreover, we understand that metabolic changes associated with changes in nutrition and increased activity tend to reverse many of the health issues associated with overfatness [2–6]. So much so, that over the last half-century the use diet and exercise to prevent many non-communicable diseases (e.g., diabetes and metabolic syndrome, cardiovascular disease, cancer) associated with overfatness and has become cornerstone of therapy for ameliorating issues of overfatness that lead to the non-communicable diseases [1, 6–12].

Unfortunately, while we have previously reported in meta-analysis [8] that there is a lower level of effectiveness in treatment by simply establishing a hypocaloric condition for changing body mass or body composition, the conversation both within and outside of healthcare and fitness continues to focus on concept of the Caloric balance and one's overall body mass (or more importantly body composition) [6, 11, 13–19]. So much so that weight loss and maintenance have often been discussed based on the idea of the Calorie balance [12–14, 16, 17]. Where the central tenet focuses on the idea that consumption of more Calories than expended in activities throughout the day would lead to weight gain, while the opposite is associated with weight loss.

From this authors point of view, it appears to be that the simplicity of this idea may be the crux for its continued use. Yet, the rationale has several logical flaws that hamper its overall justification for altering or maintaining body mass [11, 12, 14, 20, 21]. The first being the semantic question that should be constantly asked when the discussion is raised: *how much does a Calorie weigh?* Where it must be remembered that Calories are mass-less units of energy (heat required to increase 1 kg water 1-degree Centigrade) and as such Calories cannot contribute to weight. Beyond this rhetorical point, the largest flaw is that the set point generally used for the balance is not universal for all individuals, e.g., 2000 Cal/day, and using such generalities may give a balance that automatically establishes conditions for overconsumption of food and thus weight gain [2, 7, 14, 20–24]. Moreover, the expected energetic expenditure throughout the day is typically established via one of many regression equations that allows for an estimated set point (i.e., basal metabolic rate) that may not accurately establish a true set point for the person [13, 20–25]. Or accurately reflect the estimated energy balance points for inducing weight loss [26]. As most of the regression equations that have been generalized to the whole

population were established based on a non-generalized population. Meaning that for women, minorities, or other under-represented populations using many of the established equations may not provide an accurate representation of estimated energetic needs. Lastly, as have been previously stipulated [4, 8, 10], the use of a hypocaloric dietary interventions without exercise have limited effectiveness at inducing long-term weight loss or body compositional changes.

As such, this idea has begun to be called into question. The premise that has been the foundation to calling into question the validity of Caloric balance is not simply because of the flaw in the estimation of energetic demand, but what the balance does not consider; foods consumed are used for other metabolic processes beyond those associated with energetics [7, 21, 22, 25, 27–30]. As such, we must begin to revisit how to advise food consumption for those attempting to lose body mass. Regardless of when foods are being consumed, or the composition of food that is being consumed [31, 32].

From this perspective, the idea of nutrient balance has come to the forefront as a counter to the idea of Caloric balance [7, 18, 22, 28, 31–33]. This idea is not something new, however the application of the nutrient balance in regard to weight loss and maintenance is. Yet, outside of attempting to support an ill-fated hypothesis on obesity or for a nutrient-for-nutrient replacement [34–36], there have not been many investigations that we have seen to date which compared Caloric relative to nutrient balance diets.

Thus, the purpose of this investigation was to examine the relationship of weight loss and subsequent maintenance based on use of Caloric balance versus using Nutrient balance. Where it is hypothesized that use of nutrient balance allows not only for greater weight loss but will allow for a greater beneficial change in body composition (i.e., maintaining fat-free mass) versus the use of Caloric balance when combined with exercise in a weight loss regimen.

MATERIALS AND METHODS

Subjects

Potential participants were recruited through advertisement and postings at fitness centers and gyms from November 2019 through January 2020, September 2021 through April 2022, and January 2023 through March 2023. To ensure power of analysis, a N-size calculation was completed prior to enrollment with the indicated population needed for appropriate power being 38 participants. From 250 interested participants, 55 participants provided informed consent to begin the study, and 53 completed all aspects of the study (1 voluntarily withdrew and 1 did not return a completed excel spreadsheet, both from the nutrient balance condition). To be included in

TABLE 1. Demographic information and the measures of interest for body composition (Average+/-SD) for participants in study groups.

	Group					
Participants (F/M)	53 (27/26)					
Age (year)	30.1 +/-7.37					
Height (cm)	167.6+/-10.9					
	Pre			**Post**		
Body Mass (kg)	86.2+/-19.6			82+/-18		
Fat Mass (kg)	32.5+/-9.3			27.2+/-7.6		
% Fat Mass	0.37+/-0.05			0.33+/-0.04		
Fat-Free Mass (kg)	53.8+/-12.1			54.8+/-11/8		
% Fat-Free Mass	0.63+/-0.05			0.67+/-0.04		
	Caloric Balance Group		**Nutrient Balance Group**		**Control**	
Participants (F/M)	18 (8/10)		16 (8/8)		19 (11/8)	
Age (year)	30.65+/-7.49		30.75+/-7.46		29.45+/-6.55	
Height (cm)	167.34+/-11.3		167.78+/-10.8		167.42+/-13.5	
	Pre	Post	Pre	Post	Pre	Post
Body Mass (kg)	87.16+/-19.13	83.51+/-17.63^	84.10+/-18.53	80.0 +/-17.0*$^	87.38+/-21.88	83.48+/-20.1^
Fat Mass (kg)	32.56+/-9.37	28.48+/-7.28	31.25+/-8.69	25.29+/-6.76*$^	33.54+/-10.22	29.36+/-8.64
% Fat Mass	0.37+/-0.05	0.35+/-0.04	0.37+/-0.05	0.31+/-0.04*	0.38+/-0.04	0.33+/-0.03
Fat-Free Mass (kg)	54.61+/-12.22	55.03+/-11.9	52.85+/-11.71	55.71+/-11.5^	53.83+/-12.9	54.12+/-12.56
% Fat-Free Mass	0.63+/-0.05	0.65+/-0.04	0.63+/-0.05	0.69+/-0.04*	0.62+/-0.04	0.67+/-0.03

*Denotes significant difference to Caloric group ($p < 0.05$), $denotes significantly different from control ($p < 0.05$), ^ denotes significantly different from pre-test ($p < 0.05$)

the study, a participant had to be an adult between 18 and 65 years old, overfat (classified as BMI > 25 with WHR or % BF being greater than 10% above "normal" for age and gender). All participants provided medical clearance for participating in diet and wellness program from their personal physician prior to beginning their involvement in the study and were at least moderately active (e.g., moderate physical activity or exercise regimen of at least 45-min 3 or more days per week), had no comorbidity (i.e., non-communicable disease) and were not involved in competitive athletics during the time of the study, table 1.

Following enrollment, and prior to pre-intervention testing, participants were randomly match-assigned (based on matching gender, age, training history, familial/social factors of fatness between groups) to either the control (exercise only and self-selected diet, ad libitum nutrient consumption with no restriction or advice on composition) or dietary intervention group (either nutrient or Caloric balance diets). For those assigned to the dietary intervention, participants were further matched-assigned to follow either the nutrient balance diet or the Caloric balance diet. After assignment, each was provided with an electronic food scale (accurate to 0.01 g), an electronic food log (Excel Spreadsheet), and a standardized exercise regimen [4] to follow during the duration of the study.

All aspects of the study followed Helsinki protocol for using human volunteers and were approved by the independent IRB of Scientific Health: Education and Human Performance (SH-HP-2019-3A) prior to beginning the study. All participants were fully and completely informed about the risks and rewards for participation in the study, participants did not receive monetary rewards for participation but did receive fuel cards to offset cost for transportation for evaluations. Each participant acknowledged their agreement to participate in the study and were aware that they could leave the study at any time without penalty or recourse.

Study Design

Due to ethical constraints, i.e., recruiting individuals attempting to lose weight into a study where they would be encouraged to halt that behavioral change, the study design did utilize control group that was encouraged to eat as was normal prior to enroll to meet desired weight loss, but did not provide specific details for dietary composition. All participants used a standard exercise intervention and followed either their normal diet prior to enrollment or one of the two dietary interventions for 8-weeks.

Exercise Regimen

All participants followed a standardized periodized exercise regimen for the 8-week study (with 1-week familiarization) based on a portion of exercise protocol that was previously used to induce long-term body compositional changes [4]. The focus of the training within the periodization was improved endurance coupled with reduced fat-mass and involved 5–6 days/week of exercise with 1–2 days/week of active rest or self-selected endurance activity, see table 2 for breakdown. To summarize the exercise, focused on resistance training using both standard set, rep, rest intervals along with circuit resistance training and a concurrent endurance training using a combination of "steady state" effort and interval endurance exercise.

Each exercise session completed, along with records for activities of daily living (including total steps per day), over the length of the study was logged with a trainer at the gym/fitness center following completion of the exercise session, with a 95.3% compliance rate being seen for the participants (range of 91–100%). To ensure control variability of the exercise component, a comparison of activities of daily living log was done between the familiarization week and the weeks of intervention. Comparison indicated minimal changes (ICC = 0.915) between the familiarization week and the 8-weeks of intervention with reduction in non-exercise related activity accounting for points of disagreement.

Diet Interventions

Following enrollment and during the familiarization week, participants were randomly matched-assigned based demographic information collected upon enrollment (i.e., age, gender, training history and body mass) to 1 of 2 dietary interventions. Participants were assigned to either follow a nutrient balanced diet or a Calorie balanced diet, or to a self-selected control dietary intervention where advice on nutrient ranges were not provided the participants.

Those assigned to the nutrient balance diet followed a diet pattern based on total amounts of food that should be consumed based on the following breakdown [7, 9, 22, 32, 33, 37, 38]:

- Net Carbohydrate: 2–2.5 g/kg body mass (or 120 g/day, whichever is greater)
- Protein: 1.8–2.2 g/kg body mass
- Fat: 1.0 g/kg body mass (with at least 2 g/day ALA, 0.5 g/day EPA, 0.5 g/day DHA, and 12–17 g/day Omega-6)

Where values for macronutrients consumed were modified over the length of the study based on changes in self-recorded body mass. Additionally, participants were educated for determining Net Carbohydrates, i.e., Carbohydrate load, through subtraction of amount of dietary fiber consumed from the total carbohydrates consumed.

Those assigned to the Caloric balance diet first had their basal metabolic rate (BMR) estimated via Harris-Benedict equation:

- Female: ((9.6*BM + 1.8*H – 4.7*A) + 665) *ACF;
- Male: ((13.7*BM + 5.6*H – 6.8*A) + 66) *ACF.

Where BM = Body Mass (kg), H = Height (cm), A = Age (years, to closest year), ACF = activity conversion factor (energy expenditure beyond resting metabolism, established to be 1.6 for purposes of the study here).

The equation was used to allow for modification to occur to Caloric balance over the length of study without needing direct determination of metabolic rate via gas exchange analysis. Since the intention was to induce weight loss over the 8-week intervention, the BMR value was reduced to 95% of BMR in accordance with previously established parameter [4]. Following determination of BMR,

TABLE 2. Summary of exercise protocol providing weekly details for exercise selection and training parameters (set, rep, %1RM and rest intervals) meant to provide exercise stimulus within the 8-week intervention [4].

Wk	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
1	Lift #1	ET 3-K Easy	Lift #2	MI-ET	Lift #1	ET 5-K Moderate	Active Rest
2	Lift #2	Active Rest	MI-ET	Lift #3	Lift #1	MI-ET	Active Rest
3	CRT1	CRT2	MI-ET	CRT2	Active Rest	CRT1	Active Rest
4	CRT1	MI-ET	CRT2	ET 3-K Hard	CRT1	Active Rest	MI-ET
5	Lift #2	Active Rest	Lift #3	MI-ET	Lift #1	Active Rest	ET or Active Rest
6	Lift #1	Lift #2	Active Rest	Lift #3	MI-ET	Lift #1	Active Rest or ET
7	Lift #2	MI-ET	Lift #3	MI-ET	Lift #1	Active Rest	ET or Active Rest
8	CRT1	MI-ET	CRT2	ET 3-K Hard	CRT1	MI-ET	ET or Active Rest

ET Hard indicates steady state effort at > 75% $\dot{V}O_{2max}$; ET Moderate indicates steady state effort 65–75% $\dot{V}O_{2max}$; ET Easy indicates steady state effort at 40–60% $\dot{V}O_{2max}$.

Lift

Lift #1 70% 1RM 3 × 8–10, 60–90 sec rest	Lift #2 70% 1RM 3 × 8–10, 60–90 sec rest	Lift #3 40–50% 1RM 4 × 7–9, 60-sec rest
Bench Press	Incline Bench Press	Squat to Squat Jump
Squat	Dead Lift	Plyometric Push
Lunges (Walking or Multidirectional)	Lateral Step-ups	Power Skips
	Lateral Pulldown	Keg Toss w/ Med Ball
Barbarian Rows	Romanian Dead Lifts	Depth Jumps
Push-Press	Calf Press/Toe Raises	Lateral Push-offs
Super Set: Dips and Arm Curls	Shoulder Circuit (Lateral Raise, to Front Raise, to Rear Raise, I's and Y's)	Chest Drops w/ Med Ball
		Split-Stance Squats
		Glut-Ham Hyperextension
Glut-Ham Hyperextension		
Chest Flies		
Core Routine	Core Routine	Core Routine

CRT

CRT1				CRT2			
Exercise	**Set**	**Rep/Time**	**Intensity**	**Exercise**	**Set**	**Rep/Time**	**Intensity**
Warm-up	1	5-min	50% $\dot{V}O_{2max}$	MI-ET	1	12 min	
Core Routine	1	1 circuit	N/A	Core Routine	1	1 circuit	N/A
Bench Press	1	25 rep	50% 1RM	Machine Squat	2	25 rep	50% 1RM
Lateral Pull-down	1	25 rep	50% 1RM	Seated Row	2	25 rep	50% 1RM
Smith-Machine Squat	1	25 rep	50% 1RM	Military Press-DB	2	25 rep	50% 1RM
Military Press	1	25 rep	50% 1RM	Push-ups	2	25 rep	N/A
Core Routine	1	1 circuit	N/A				
MI-ET	1	6 min		DB Dead lift	2	25 rep	50% 1RM
Leg Press	1	25 rep	50% 1RM	DB Shrugs	2	25 rep	50% 1RM
Shrugs	1	25 rep	50% 1RM	DB Bench Press	2	25 rep	50% 1RM
Row	1	25 rep	50% 1RM	Lateral Pull-down	2	25 rep	50% 1RM
Dumb-bell Chest Flies	1	25 rep	50% 1RM	Core Routine	1	1 circuit	N/A
Core Routine	1	1 circuit	N/A				
MI-ET	1	6 min		1-Leg Leg Press	2	25 rep	50% 1RM
Dumb-bell Shoulder Raises	1	25 rep	50% 1RM	Flies/Reverse Flies	2	25 rep	50% 1RM
Calf-Press	1	25 rep	50% 1RM	Cable Curls	2	25 rep	50% 1RM
Dumb-bell Bicep Curl	1	25 rep	50% 1RM	1-Arm Triceps Pushdown	2	25 rep	50% 1RM
Triceps Cable Extensions	1	25 rep	50% 1RM	Core-Strength Routine	1	2 circuit	N/A
Core-Strength Routine	1	2 circuit	N/A	MI-ET	1	12 min	
MI-ET	1	6 min					

MI-ET set-up and progression:

Week	1	2	3-thru-4	5	6-thru-7	8
Total time (min)	6	12	18	24	30	36
Total Intervals completed	1	2	3	4	5	6
	Training Intensity (% $\dot{V}O_{2max}$) and time per segment					
Segment #	1	2	3	4	5	6
% $\dot{V}O_{2max}$	50–60	90–100	50–60	80–90	50–60	70–80
Time (sec)	30	30	60	60	90	90

Each interval is completed by progression from segment #1 to segment #6 without stopping or resting. Repeated intervals are completed by repeating the segment progression for the required number of intervals without stopping between progressions.

Core Routine: Progress from 1-set @ 30-secs and progress to fatigue and then add additional set working in cycle from first exercise to last exercise with 15-sec rest between

Crunches; Pelvic Lifts; Planks; Superman's/Hyperextensions; Jack-knives; Medicine Ball Crunches; Retro-twits.

assignment of food to consume was provided to each participant based on the compositional breakdown of [4, 7, 32]:

- 40–60% from carbohydrates
- 20–30% from lipids (with subdivided into 5–10% polyunsaturated, 15–20% monounsaturated, < 7% saturated)
- 10–20% from protein.

Regardless of dietary group, all participants were asked to track consumption of fiber (ensuring at least 30 gram/day) and meeting all recommendations for vitamin and electrolytes consumed (recommended allotments were provided via informational handout).

Each volunteer was provided an electronic food log (Excel worksheet) that allowed for pre-filled cells with expected amounts of food (based on experimental design and equations) to be consumed based either on energetic breakdown (i.e., % of Cal/day) or nutrient balance (i.e., g/kg), or left blank for the control group. Entry logs allowed for documentation of macronutrient consumed and indication for types of macronutrients consumed (e.g., type of carbohydrate or lipid/fat, amino acid compositions) provided by food label documentation. Participants were instructed to log their individual meal intake into the worksheet and were reminded (by a text and email massage, or the trainer following exercise) every other day to log their food to allow for reduced recall bias [39, 40] and ensure reliability and validity of food recall.

A 3-question Likert-scale (strongly agree to strongly disagree) survey was administered every week through email communication to assess: 1) ease to follow recommendations(statement: I found the dietary guidelines easy to follow, regardless of where I have my meals), 2) willingness to self-select to continue diet (statement: I would openly follow this diet after the study has concluded), and 3) ability to understand recommendations (statement: I found the guidelines provided are clear and easy to understand to build my meals throughout the day). The Likert survey was administered to address secondary questions, regarding the subjective idea of following dietary recommendations, along with to serve as a reminder for participants to continue recording their foods consumption.

At the end of the 8-week study, all electronic food logs where collected, and any personal identification was removed for analysis of balance. Given that we have already shown acute (i.e. day-to-day) oscillations in energy balance (and by extension nutrient balance) seem to have limited impact on long-term body compositional and health status [41], the dietary logs were tabulated for weekly averages for each participant for their respective Caloric and nutrient balance. Determination of differences between expected consumption and actual consumption was then performed for these weekly averages for both absolute and percent differences based on the following equation:

Absolute Difference = Average Consumed-Expected Consumed

Percent Difference = (Average Consumed-Expected Consumed)/ Expected Consumed.

Where a positive value was an indication of surplus, while a negative value indicated a deficit.

Body Mass and Compositional Analysis

All participants were asked to report to their initial and post-training meeting in a hydrated state (having consumed 1–1.5 liters of fluid/day +1 liter of fluid for each hour of exercise) for determining body composition. Height, to nearest ¼ cm, and weight, to nearest ¼ g, were measured via standard medical scale and standiometer with subjects in gym clothing and socks (no shoes). All measurements were made after calibration of the scale and were assessed at the same time of day for that individual. Prior to height and weight measurements, participants voided bowels and bladder; during which time a urine sample was collected and used to assess hydration via USG hydrometer, USG (1.004–1.015) to ensure proper hydration status prior to assessment of body composition measurements via bioelectrical impedance (BIA). BIA was measured three consecutive

tests via full body impedance (Omron HBF-514C, Omron Healthcare Inc. Hoffman Estates, IL.), r = 0.993[42], using the average of three measurements for recording and analysis. Participants were then advised to re-weigh themselves using a scale of convenience for determining body mass to use for calculation of BMR or determination of nutrients g/kg body mass.

Data Analysis

Data was tabulated via electronic worksheet for analysis (available upon request and release from participant for external use). All dietary values were converted for comparison based on conversion of Caloric content of food consumed for comparison of energy balance for both groups Additionally, food logs for both groups were tabulated to allow for determining nutrient balance for both groups. With weeks 1 and 8 and averages over the 8-weeks were used for analysis of dietary metrics for both groups. Both pre- and post-study values of body composition and body mass were tabulated for absolute and relative percentage change. The converted values for Caloric content and for nutrient composition, the determination of net positive or negative balance for both Caloric content and nutrient compositions along with body composition measures were imported into R (R Foundation, https://www.r-project.org/) for statistical analysis and measures of central tendency. Differences relative to the control group and then between and within groups for relative balances for Caloric balance and nutrient balance, and for changes in body mass and composition that occurred over the length of the study were analyzed via ANOVA (within groups via repeated measures and mixed (time*group) for between group), $p < 0.05$. Changes in body composition where analyzed for via Pearson correlation to determine the relationship between changes in composition and the average relative nutrient or Caloric balances ($p < 0.05$). To address if there were effectiveness of nutrient balance relative to Caloric balance for inducing relative or absolute changes in body composition values (i.e., body mass, fat-free mass, fat mass) a treatment effect and 95% confidence intervals ($CI_{.95}$) was calculated based on the following equation:

Absolute Chang: $(\mu_{\text{nutrient}} - \mu_{\text{Caloric}})/\sigma_{\text{nutrient}}$

Relative Change: $(\mu_{\Delta\text{ nutrient}} - \mu_{\Delta\text{ Caloric}})/\sigma_{\Delta\text{ nutrient}}$

Lastly, to determine evaluation of appeasement for following dietary intervention a 3×2 Chi-square analysis of Likert categorizations (agree/strongly agree; neutral; disagree/strongly disagree) between the two groups was performed ($p < 0.05$).

RESULTS

As seen in table 3, there were differences seen between the two test conditions based on food intake for individuals. For all groups, there were no differences in the estimated Caloric requirements, $p = 0.8$, but there were significance differences in the consumed energy content of foods between the two groups, $p<0.05$. Along with significant

TABLE 3. Relative nutrient (g/kg) and Caloric (% of BMR) balances based on the use of the nutrient (g/kg) or Caloric (Cal/d) balance dietary plans, Average ($CI_{.95}$) for the first and last week of the 8-week dietary intervention.

	Control		Caloric		Nutrient	
	Week 1	**Week 8**	**Week 1**	**Week 8**	**Week 1**	**Week 8**
Average Energy Balance-Estimated (Cal/d)	2771.6 (2573.8, 2969.5)	2690.2 (2508.2, 2872.1)	2792.5 (2579.5, 3005.4)	2707.7 (2508.2, 2907.3)	2753.1 (2549.9, 2956.3)	2681.6 (2493.3, 2869.9)
Average Energy Consumed (Cal/d)	2341.7* (2128, 2555.5)	2224.1* (2027.8, 2420.4)	2772.9 (2512.4, 2937.4)	2552 (2342.9, 2841.4)	2253.9*^$ (2072.9, 2434.9)	2154.8*^$ (1988.6, 2321)
Average Carbohydrate Consumed (g/kg)	3.25* (1.85, 2.7)	2.9* (1.8, 2.65)	4.42^ (4.32, 4.52)	4.53^ (4.44, 4.62)	2.25*^$ (1.85, 2.7)	2.3*^$ (1.8, 2.65)
Average Carbohydrate Consumed (Cal/d)	886.92* (817.8, 959.2)	831.49* (696.1, 887.8)	1535.9$ (1418.7, 1652.9)	1489.25$ (1379.5, 1599)	756.9*^$ (696.1, 817.7)	723.62*^$ (667.8, 779.4)
Average Protein Consumed (g/kg)	1.63 (1.57, 1.84)	1.95* (1.51, 2.48)	1.61 (1.57, 1.64)	1.65$ (1.61, 1.68)	2.2*^$ (1.4, 2.65)	2.3*^ (2.0, 2.7)
Average Protein Consumed (Cal/d)	562.5 (515.9, 608.1)	727.6* (652.9, 762.1)	558.5 (515.9, 601.1)	541.55 (501.6, 581.5)	740.1*$ (680.7, 799.5)	727.6*$ (652.9, 762.1)
Average Lipid Consumed (g/kg)	0.94^ (0.88, 0.96)	1.06* (0.79, 1.23)	0.89^ (0.87, 0.89)	0.91^ (0.90, 0.93)	1.02*$ (0.7, 1.1)	1.04* (0.7, 1.11)
Average Lipid Consumed (Cal/d)	686.9 (637.46, 755.41)	728.6 (679.8, 799.4)	698.1 (644.9, 751.4)	676.9 (627.46, 726.41)	756.9 (696.1, 817.7)	723.6 (667.8, 779.4)

* Denotes significant difference to Caloric group ($p < 0.05$), $denotes intake significantly different from control ($p < 0.05$), ^ denotes intake significantly different from expected ($p < 0.05$).

differences in the consumption of carbohydrates ($p < 0.01$), lipids ($p < 0.05$) and proteins ($p < 0.05$) between the nutrient balance and Caloric balance groups. Yet non-significant differences were seen in protein or lipid consumption between the Nutrient balance and the control (self-selected diet) group ($p=0.34$) at the end of the 8-week intervention.

The Caloric balance diet significantly overconsumed carbohydrates relative to their required nutrient load ($p < 0.03$) and was closer to what would be expected in an athletic individual not attempting to lose body mass, which was also significantly greater relative to the nutrient balance cohort at week 1 and week 8, table 4, ES of 4.43 (3.3, 5.6) and 4.6 (3.42, 5.81), respectively. Along with the Caloric balance cohort consuming 0.09 g/day less than the expected amount of lipids (1.0 g/kg per day) in the diet. Even though it was within guidelines for g/kg per day, the Caloric balance cohort also consumed significantly less protein per day ($p < 0.05$) than was consumed by the nutrient balance cohort at week 1 and week 8, table 3 and figures 1–2, ES of 4.5 (3.34, 5.67) and 4.68 (3.47, 5.9), respectively.

Nutrient balance diet showed a significant difference in total Caloric intake relative to estimated BMR values, average ($CI_{.95}$) for week 1 -499.2 Cal/d (-558.8, -439.6) and week 8 -526.9 Cal/d (-587.7, -466.1), ($p < 0.01$). This difference also meant that nutrient balance was significantly more effective intervention to reduce Caloric intake relative to the Caloric balance diet ($p < 0.01$), ES of 4.54 (2.88, 6.24) and 4.73 (3.0, 6.5) for weeks 1 and 8, respectively.

Nutrient balance was able to provide participants with a more effective means meeting the nutrient demands for the individual volunteer, figure 2. While at the same time the use of Caloric balance negatively impacted the ability for the participants to meet their nutrient demands, figure 3. This was in particularly seen with meeting protein requirements for the %Cal/d group.

Additionally, see table 3 and 4, the group that followed the nutrient balance showed a significant difference in the change in the relative values of body composition (i.e., percent fat mass, fat-free mass) relative to the Caloric balance group, $p < 0.01$. That continued for absolute changes in fat-free mass, $p < 0.01$, and trends toward being significant for fat mass, $p = 0.10$.

Nutrient balance diet was shown to be more effective for retaining fat-free mass both absolute and relative percentage, ES of 2.85 (2.11, 3.58) and 0.67 (0.50, 0.84), and reducing the relative fat mass, ES of 0.56 (0.40, 0.70), table 3. Yet, since the

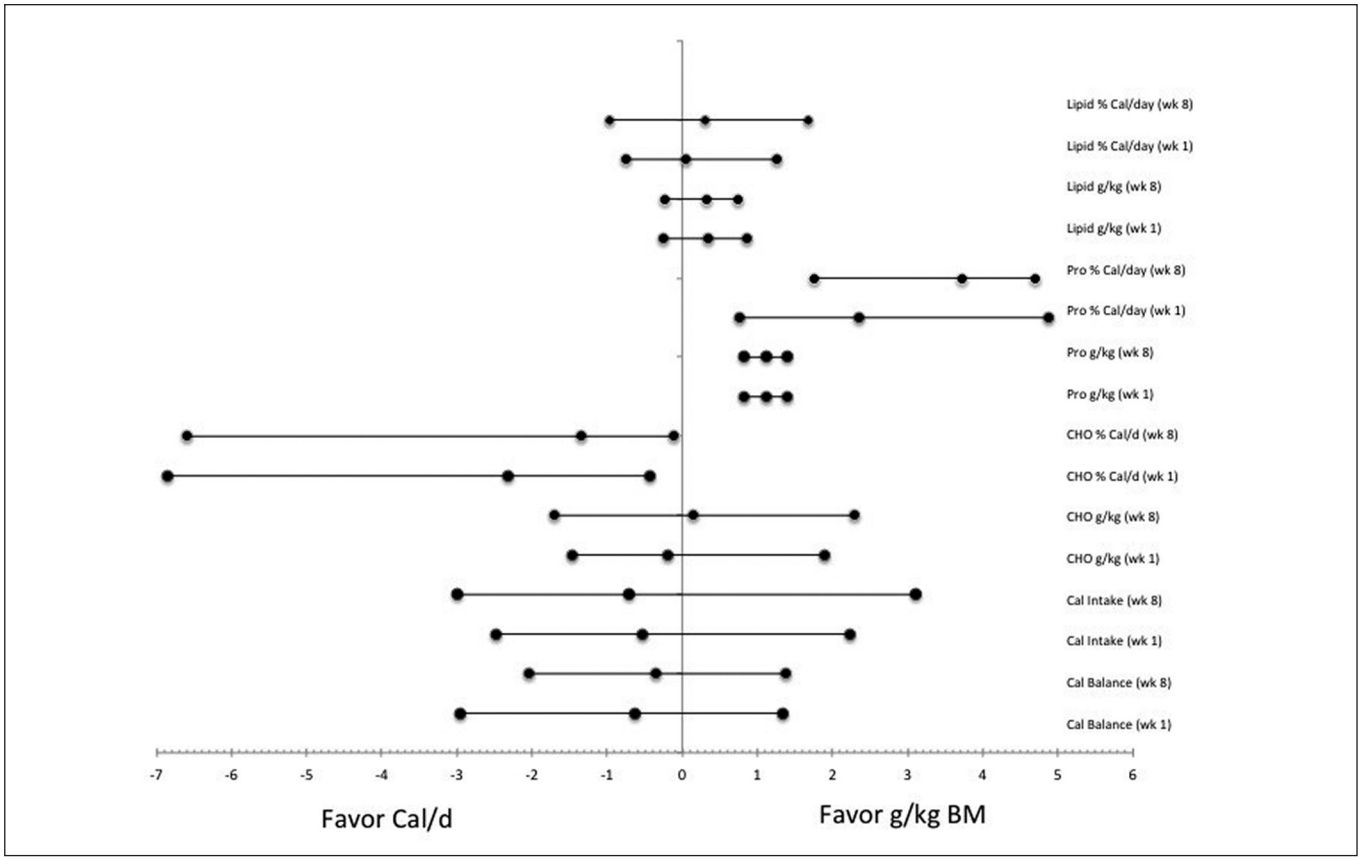


FIG. 1. The favorability for effectiveness in following the nutrient balance versus Caloric balance diet has on meeting energy (% Cal/d) and nutrient consumption (g/kg) from carbohydrates (CHO), proteins (Pro), and lipids requirements during week 1 and week 8 of the 8-week dietary intervention.

CI.95 crosses 0.00, there was no indication for greater effectiveness to induce a change in body mass, ES of 0.23 (-0.23, 0.70).

There were non-significant correlations for the change in body mass for both absolute and relative differences (percent change) to the difference in Caloric balance or for the nutrient balance of each macromolecule. There were only two significant, but moderate, correlations noted for body composition values (e.g., fat mass, fat-free mass). One occurred between nutrient balance for carbohydrates with changes in fat mass ($r = 0.53$). The other with protein balance relative to fat-free mass ($r = -0.49$). Both seen in the nutrient balance group, only.

The subjective nature of the diet also indicated favorability for the nutrient balance versus the Caloric balance for understanding the diet ($\chi^2 = 13.77$, $p < 0.02$) and the ease to follow ($\chi^2 = 8.25$, $p < 0.05$). Yet, there was no difference in the preference to follow a nutrient balance or a Caloric balance diet ($\chi^2 = 3.023$, $p > 0.1$).

DISCUSSION

The use of diet and exercise in concert with each other has become the hallmark for lifestyle intervention related to health issues associated with overfat [1, 2,5, 9, 15, 43–45, 46]. Within these interventions there has tended to be hyperfocus on weight loss as a primary treatment goal. A goal which historically centered on advice for weight loss and maintenance related to the principles of the Caloric balance [12–14, 16, 17]. However, this idea has recently come into question. As we have started to recognize logical flaws in the argument that changes in a mass-less unit (i.e., Calorie) can lead to changes in body mass for an individual [7, 9, 11, 12, 21, 22, 30, 32, 47]. Along with our better understanding that neuroendocrine and regulatory functions have an effect on both body composition (i.e., fat mass, fat-free mass) and total body mass can occur relatively independently of one's energy balance set-point [9, 22, 29, 32], or how energy set-point comes from flaws in determination or estimation either during a period of weight loss or under conditions of weight maintenance [7,15, 23, 26, 47–49]. Not to mention the inherent risk of using weight and mass as reinforcers for the continuation of lifestyle treatment, as the scale can serve as a negative reinforcer, leading to the termination of beneficial lifestyle choices (i.e., better diet and exercise selections) [50–53]. As such, we suggest that it is time to rethink the advice and recommendations that we provide those seeking weight loss or weight maintenance and determine if advice based on a nutrient balance would be more beneficial than the Caloric balance recommendation in a condition where weight loss was a goal of a diet and exercise intervention.

As would be expected based on the previously reported findings [4, 6, 8, 10–12], there was a general trend for all participants

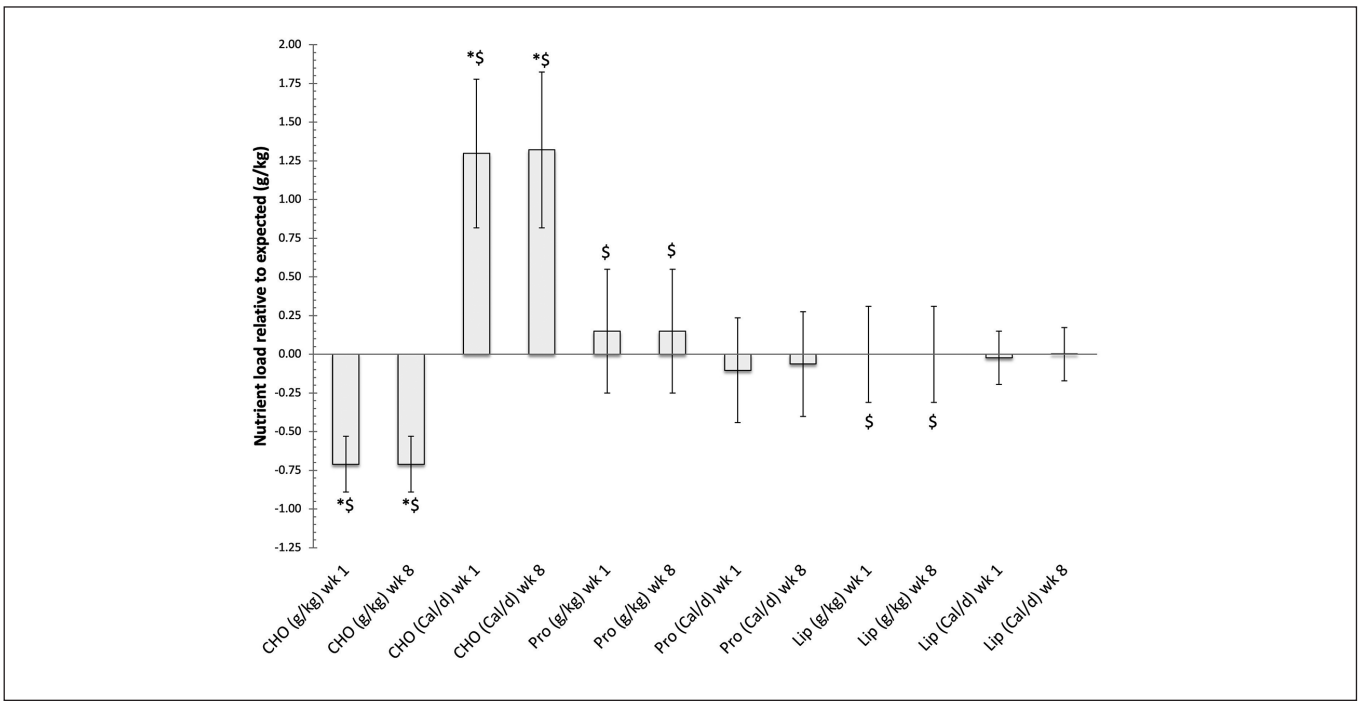


FIG. 2. The relative difference in nutrient load in diet versus expected load (Average+/-SD) while following either a Caloric balance (Cal/d) or nutrient balance (g/kg) diet during week 1 and week 8 of the 8-week dietary intervention. Note: CHO = carbohydrates, Pro = Protein, Lip = Lipids

* Denotes control group significantly different from Caloric balance group, $p < 0.05$

$ Denotes nutrient balance group significantly different from Caloric balance group, $p < 0.05$.

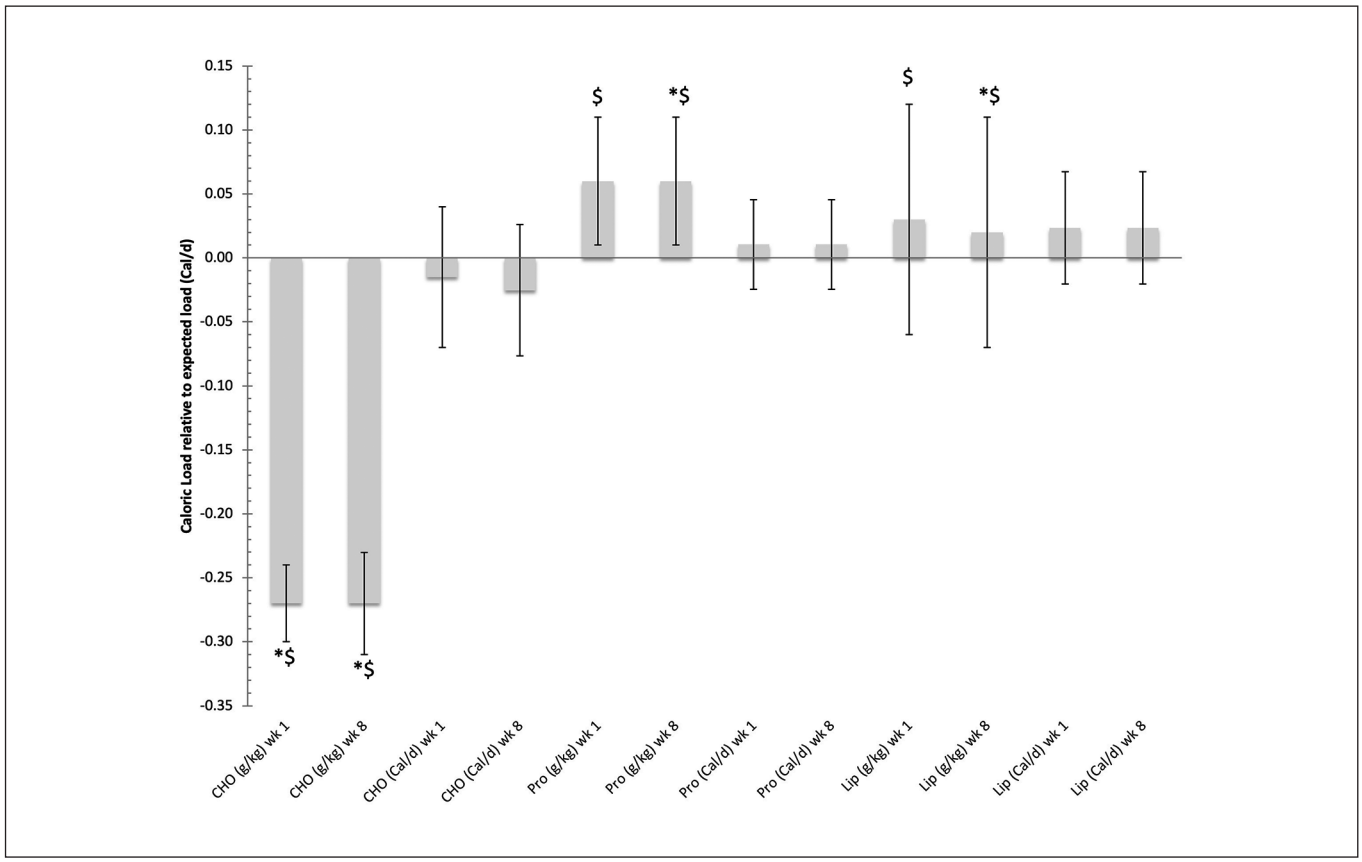


FIG. 3. The relative difference in Caloric load in diet versus expected load (Average+/-SD) while following either a Caloric balance (Cal/d) or nutrient balance (g/kg) diet during week 1 and week 8 of the 8-week dietary intervention. Note: CHO = carbohydrates, Pro = Protein, Lip = Lipids

* Denotes control group significantly different from Caloric balance group, $p < 0.05$

$ Denotes nutrient balance group significantly different from Caloric balance group, $p < 0.05$.

TABLE 4. Changes in the body compositional measure of interest, Average ($CI_{.95}$), based on the nutrient and Caloric balances testing conditions for each group.

Measures of Body Composition	Caloric Balance Group	Nutrient Balance Group	Control Group
Absolute Change Body Mass (kg)	-3.65 (-4.92, -3.22) $	-4.1 (-4.77, -2.63)^$	-3.39 (-5.38, -1.39)
% Change Body Mass	-0.05 (-0.04, -0.06)	-0.04 (-0.03, -0.05)	-0.05 (-0.06, -0.04)
Absolute Change Fat Mass (kg)	-4.08 (-3.92, -5.92)	-5.96 (-5.34, -6.58)*$	-4.18 (-4.06, -5.09)
% Change Fat Mass	-0.06 (-0.05, -0.06)	-0.07 (-0.06, -0.08)^	-0.05 (-0.06, -0.05)
Absolute Change Fat-Free Mass (kg)	0.42 (-0.40, 1.24) $	2.26 (2.02, 2.49)*$	0.29 (0.28, 0.30)
% Change Fat-Free Mass	0.01 (0.00, 0.01)	0.03 (0.02, 0.04)*$	0.00 (-0.01, 0.01)

*Denotes significant difference to Caloric group ($p < 0.05$), ^ denotes trending toward significant difference to Caloric Balance ($p < 0.10$),$Denotes significant difference relative to control ($p < 0.05$).

to experience some degree of weight loss over an 8-week diet and exercise intervention. Yet, there is a small non-significant correlation ($r = 0.08$) between the use of a hypocaloric diet and the change in body mass (e.g., weight loss) or the percentage of mass change ($r = 0.21$), regardless of the method employed. Meaning that while weight loss occurred, the relationship of the negative Caloric balance with weight loss may be independent to each other, even if others have offered for a possible cause-and-effect relationship [3, 15, 26, 49]. Yet this speculation drawn from the findings here is a position that agrees with previously reported findings and a speculation that we may be addressing the treatment concepts incorrectly when discussing dietary roles for altering body mass or health issues associated with overfatness [4, 8, 48].

When these relationships were parsed into the method of dietary intervention, there were correlations noted for alternations on body composition with specific aspects of the dietary interventions. In which, an interesting relationship becomes evident from the results here. Even if the discussion of intervention was to focus on developing a hypocaloric diet, by focusing on nutrient balance (g/kg body mass) one was able to meet minimal requirements for macronutrients (i.e., carbohydrates, proteins, lipids) [7, 9, 29, 54] more effectively than with a Caloric balance focused diet. As consumption of nutrients based on g/kg body mass allowed one to meet metabolic needs, yet at a significantly lower total Caloric density for foods consumed each day. A phenomenon that occurred even though the focus of dietary advice in both interventions was to ensure a set-point within a recognized balance, as the use of Caloric ranges, e.g., 40–60% of Calories from carbohydrates, 10–20% of Calories from proteins, 20–30% of Calories from lipids proposed by the authors advocating for the Caloric balance [7, 29, 32]. While we are addressing the difference in terms of Caloric density, the absolute and relative difference from BMR should not be seen as a contributing factor based on what has become a recognized imbalance required for changes in body mass or body composition [12, 14], nor does the conversation typically relate with the changes to metabolic rates during dietary restriction [13, 15, 25, 45]. This focus ignores the metabolic contributing factors may be at play for the differences seen, independent of the relative Caloric contribution to an energy balance. Yet with limited empirical evidence, the idea deserves future investigation, as once again the overall idea of Caloric balance may be a misguided ideal for treatment for individuals attempting to reverse issues of overfatness or attempting lose unwanted body mass.

Moreover, when consumption of nutrients centered on percentage of Calories per day there was on average a 1.5-fold overconsumption of carbohydrates beyond requirements and was similar to what would be recommended for athletes not attempting to lose body mass [29, 54]. The higher carbohydrate consumption was accompanied with an average 0.4 g/kg under consumption of protein relative to requirements for Nitrogen and protein balance [22, 33]. Given the similar physiological stress of the exercise regimen used, these dietary differences may provide the metabolic rationale for the differences seen in changes in body composition between the dietary intervention groups. As excess carbohydrate, and in particular fructose, consumption is a known signal for lipogenesis (independent of hormonal signals) at adipose tissues throughout the body [28, 55, 56]. While at the same time consumption of protein (amino acids) have been indicated as key regulator in maintaining fat-free mass during weight loss [9, 22, 33]. A key difference in nutrients is very important when a goal of lifestyle modification is to ameliorate health issues of overfatness, and failure to make this shift may be detrimental to that goal, as reduction of fat mass with retention of fat-free mass has been shown to be necessary for obtaining this goal [2, 4, 6, 8, 10, 57].

These later points appear to be key here. As others have reported, alteration of physical activity coupled with changes in body composition and not necessarily a change of body mass should be the focus of intervention programs for those who are overfat [1, 3, 5, 6, 10, 11, 57–59]. Additionally, as we have previously indicated along with other authors, focusing on non-body mass metrics appear to induce continuous employment of interventions in otherwise classified yo-yo'ers [4, 53]. As using non-body mass metrics for goal-setting may encourage continuous use of diet and exercise that otherwise would have been abandoned without supervisory coercion from an authority figure (i.e., medical or fitness professional) [4, 53, 60–62].

Which is furthered by the idea that when seeking long-term interventions there is the need to produce psychological appeasing plan that would lead to a self-selection for continuation beyond the supervision period [6, 63–66]. As such, if dietary interventions are to be incorporated, they must be not only effective but provide mechanisms that would encourage use outside of the intervention and across multiple environments [50, 53, 60, 67, 68]. Something that we have previously reported as it related to the use of exercise for historical yo-yo'ers [4] and was also found here regarding dietary interventions. Subjectively, participants showed a greater likelihood to select a nutrient balance (g/kg) diet versus a Caloric balance diet. Where common rationale given during exit interviews included the ease of not needing to perform calculations to determine Calories contained in foods (as previously performed), ability to learn portion size, and readily prepare meals using portion sizing when following the nutrient balance; while those following the Caloric balance diet offered that the diet plan was onerous in needing to not only weigh food but then compute Calories without knowing if they were obtaining the macronutrients necessary. Moreover, the control group which followed a self-selected dietary plan used dietary intake that mirrored the nutrient balance group's intervention. Taken together, these points indicate that recommendations following a nutrient balance might intrinsically be more appeasing and thus more likely to be followed over the long-term. A point that is necessary should we seek to have short-term interventions establish lifestyle changes that can be carried over beyond the end of the intervention. An issue that has received limited investigations that deserves more attention for long-term benefits.

While we have positive results, there are some limitations to our study. Unfortunately, there has been limited investigation to compare our responses with and the investigation should hopefully serve as foundation for future research on the subject. Dietary information came from diet recall logs that have limitations in themselves. Additionally, we had intervention groups where all participants showed intrinsic motivation to have improvements in their body composition and overall health status that might not allow for generalization to lesser-motivated individuals [52, 67, 69, 70]. Additionally, because of the ethical limitations of not recruiting participants actively attempting to lose weight into a study where they would not be encouraged to lose weight, we did not have a traditional control group (as we allowed participants to participate in the exercise regimen but follow a self-selected

dietary method without advice on ranges of intake for macronutrients to function as our control here) to compare the two dietary interventions with. Moreover, hormone changes were not evaluated here and given the role of the regulatory processes in both body weight and overall health status it is difficult to stipulate unequivocally that nutrient balance would elicit the most beneficial responses to improve overall health status. As such, it is recommended that future research on this subject occur.

CONCLUSIONS

When used in conjunction with an exercise regimen following a diet based on nutrient balance (g/kg body mass) is more effective than following a Caloric balance (% Cal/day) for inducing body compositional changes in individuals who are actively attempting to lose weight. Additionally, those that followed the nutrient balanced condition were more likely to meet nutrient requirements for normal metabolic functions that would ensure body compositional changes would maintain fat-free mass and possibly improve health status. The use of nutrient balance as a diet mechanism appears to have a higher degree of self-selection that should allow for maintaining of the dietary modifications outside of the intervention window. Thus, using nutrient balance of g/kg may be a more effective means to allow body compositional changes and fat loss that may ameliorate issues of overfatness and may be a more valid means to recommend when discussing a dietary intervention to lose, and then maintain the new, body mass.

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Conflict of Interest

The author has no conflict of interest with the publication of the manuscript or findings contained therein.

Authors' Contribution

JEC is responsible for the developing experimental protocol, collection of results and analysis of findings, and drafting of the manuscript.

Availability of data and materials

All methodology for conducting the study is available upon request. Data is available upon request and release of information by study participants for outside analysis.

Ethical Statements and Informed Consent

All procedures for the study were approved by the IRB of Scientific Health: Education and Human Performance prior to recruitment of participants into the study (SH-HP-2019-3A). All participants were fully and completely informed about the risks and rewards for participation in the study, participants did not receive monetary rewards for participation but did receive fuel cards to offset cost for transportation for evaluations. Each participant acknowledged there agreement to participate in the study and were aware that they could leave the study at any time without penalty or recourse.

REFERENCES

1. BoBooth FW, Gordon SE, Carlson CJ, Hamilton MT. Waging war on modern chronic diseases: primary prevention through exercise biology. J Appl Physiol (1985). 2000;88(2):774-787. doi: 10.1152/jappl.2000.88.2.774
2. Clark JE. An overview of the contribution of fatness and fitness factors, and the role of exercise, in the formation of health status for individuals who are overweight. J Diabetes Metab Disord. 2012;11(1):19. doi: 10.1186/2251-6581-11-19
3. Anton SD, Manini TM, Milsom VA, et al. Effects of a weight loss plus exercise program on physical function in overweight, older women: a randomized controlled trial. Clin Interv Aging. 2011;6:141-149. doi: 10.2147/CIA.S17001
4. Clark JE. Periodization of exercise induces long-term weight loss while focusing strictly on improvements in cardiovascular and musculoskeletal fitness for individuals who are overfat. Sport Sci Health. 2018;14(3):517-530. doi: 10.1007/s11332-018-0450-5
5. Strasser B. Physical activity in obesity and metabolic syndrome. Ann NY Acad Sci. 2013;1281:141-159. doi: 10.1111/j.1749-6632.2012.06785.x
6. Thomas SL, Hyde J, Karunaratne A, Kausman R, Komesaroff PA. "They all work…when you stick to them": a qualitative investigation of dieting, weight loss, and physical exercise, in obese individuals. Nutr J. 2008;7:34. doi: 10.1186/1475-2891-7-34
7. Aragon AA, Schoenfeld BJ, Wildman R, et al. International society of sports nutrition position stand: diets and body composition. J Int Soc Sports Nutr. 2022;14(1). doi: 10.1186/s12970-017-0174-y
8. Clark JE. Diet, exercise or diet with exercise: comparing the effectiveness of treatment options for weight-loss and changes in fitness for adults (18–65 years old) who are overfat, or obese; systematic review and meta-analysis. J Diabetes Metab Disord. 2015;14:31. doi: 10.1186/s40200-015-0154-1
9. Clark JE. Diets and Diet Therapy: Diet Supplements for Exercise. In: Ferranti P, Berry EM, Anderson JR, eds. Encyclopedia of Food Security and Sustainability. Vol 2. Oxford, UK; Cambridge, MA, USA: Elsevier; 2019. p. 161-170.doi: 10.1016/B978-0-08-100596-5.21957-4
10. Hall KD. Diet versus exercise in „the biggest loser" weight loss competition. Obesity. 2013;21(5):957-959. doi: 10.1002/oby.20065
11. Strasser B, Spreitzer A, Haber P. Fat loss depends on energy deficit only, independently of the method for weight loss. Ann Nutr Metab. 2007;51(5):428-432. doi: 10.1159/000111162
12. Thomas DM, Martin CK, Lettieri S, et al. Can a weight loss of one pound a week be achieved with a 3500-kcal deficit?

Commentary on a commonly accepted rule. Int J Obes (Lond.). 2013;37(12):1611-1613. doi: 10.1038/ijo.2013.51
13. Brown RE, Canning KL, Fung M, et al. Calorie Estimation in Adults Differing in Body Weight Class and Weight Loss Status. Med Sci Sports Exerc. 2016;48(3):521-526.doi: 10.1249/MSS.0000000000000796
14. Hall KD. What is the required energy deficit per unit weight loss? Int J Obes (Lond.). 2008;32(3):573-576. doi: 10.1038/sj.ijo.0803720
15. Peos JJ, Helms ER, Fournier PA, Sainsbury A. Continuous versus intermittent moderate energy restriction for increased fat mass loss and fat free mass retention in adult athletes: protocol for a randomised controlled trial-the ICECAP trial (Intermittent versus Continuous Energy restriction Compared in an Athlete Population). BMJ Open Sport Exerc Med. 2018;4(1):e000423. doi: 10.1136/bmjsem-2018-000423
16. Pieper C, Redman L, Racette S, et al. Development of adherence metrics for caloric restriction interventions. Clin Trials. 2011;8(2):155-164. doi: 10.1177/1740774511398369
17. Shick SM, Wing RR, Klem ML, McGuire MT, Hill JO, Seagle H. Persons successful at long-term weight loss and maintenance continue to consume a low-energy, low-fat diet. J Acad Nutr Diet. 1998;98(4):408-413. doi: 10.1016/S0002-8223(98)00093-5
18. Smith RL, Soeters MR, Wust RCI, Houtkooper RH. Metabolic Flexibility as an Adaptation to Energy Resources and Requirements in Health and Disease. Endocr Rev. 2018;39(4):489-517. doi: 10.1210/er.2017-00211
19. Zheng H, Lenard NR, Shin AC, Berthoud HR. Appetite control and energy balance regulation in the modern world: reward-driven brain overrides repletion signals. Int J Obes (Lond.). 2009;33 Suppl 2:S8-13. doi: 10.1038/ijo.2009.65
20. Henry CJK. Basal metabolic rate studies in humans: measurement and development of new equations. Public Health Nutr. 2007;8(7a):1133-1152. doi: 10.1079/phn2005801
21. Lam YY, Ravussin E. Analysis of energy metabolism in humans: A review of methodologies. Mol Metab. Nov 2016;5(11):1057-1071. doi: 10.1016/j.molmet.2016.09.005
22. Clark JE. Metabolism and nutrition: integration of concepts in a holistic approach to teaching metabolism. HAPS Educator. 2021;25(2):82-102. doi: 10.21692/haps.2021.026
23. Porter J, Nguo K, Collins J, et al. Total energy expenditure measured using doubly labeled water compared with estimated energy requirements in older adults: analysis of primary data. Am. J. Clin. Nutr. 2019;110:1353-1361. doi: 10.1093/ajcn/nqz200
24. Ramirez-Zea M. Validation of three predictive equations for basal metabolic rate in adults. Public Health Nutr. Oct 2005;8(7A):1213-1228. doi: 10.1079/phn2005807
25. Thurber C, Dugas LR, Ocobock C, Carlson B, Speakman JR, Herman P. Extreme events reveal an alimentary limit on sustained maximal human energy expenditure. Sci Adv. 2019;5(eaaw0341). doi: 10.1126/sciadv.aaw0341
26. Gerving C, Lasater R, Starling J, et al. Predicting energy intake in adults who are dieting and exercising. Int J Obes (Lond.). 2022;46(12):2095-2101. doi: 10.1038/s41366-022-01205-0
27. Curi R, Newsholme P, Marzuca-Nassr GN, et al. Regulatory principles in metabolism-then and now. Biochem. J. 2016;473(13):1845-1857. doi: 10.1042/BCJ20160103
28. Da Poian AT, El-Bacha T, Luz MRMP. Nutrient utilization in humans: metabolism pathways. Nature Education. 2010;3(9):11.
29. Kerksick CM, Arent S, Schoenfeld BJ, et al. International society of sports nutrition position stand: nutrient timing. J Int Soc Sports Nutr. 2017;14:33. doi: 10.1186/s12970-017-0189-4
30. Lambert CP, Frank LL, Evans WJ. Macronutrient considerations for the sport of bodybuilding. Sports Medicine (Auckland, NZ). 2004;34(5):317-327. doi: 10.2165/00007256-200434050-00004
31. Di Francesco A, Di Germanio C, Brenier M, de Cabo R. A time to fast. Science. 2018;362:770-775. doi: 10.1126/science.aau2095
32. Fern EB, Watzke H, Barclay DV, Roulin A, Drewnowski A. The Nutrient Balance Concept: A New Quality Metric for Composite Meals and Diets. PLoS One. 2015;10(7):e0130491. doi: 10.1371/journal.pone.0130491
33. Phillips SM, Fulgoni VL, 3rd, Heaney RP, Nicklas TA, Slavin JL, Weaver CM. Commonly consumed protein foods contribute to nutrient intake, diet quality, and nutrient adequacy. Am. J Clin Nutr. 2015;101(6):1346S-1352S. doi: 10.3945/ajcn.114.084079
34. Feinman RD, Fine EJ. „A calorie is a calorie" violates the second law of thermodynamics. Nutr J. 2004;3(1). doi: 10.1186/1475-2891-3-9
35. Howell S, Kones R. „Calories in, calories out" and macronutrient intake: the hope, hype, and science of calories. Am J Physiol Endocrinol Metab. 2017;313(5):E608-E612. doi: 10.1152/ajpendo.00156.2017
36. Ludwig DS, Ebbeling CB. The Carbohydrate-Insulin Model of Obesity: Beyond „Calories In, Calories Out". JAMA Intern Med. 2018;178(8):1098-1103. doi: 10.1001/jamainternmed.2018.2933
37. Carbone JW, Pasiakos SM. Dietary Protein and Muscle Mass: Translating Science to Application and Health Benefit. Nutrients. 2019;11(5). doi: 10.3390/nu11051136
38. World Health Organization (WHO). Protein and amino acid requirements in human nutrition. Geneva, Switzerland: World Health Organization; 2007. p.9-34.
39. Naska A, Lagiou A, Lagiou P. Dietary assessment methods in epidemiological research: current state of the art and future prospects. F1000Res. 2017;6:926. doi: 10.12688/f1000research.10703.1
40. Serban CL, Chirita-Emandi A, Perva IT, et al. Intake Differences between Subsequent 24-h Dietary Recalls Create Significant Reporting Bias in Adults with Obesity. Applied Sciences. 2022;12(5). doi: 10.3390/app12052728
41. Clark JE. The impact of duration on effectiveness of exercise, the implication for periodization of training and goal setting for individuals who are overfat, a meta-analysis. Biol Sport. 2016;33(4):309-333. doi: 10.5604/20831862.1212974
42. Vasold KL, Parks AC, Phelan DML, Pontifex MB, Pivarnik JM. Reliability and Validity of Commercially Available Low-Cost Bioelectrical Impedance Analysis. Int J Sport Nutr Exerc Metab. 2019;29(4):406-410. doi: 10.1123/ijsnem.2018-0283
43. Byrne NM, Sainsbury A, King NA, Hills AP, Wood RE. Intermittent energy restriction improves weight loss efficiency in obese men: the MATADOR study. Int J Obes (Lond.). 2018;42(2):129-138. doi: 10.1038/ijo.2017.206
44. Mattson MP, Longo VD, Harvie M. Impact of intermittent fasting on health and disease processes. Ageing Res Rev. 2017;39:46-58. doi: 10.1016/j.arr.2016.10.005
45. Rynders CA, Thomas EA, Zaman A, Pan Z, Catenacci VA, Melanson EL. Effectiveness of Intermittent Fasting and Time-Restricted Feeding Compared to Continuous Energy Restriction for Weight Loss. Nutrients. 2019;11(10). doi: 10.3390/nu11102442
46. Seimon RV, Roekenes JA, Zibellini J, et al. Do intermittent diets provide physiological benefits over continuous diets for weight loss? A systematic review of clinical trials. Mol Cell Endocrinol. 2015;418 Pt 2:153-172. doi: 10.1016/j.mce.2015.09.014
47. Kenny GP, Notley SR, Gagnon D. Direct

calorimetry: a brief historical review of its use in the study of human metabolism and thermoregulation. Eur J Appl Physiol. 2017;117(9):1765-1785. doi: 10.1007/s00421-017-3670-5
48. Benton D, Young HA. Reducing Calorie Intake May Not Help You Lose Body Weight. Perspect Psychol Sci. 2017;12(5):703-714. doi: 10.1177/1745691617690878
49. Careau V, Halsey LG, Pontzer H, et al. Energy compensation and adiposity in humans Curr. Biol. 2021;31(20):4659-4666 e4652. doi: 10.1016/j.cub.2021.08.016
50. Baum WM. Purpose and reinforcement. In: Understanding Behaviorism: Behavior, Culture and Evolutions. 3rd ed. Chichester, UK: John Wiley and Sons; 2017. p.81-96
51. Hansen PG, Skov LR, Skov KL. Making Healthy Choices Easier: Regulation versus Nudging. Annu Rev Public Health. 2016;37(1):237-251. doi: 10.1146/annurev-publhealth-032315-021537
52. Micklewright D, Kubis H-P, Albelwi TA, Rogers RD. Carrots for the donkey: Influence of evaluative conditioning and training on self-paced exercise intensity and delay discounting of exercise in healthy adults. PLoS One. 2021;16(10):e0257953. doi: 10.1371/journal.pone.0257953
53. Outland L, Stoner-Smith M. Promoting homeostasis to avoid rebound weight gain in yo-yo dieters. The Internet Journal of Advanced Nursing Practice. 2013;12(1).
54. Kerksick CM, Wilborn CD, Roberts MD, et al. ISSN exercise & sports nutrition review update: research & recommendations. J Int Soc Sports Nutr. 2018;15(1):38. doi: 10.1186/s12970-018-0242-y
55. Hellerstein MK. De novo lipogenesis in humans: metabolic and regulatory aspects. Eur J Clin Nutr. 1999;53(Suppl 1):S53-S65. doi: 10.1038/sj.ejcn.1600744
56. Jensen MD. Adipose tissue and fatty acid metabolism in humans. J R Soc Med. 2002;95(Suppl 42):3-7.
57. Schwingshackl L, Dias S, Strasser B, Hoffmann G. Impact of different training modalities on anthropometric and metabolic characteristics in overweight/obese subjects: a systematic review and network meta-analysis. PLoS One. 2013;8(12):e82853. doi: 10.1371/journal.pone.0082853
58. Bacon L, Aphramor L. Weight science: evaluating the evidence for a paradigm shift. Nutr J. 2011;10:9. doi: 10.1186/1475-2891-10-9
59. Jakicic JM. The effect of physical activity on body weight. Obesity (Silver Spring). 2009;17 Suppl 3:S34-38. doi: 10.1038/oby.2009.386
60. Bandura A. Health promotion by social cognitive means. Health Educ Behav. 2004;31(2):143-64. doi: 10.1177/1090198104263660.
61. Hainer V, Toplak H, Mitrakou A. Treatment modalities of obesity: what fits whom? Diabetes Care. 2008;31 Suppl 2:S269-277. doi: 10.2337/dc08-s265
62. Locke EA, Latham GP. New directions in goal-setting theory. Curr Dir Psychol Sci. 2006;15(5):265-268. doi: 10.1111/j.1467-8721.2006.00449.x
63. Clark JE, Sirois E. Coercion versus self-selection when treating issues of overfatness: A narrative review. Health Educ J. 2023;82(5):475-486. doi: 10.1177/00178969231171886
64. Malott RW. Self Management. In: Herson M, Rosqvist J, eds. Encyclopedia of behavior modification and cognitive therapy. Vol1: Adult clinical applications. Newbury Park, CA: Sage; 2005. p. 516-521.
65. Bindl UK, Parker SK, Totterdell P, Hagger-Johnson G. Fuel of the self-starter: How mood relates to proactive goal regulation. J Appl Psychol. 2012;97(1):134-150. doi: 10.1037/a0024368
66. Olson EA, McAuley E. Impact of a brief intervention on self-regulation, self-efficacy and physical activity in older adults with type 2 diabetes. J Behav Med. 2015;38(6):886-898. doi: 10.1007/s10865-015-9660-3
67. Albelwi TA, Rogers RD, Kubis H-P. Exercise as a reward: Self-paced exercise perception and delay discounting in comparison with food and money. Physiol Behav. 2019;199:333-342. doi: 10.1016/j.physbeh.2018.12.004
68. Clark JE, Sirois E, Wiszniak MF. The impact of bias on developing healthy lifestyles, understanding if personal perspectives impact modeling and recommendations of diet and exercise by educators to their students. Sport Sci Health. 2023;19:1139-1151. doi: 10.1007/s11332-023-01042-2
69. Jancey J, Lee AH, James AP, et al. Long term sustainability of a physical activity and nutrition intervention for rural adults with or at risk of metabolic syndrome. Aust N Z J Public Health. 2020;44(5):421-426. doi: 10.1111/1753-6405.13036
70. Lavoie K, Lenzen SA, Daniëls R, van Bokhoven MA, van der Weijden T, Beurskens A. Disentangling self-management goal setting and action planning: A scoping review. PLoS One. 2017;12(11):e0188822. doi: 10.1371/journal.pone.0188822.

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Blood flow restriction as a post-exercise recovery strategy: A systematic review of the current status of the literature

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ABSTRACT: The aim of this study was to systematically review the current literature on blood flow restriction (BFR) as a post-exercise recovery strategy. Experimental studies investigating the effect of BFR on recovery after exercise were included. Only studies meeting the following inclusion criteria were selected: (a) studies investigating about BFR as a post-exercise recovery strategy in athletes and healthy individuals; (b) the full text being available in English; (c) experimental research study design. Studies that exclusively analyzed BFR as a recovery strategy during the exercise (e.g., recovery strategy between bouts of exercise) were excluded. A literature review was conducted on the PubMed, Cochrane, and Web of Science electronic databases up until May 7th, 2023. The main findings were that (i) 9 studies investigated passive BFR as a post-exercise recovery strategy, which shows a significant lack of research in both team and individual sports (especially in female populations), and only 2 studies used active BFR protocols; (ii) although a high quality range of studies was observed, there were methodological limitations such as BFR interventions that were usually conducted after fatiguing protocols or fitness tests, which may not represent the real exercise (e.g., a sprint session of 6 sets of 50 m may induce muscle damage but it does not represent the demands of a team sport like rugby or soccer); (iii) there is a lack of consistency in BFR protocols (e.g., number of cycles or duration of the occlusion-reperfusion periods) for recovery; (iv) some studies showed beneficial effects while others found no positive or detrimental effects of BFR as a post-exercise recovery strategy in comparison with the control/SHAM group. In conclusion, only 11 studies investigated BFR as a post-exercise recovery strategy and there is not any significant amount of evidence in team or individual sports (especially in female populations). BFR could be a potential post-exercise recovery strategy, but practitioners should use caution when applying this method of recovery for their athletes and clients. In addition, it would be of interest for high performance-related practitioners to have a better understanding of the benefits of BFR interventions combined with either active or passive forms of exercise as a post-exercise recovery strategy.

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INTRODUCTION

The duration, intensity, and frequency of exercise contribute to the nature and magnitude of the training effect [1]. Scientific research has become a key piece in the process of understanding training load, which allows to optimize performance, prevent undertraining and overtraining scenarios, and reduce the injury risk [1, 2]. Athletes may experience high levels of stress because of training load, competition demands, travel or lifestyle [3]. Sports such as soccer, basketball, or hockey require high-intensity and multidirectional movements over extended periods during the game, which induce a physiological and metabolic stress [4, 5]. For example, professional soccer players may run 10–12 km per match, being 5–10% at high-intensity [6–8]. Specifically, performing high-intensity accelerations or decelerations may have a significant impact on the players' mechanical load [9] and muscle damage [10]. Also, these actions are positively correlated with the rating of perceived exertion [11] and neuromuscular fatigue [9].

Currently, athletes are often required to play during periods of fixture congestion, which is defined as a minimum of two successive bouts of match-play with recovery periods of less than 96 hours [12]. Contemporary sport has led to an increase in the number of domestic and international competitions and some of them require playing overtime periods as well [12]. For instance, performance deteriorates 1 to 4 days after a soccer game and acute inflammatory responses were observed with (1) a post-match peak of leukocyte count, cortisol, and cytokines; (2) a 24-hour peak of delayed-onset muscle soreness, C-reactive protein, and thiobarbituric acid reactive substances; (3) a 48-hour peak of creatine kinase, lactate dehydrogenase, and protein carbonyl; and (4) 72-hour peak of uric acid [13].

This has serious implications for sport performance practitioners since players might not achieve complete physical performance recovery during congested schedules [14].

In consequence, efficient recovery strategies are necessary and thus, the use of blood flow restriction (BFR) has been suggested as a strategy to accelerate recovery processes [15]. BFR consists of restricting arterial inflow and completely restricting venous outflow due to the application of a tourniquet or inflatable cuff around the most proximal region of the working upper and/or lower limbs [16, 17]. The cuff's inflation generates a gradual compression of the vasculature underneath the cuff so the blood flow to structures distal the cuff is restricted, but it more severely affects venous outflow from under the cuff that is proposed to also impede venous return [16]. This compression implies a hypoxia condition within the muscle tissue [18, 19]. From a practical perspective, recent studies recommended the use of BFR combined with various forms of exercise (e.g., resistance exercise, aerobic exercise, or passively) even though other factors such as intensity, volume, restriction time, amount of cuff pressure, size, and cuff material) need to be considered [16, 20, 21].

Although a better knowledge of the underlying mechanisms through which BFR may positively impact post-exercise recovery, the rationale behind the use of this technique may be related to both metabolic and vascular pathways [22]. BFR interventions were initially developed in order to decrease the damage caused to internal organs by ischemia and reperfusion [22, 23] but it may be a useful strategy for performance purposes [22]. For example, the primary mechanisms by which BFR is thought to stimulate muscle growth may include metabolic accumulation which leads to a subsequent increase in anabolic growth factors, fast-twitch fiber recruitment, and more protein synthesis through the mammalian target of rapamycin (mTOR) pathway [24]. In addition, nitric oxide synthase-1 (NOS-1), heat shock proteins, and myostatin have also been shown to be affected by an occlusion stimulus [24]. Also, a different study found that the recovery of functional outcomes after applying BFR post-exercise may be due to a lower decrease in creatine kinase and muscle soreness [25].

However, the benefits of BFR as a strategy to accelerate post-exercise recovery processes are still unclear. Although another review was published in 2020, an update is necessary given the large number of sports performance-related practitioners that are currently using BFR for recovery [15]. In addition, one might wonder if the conclusion of such review (i.e., effective intervention to accelerate performance recovery) is strong enough from a practical application perspective based on the characteristics of the studies that were included. Given that research on the effects of BFR as a recovery strategy is scarce, the aim of this study was to systematically review the current literature on BFR as a recovery strategy in order to investigate the effect of BFR protocols, which were performed after exercise in athletes and healthy individuals, on recovery-related parameters.

MATERIALS AND METHODS

Study design

A literature review was conducted on the PubMed, Cochrane, and Web of Science electronic databases up until May 7th, 2023. This systematic review was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [26] and considerations for systematic reviews in sport sciences [27]. The following search strategy by title and abstract was designed:

["Blood flow restriction" OR "BFR" OR "occlusion" OR "ischemic conditioning" OR "ischemia-reperfusion"] AND ["sport*" OR "exercise" OR "athlete" OR "player" OR "resistance train*" OR "strength train*"] AND ["recovery" OR "cool-down" OR "post-conditioning" OR "post-session" OR "post-training" OR "post-workout" OR "post-match" OR "post-game" OR "post-exercise"].

Study selection

Only studies meeting the following inclusion criteria were selected: (a) studies investigating about BFR as a post-exercise recovery strategy in athletes and healthy individuals; (b) the full text being available in English; (c) experimental research study design. Studies that exclusively analyzed BFR as a recovery strategy during the exercise (e.g., recovery strategy between bouts of exercise) were excluded.

Two independent reviewers selected the studies based on the inclusion and exclusion criteria. All references were stored in the Mendeley reference management system (Elsevier, Amsterdam, The Netherlands). Since duplicates were observed, these were removed. Then, the titles and abstracts were examined. Finally, articles were accessed full text and only studies meeting the inclusion criteria were included in the study. If there was any disagreement between the reviewers, a third collaborator was involved in the decision-making process. A graphical description of the selection process may be observed in Figure 1.

Data abstraction

The following data were extracted from each study by the reviewers: authors, year of publication, sample size, sample characteristics (e.g., age, gender, or body composition variables), type of exercise protocol or activity, characteristics of the BFR intervention, outcome variables (i.e., recovery-related parameters), and main findings regarding changes in these recovery-related variables after the BFR intervention.

Methodological quality assessment

The methodological quality of each study was assessed using the PEDro scale [28] if the study had an experimental design with randomly assigned experimental and control groups while the MINORS scale [29] was used for non-randomized trials. The PEDro scale consists of 11 items, which include: eligibility criteria, random allocation, concealed allocation, similarity at baseline, subject blinding, therapist blinding, assessor blinding, > 85% follow-up, intention-to-treat analysis, between-group statistical comparison, and point and

variability measures [28]. The first item was not included to calculate the total PEDro score as suggested by previous research, so the maximum score was 10 points (low quality: <3; moderate quality: 4–5; high quality: 6–10) [30–32]. When it comes to the MINORS scale, it consists of 12 items (i.e., a clearly stated aim, inclusion of consecutive patients, prospective collection of data, endpoints appropriate to the aim of the study, unbiased assessment of the study endpoint, follow-up period appropriate to the aim of the study, loss to follow up less than 5%, prospective calculation of the study size, adequate control group, contemporary groups, baseline equivalence of groups, and adequate statistical analysis), being the last 4 items specifically for comparative studies [29]. Each item was scored on a scale of 0–2 (0: not reported; 1: reported but inadequate; 2: reported and adequate) for a total score of 24 points (low quality: <8; moderate quality: 9–16; high quality: 17–24) [32]. Any hesitation in the scoring process was resolved by consensus between two independent researchers.

RESULTS

Study selection

A total of 1947 studies were identified following the search strategy. Duplicates were removed and a total of 656 titles and abstracts were examined. Of these, 46 were selected for full-text screening. Since 35 studies did not meet the inclusion criteria, 11 studies were selected for the study (Figure 1).

Characteristics of the selected studies

Table 1 shows the characteristics of the selected studies. These studies have included a total of 206 participants, being 195 male and 11 female participants. The studies collected data from team sports (i.e., soccer and rugby) [33–36], individual sports (i.e., cycling and judo) [37, 38], and other recreational activities in general (i.e., trained/active/healthy individuals) [25, 39–42]. The average age group in these studies ranged between ~17 and ~32 years old.

The exercise protocols were not standardized considering that each study used a different method. However, all BFR interventions were conducted passively with the participant on a supine position and on the proximal portion of the thigh, except for 2 studies that placed the cuffs with active recovery protocols [36, 41]. There were 5 studies that used bilateral BFR [25, 33, 34, 36, 38] while 6 studies used unilateral BFR [35, 37, 39–42]. The cuffs for the experimental groups were usually inflated at 220 mmHg [25, 35, 39, 40] or 50 mmHg above systolic blood pressure [33, 37, 38]. Two studies used 60% of individually calculated pressures [34, 36] and one study used 80% of individual's resting arterial occlusion pressure [41]. The cuffs for the control/SHAM groups were usually inflated between 15- and 20-mmHg.

Specifically, the BFR protocols consisted of a total of 3 cycles of 5-minute occlusion followed by 5-minute reperfusion or 2 cycles of 3-minute occlusion followed by 3-minute reperfusion [34, 39, 40, 42]. Another study [37] tried two different BFR protocols: 2 cycles of

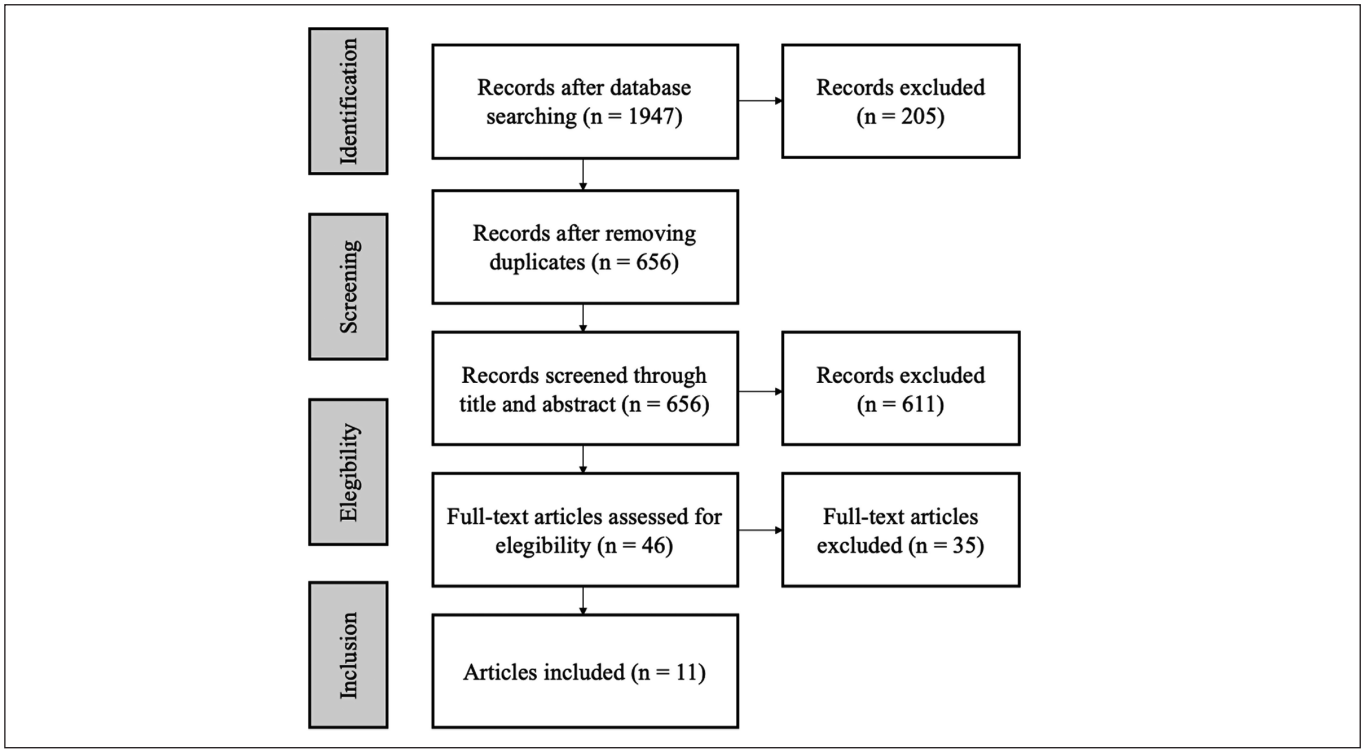


FIG. 1. Flowchart of the selection process.

Table 1. Characteristics of included studies.

Reference	Population	Sample size	Sample characteristics	Exercise protocol	BFR intervention	Outcome variables
Arriel et al. (2018) [37]	Cyclists	*n* = 28 (male) Post-exercise ischemic conditioning 2 × 5 group, n = 7 Post-exercise ischemic conditioning 5 × 2 group, n = 7 SHAM 2 × 5 group, n = 7 SHAM 5 × 2 group, n = 7	Post-exercise ischemic conditioning 2 × 5 group: Age = 27.6 ± 4 years old Height: 1.77 ± 0.05 m Weight: 80.3 ± 10.7 kg Post-exercise ischemic conditioning 5 × 2 group: Age = 25.0 ± 4.5 years old Height: 1.76 ± 0.06 m Weight: 76 ± 8.7 kg SHAM 2 × 5 group: Age = 27.8 ± 4.2 years old Height: 1.76 ± 0.02 m Weight: 77.8 ± 7.5 kg SHAM 5 × 2 group: Age = 28.3 ± 2.3 years old Height: 1.75 ± 0.02 m Weight: 74.6 ± 6.2 kg	Maximal incremental cycling test	Post-exercise ischemic conditioning 2 × 5 group (50 mmHg above systolic blood pressure): 2 cycles of 5 min occlusion / 5 min reperfusion. Post-exercise ischemic conditioning 5 × 2 group (50 mmHg above systolic blood pressure): 5 cycles of 2 min occlusion / 2 min reperfusion. SHAM 2 × 5 group (20 mmHg above systolic blood pressure): 2 cycles of 5 min occlusion / 5 min reperfusion. SHAM 5 × 2 group (20 mmHg above systolic blood pressure): 5 cycles of 2 min occlusion / 2 min reperfusion. 5 min after the end of the test, participants adopted a supine position and the occlusion was performed with a blood pressure cuff (77.0 cm length × 21.5 cm width), which was applied unilaterally to the sub-inguinal region of the upper thigh.	Before the incremental test: Perceived recovery scale Muscle soreness Creatine Kinase During the incremental test: Mean heart rate Maximum heart rate Heart rate recovery Peak power output Peak power output Rating of perceived exertion
Beaven et al. (2012) [40]	Recreationally trained individuals	*n* = 14 (10 males and 4 females) 2 groups of participants following a crossover design: experimental (occlusion) group and control group	Age: 32.0 ± 7.0 years old Body mass: 76.4 ± 12.9 kg	Exercise protocol involving lower-body strength test, power test and repeated sprints	Participants adopted a supine position immediately after the exercise protocol. Unilateral occlusion cuff (BJ Dare Medical Equipment, China), which was placed on the proximal portion of the leg. The cuff had a pneumatic bag along its inner surface which was connected to a pressure gauge that was manually inflated to either 15 mmHg (control group) or 220 mmHg (BFR group) for 3 min. The cuff was alternated with the contralateral leg for an additional period of 3 min. This cycle was repeated twice for a total of 12 min, so both legs had BFR intervention for 6 min per leg.	From CMJ and Squat Jump: Maximum and mean values for eccentric and concentric peak power, peak velocity, and peak acceleration Maximum and mean values for concentric work Jump height Time to peak power and velocity From other tests: CMJ power, squat jump power, leg press maximum strength, leg press average strength, leg press total power, leg press work, leg press velocity, and cumulative sprint times
Castilla-López & Romero-Franco (2023) [36]	Youth soccer players	*n* = 40 (male) 2 groups of participants following a crossover design: experimental (occlusion) group and control group	Age = 17.1 ± 0.8 years old Height: 1.77 ± 0.06 m Weight: 70.2 ± 7.0 kg	Match (inclusion criteria: > 50 minutes played)	Active BFR protocol with players completing a recovery session which consisted of 5-minute running warm-up, 6 high-speed running actions (intensity: 60–70%), and interval drill in the form of rondos with the ball (9 v 2 – 3 × 5 minutes, rest: 90 seconds). This protocol was applied 24 hours after the match. Participants wore the Occlusion Cuff® (Belfast, United Kingdom) with a wrap size (7 × 82 cm in length). The cuffs were placed below the gluteal line in both legs and inflated at the same time. Participants adopted an upright position to set the blood pressure to ~60% of the limb occlusion pressure. The elastic wraps were deflated for 90 seconds between drills.	CMJ height RPE Hooper index
Ceylan et al. (2023) [38]	Elite judo athletes	*n* = 13 (male) 2 groups of participants following a randomized crossover design: experimental group and placebo group	Age: 18.6 ± 0.9 years old Height: 1.74 ± 0.05 m Body mass: 72.4 ± 7.1 kg	Special judo fitness test	Participants adopted a supine position and a pneumatic cuff (77.0 cm length × 21.5 cm width; Riester 5255, Rudolf Riester) was placed around the upper thigh. It was inflated to 50 mmHg above the systolic blood pressure to inhibit arterial flow for 5 min. 3 cycles for each leg with 5 min of reperfusion for each BFR episode. The BFR group achieved a mean pressure of 180 (12) mmHg while the control group was set at 20 mmHg.	Heart rate Lactate Systolic and diastolic blood pressure (mmHg) CMJ height Handgrip strength Muscle soreness

Table 1. Continue.

Reference	Population	Sample size	Sample characteristics	Exercise protocol	BFR intervention	Outcome variables
Daab et al. (2021) [33]	Semi-professional soccer players	$n = 12$ (male) 2 groups of participants following a randomized crossover design: experimental group and placebo group	Age = 23.0 ± 1.0 years old Height= 1.79 ± 0.01 m Body mass = 77.9 ± 3.4 kg	Loughborough intermittent shuttle running test	Participants adopted a supine position, and a pneumatic cuff (77.0 cm length × 21.5 cm width) was placed on the proximal portion of the thigh. The protocol consisted of three cycles of 5-minute occlusion and 5-minute reperfusion. Bilaterally vascular occlusion was applied to the BFR group at a pressure of 50 mmHg above the systolic blood pressure and 0 mmHg during the reperfusion. The pressure for the placebo group was set at 20 mmHg.	Squat jump height CMJ height Maximal voluntary contraction of quadriceps (N) 20 m sprint speed Creatine Kinase Lactate dehydrogenase C-reactive protein Muscle soreness
Garcia et al. (2017) [35]	Amateur rugby players	$n = 8$ (male) 2 groups of participants following a randomized crossover design: experimental group and control group	Age = 24.0 ± 4.0 years old Height= 1.79 ± 0.05 m Body mass = 88.0 ± 9.0 kg	8 drills (5 min work per set followed by 30 s passive rest): jumps, skill passing, position scrum with member alternation, slalom agility sprints, rest and hydration, dragon walks, slalom agility sprints, and 20 m sprint	Participants adopted a seated position, and a pneumatic cuff (96 cm length × 13 cm width) was placed on the sub-inguinal portion of the thigh. The protocol consisted of three cycles of 5-minute occlusion, alternated with 2 minutes of reperfusion. The occlusion and reperfusion phases were alternated between thighs. Occlusion was applied to the BFR group at a pressure of 220 mmHg and 0 mmHg during the reperfusion. No cuffs were applied to the control group, which sat passively for 21 minutes.	T-test time CMJ height Continuous CMJ (30 s) height Perceived recovery scale
Lillquist et al. (2023) [42]	Healthy individuals	$n = 20$ (male) 2 groups of participants following a randomized crossover design: experimental group and control group	Age = 21.0 ± 2.8 years old Height= 1.81 ± 0.07 m Body mass = 81.9 ± 13.7 kg	100 box drop jumps (10 sets × 10 repetitions). 10 seconds of recovery was allowed between drops jumps and 1 minute between sets.	BFR was applied with Delfi Portable Tourniquet System (PTS) ii and contoured (12 cm wide), inflation cuff (Delfi Medical Innovations, Inc., Vancouver, BC, Canada). The cuff was placed on the proximal portion of the thigh in each leg and the individualized tourniquet pressure was set as a percentage of limb occlusion pressure, where venous blood flow was completely restricted. session. ~198 mmHg was applied directly to one leg. Post-exercise ischemic conditioning was carried out for 3 sets of 5 minutes on the direct leg (rest between sets: 5 minutes). During the rest period, the opposite leg had 20 mmHg of pressure for 3 sets of 5 minutes per leg (rest between sets: 5 minutes). The cuff was inflated to 20 mmHg for the control group for 3 sets of 5 minutes per leg (rest between sets: 5 minutes).	Muscle soreness Knee flexion and extension peak torque
Northey et al. (2016) [39]	Recreationally trained individuals	$n = 12$ (male) 3 groups of participants following a randomized crossover design: occlusion group, sequential intermittent pneumatic compression, and passive control group	Age: 24.0 ± 6.3 years old Height: 1.80 ± 0.09 m Body weight: 84.8 ± 9.6 kg	100 back squats (10 sets × 10 repetitions) with an initial load of 70% 1RM. If the participant was not able to complete the target number of repetitions without assistance, the load was reduced by 5% of the initial load. There was a 3-minute recovery period between sets.	Occlusion group: participants adopted a supine position with a unilateral occlusion cuff (Flexiport Reusable Blood Pressure Cuff, Welch Allyn, Australia), which was placed on the proximal portion of the leg and inflated to 220 mmHg. 3 min later, the cuff was alternated to the other leg for 3 min, before being repeated on each leg (12 min in total). Sequential intermittent pneumatic compression: participants adopted a supine position with Recovery Boots (RecoveryPump, LLC., USA), which were placed on each leg. The chambers were inflated to a pressure of 80 mmHg with a deflation time of 15 seconds for 45 min. Passive control group: 45 min in a supine position.	Concentric peak isokinetic torque of the quadriceps CMJ height Squat jump height Perceived recovery status Muscle soreness

Table 1. Continue.

Reference	Population	Sample size	Sample characteristics	Exercise protocol	BFR intervention	Outcome variables
Page et al. (2017) [25]	Recreationally active individuals	$n = 16$ (male) 2 groups of participants: Experimental group, n = 8 SHAM group, n = 8	Age: 22.6 ± 2.8 years old Height: 1.79 ± 0.06 cm Body mass: 75.5 ± 8.1 kg	100 drop jumps (60-cm height box)	Participants adopted a supine position and bilateral arterial occlusion cuffs were placed on the proximal portion of the thigh (14.5 cm width; Delfi Medical Innovations, Vancouver, Canada). The inflatable cuffs were connected to a pressure gauge and were automatically inflated to 220 mmHg (BFR group) for 5 min followed by 5 min reperfusion. The pressure for the SHAM group was set at 20 mmHg. This procedure was repeated three times (i.e.,15 min of BFR and 15 min of reperfusion).	Creatine kinase Thigh circumference Muscle soreness CMJ height Maximal isometric voluntary contraction
Williams et al. (2018) [34]	Academy rugby union players	$n = 24$ (male) 2 groups of participants following a randomized crossover design: experimental group and control group	Age: 21.8 ± 3.0 years old Height: 1.85 ± 0.09 m Body mass: 96.9 ± 10.1 kg	Sprint session (6 × 50 m)	Participants adopted a supine position and occlusion cuffs (11 cm; Sports RehabTourniquet, Sportsrehab) were applied to the proximal point of the thighs. The cuff was manually inflated to 15 mmHg for the control group while the BFR group's pressure was set at 60% of individually calculated pressures (171–266 mmHg). The protocol consisted of 2 cycles of 3-min occlusion and 3-min reperfusion.	Salivary testosterone Salivary cortisol Blood lactate Creatine Kinase Perception of muscle soreness Peak power output CMJ height
Wong et al. (2022) [41]	Healthy individuals	$n = 19$ (12 male and 7 female) Each arm was randomly assigned to BFR group or SHAM. Each participant completed both conditions.	Age: 22.0 ± 3.0 years old Height: 1.71 ± 0.09 m Body mass: 76.9 ± 16.4 kg	4 sets × 90 bilateral biceps curls (Male: 4.08 kg; Women: 2.18 kg). If participants could not keep a 60-beat per minute pace, a lighter load was used. Rest: 30 s between sets	Active BFR protocol with both arms simultaneously performing 30 repetitions of biceps curls, followed by 3 sets of 15 repetitions. Rest: 30 seconds of rest between sets. 5 cm nylon cuffs (SC5 Hokanson, Bellevue, WA) were placed on the most proximal portion of both arms. Each arm was randomly assigned to either the blood flow restriction or the SHAM treatment. The cuff of the BFR group was inflated to 80% individual's resting arterial occlusion pressure while the other arm served as a sham (0 mmHg). The BFR intervention was performed 5 min and 24 hours after the fatiguing protocol.	Each arm's maximal isometric torque

Note: BFR = Blood flow restriction; CMJ = Countermovement jump; RM = repetition maximum; RPE = rating of perceived exertion

5-minute occlusion followed by 5-minute reperfusion and 5 cycles of 2-minute occlusion followed by 2-minute reperfusion. Also, two studies included active BFR protocols for recovery (e.g., BFR during the recovery session 24 hours post-match or active protocols including 30 repetitions of biceps curls without external load, followed by 3 sets of 15 repetitions).

Regarding the outcome variables that could be associated with the recovery status, the studies analyzed parameters related to muscle soreness, perceived recovery status, perceived effort, neuromuscular function (e.g., strength, speed, or power), and physiological markers (e.g., creatine kinase, salivary cortisol, lactate dehydrogenase, or C-reactive protein).

Finally, the methodological quality assessment showed that the PEDro scores for the randomized trials [25, 33–37, 39–42] were ~7.6 (range 6–10), which may be considered as high quality. Also, only one of the studies followed a non-randomized protocol, so the MINORS scale was used and the score was 21 out 24, which represents a high quality score [40]. The criteria with the lowest scores in both scales were those related to random allocation, concealed allocation, and assessor/therapist/participant blinding.

Main findings related to BFR interventions in team sports

Two studies analyzed the effect of BFR on the recovery process in semiprofessional soccer players [33] and youth players [36], and two BFR interventions were conducted on academy and amateur rugby union players [34, 35]. The youth soccer players did not get beneficial effects from the active BFR protocol for recovery of jumping ability or perceived wellness (i.e., Hooper index). In fact, the BFR group, which wore the cuffs during the recovery session, had increased ratings of perceived exertion right after the session [36]. However, the study with semiprofessional soccer players found that the BFR group got to attenuate the increases in muscle damage markers and muscle soreness in comparison with the placebo group [33]. Also, the BFR group got to attenuate the decrease of squat jump and CMJ height in 24 hours [33]. In addition, BFR could accelerate post-exercise recovery of sprint performance and maximal voluntary contraction of

quadriceps [33]. Nevertheless, BFR had no effect on perceived recovery, neuromuscular or physiological markers after the exercise protocol and BFR in the academy or amateur rugby players [34, 35].

Main findings related to BFR interventions in individual sports

One study analyzed the effect of BFR on the recovery process in cyclists with ~3.2 years of training experience [37] and another BFR intervention was conducted on elite judo athletes [38]. Both studies found beneficial effects of BFR as a recovery strategy compared to the SHAM groups. For example, BFR prevented a decrease in performance 24 hours after the incremental cycling test, which may be due to a late effect of the BFR [37]. Creatine Kinase and muscle soreness were similar between the groups of cyclists (baseline and 24 hours post exercise) [37]. However, perception of recovery scores showed that the post-exercise ischemic conditioning groups felt more tired 24 hours after BFR [37].

In judo athletes, the BFR group had a decrease in heart rate at 30- and 60-minutes during recovery [38]. In addition, CMJ performance in the BFR group was better at 60 minutes compared to the control group [38]. Moreover, the BFR group reported lower muscle soreness than the control group [38].

Main findings related to BFR interventions in recreationally active individuals

The use of BFR as a recovery strategy has been investigated in other recreational activities (i.e., trained/active/healthy individuals) [25, 39–42].

One of the studies showed that BFR interventions may accelerate the recovery process since a return to pre strength levels 24 hours earlier than the SHAM group was observed [25]. This recovery of functional outcomes may be due to a decrease in the inflammatory response observed after strenuous eccentric exercise because of reduced creatine kinase and muscle soreness [25]. In this line, a different study found that BFR interventions had a significant but marginal effect on mitigating perceptual quadriceps muscle soreness ratings 24 hours after the drop jump fatiguing protocol; however, there was no effect on muscle strength [42].

However, another study concluded that the occlusion and sequential intermittent pneumatic compression groups did not further improve recovery of muscular performance after a fatiguing exercise protocol compared to a passive control group [39]. Perceived recovery and muscle soreness were not significantly different in comparison with the control group [39]. Nonetheless, participants reported that they preferred the "novel recovery interventions" [39].

A third study on recreationally active individuals observed that BFR intervention had positive and negative effects on specific variables related to the neuromuscular function [40]. On the one hand, BFR had a positive effect on the average squat jump height right after the intervention compared to the control group [40]. Specifically, most positive effects of BFR were found 24 hours after the intervention [40]. For example, there was a likely positive effect on the rate of recovery of maximal power production (W) in the squat jump in comparison with the control group. Regarding the squat jump, there were also large positive effects of the BFR on recovery of eccentric peak power and eccentric peak acceleration. Also, the BFR had a beneficial effect in comparison with the control condition on the mean concentric and eccentric peak velocity during CMJ. Moreover, the total power generated in the leg press test showed better results for the BFR group 24 hours post intervention. In addition, the BFR group recovered at a better rate in comparison with the control group when the cumulative 10 m and 40 m sprint times were analyzed 24 hours after the intervention.

On the other hand, there were likely detrimental effects on mean eccentric peak velocity and acceleration in the CMJ and mean eccentric peak power in the squat jump immediately after the BFR intervention [40]. Other immediate effects were generally unclear or trivial [40]. Likely detrimental effects of the BFR were found in the change in rate of recovery on the mean concentric work generated in the squat jump 24 hours after the intervention [40]. Other delayed effects were generally unclear [40].

Finally, another study used an active BFR protocol [41] in which each arm was randomly assigned to either the blood flow restriction or the SHAM treatment (0 mmHg). The BFR intervention was performed 5 min and 24 hours after the fatiguing protocol, but the results indicated that this type of intervention did not improve recovery [41].

DISCUSSION

The purpose of this study was to review the current literature on the use of BFR as a post-exercise recovery strategy. The main findings were that (i) only 9 studies investigated BFR as a post-exercise passive recovery strategy, which shows a significant lack of research in both team and individual sports (especially in female populations), and only 2 studies used active BFR protocols; (ii) although a high quality range of studies was observed, there were methodological limitations such as BFR interventions that were usually conducted after fatiguing protocols or fitness tests (e.g., incremental cycling test or sprint tests), which may not represent the real exercise (e.g., a sprint session of 6 sets of 50 m may induce muscle damage but it does not represent the demands of a team sport like rugby or soccer); (iii) there is a lack of consistency in BFR protocols (e.g., number of cycles or duration of the occlusion-reperfusion periods) for recovery; (iv) some studies showed beneficial effects while others found no positive or detrimental effects of passive BFR as a post-exercise recovery strategy in comparison with the control/SHAM groups.

This review observed that there is lack of research in team and individual sports. Only 2 studies were conducted in team sports like soccer or rugby, and only 1 study for individual sports like judo or cycling, so it is difficult to draw solid conclusions about the benefits of BFR as a post-exercise recovery strategy. In addition, the methodology of these investigations has several limitations such as the sample characteristics (e.g., lack of research on multiple populations like

professional and amateur athletes, or female samples), assessor/therapist/participant blinding (perhaps due to the nature of the intervention), or the exercise protocols that have been used to induce fatigue. For instance, one of the studies in soccer players used the Loughborough intermittent shuttle running test, which is a field test that simulates the activity pattern of soccer [43] However, actions such as running backwards, jumping, or time in possession of ball that are not included and some of these activities along with tackles and sudden changes of direction require eccentric contractions, which may increase the neuromuscular demands imposed by match in comparison with Loughborough intermittent shuttle test [44]. In addition, this kind of data collections is not contextualized to elite level scenarios, in which soccer players may experience successive matches (e.g., less than 96 hours between games) in congested calendars [12]. In consequence, research on players which use BFR as a recovery strategy and is conducted in the realm of current soccer is necessary. Furthermore, there may be different forms of recovery (e.g., active and passive, or post-training session and post-match) and different variables that represent the level of recovery. Based on the studies included in this review, recovery may be understood from multiple perspectives (e.g., changes in muscle damage parameters, perceived recovery or muscle soreness, neuromuscular performance in readiness tests such as countermovement jump or isometric voluntary contractions, etc.) and different recovery protocols have been included, which may explain why some studies got positive effects and others did not.

Although BFR interventions were usually conducted with the participant on a supine position and on the proximal portion of the thigh, this literature review also found that there is a lack of consistency in BFR protocols for recovery. For example, the cuffs for the experimental groups were usually inflated at 220 mmHg [25, 39, 40] or 50 mmHg above systolic blood pressure [33, 37, 38]. In this regard, a previous review suggested that absolute tourniquet pressures from 200 to 250 mmHg have been often used regardless of body size [45]. One of the studies explained that they use a novel technology for BFR which determined the individual personal tourniquet pressure as a percentage of limb occlusion pressure, where venous blood flow was completely restricted [42]. There were 2 studies using 60% of individually calculated pressures [34, 36] and another study using 80% of individual's resting arterial occlusion pressure [41]. This shows that to date, there has been a lack of standardization of pressure for BFR and recovery. A previous study suggested that it might be recommended to establish pressures based on measurements of arterial occlusion pressure, with pressures ranging from 40 to 80% of arterial occlusion pressure [16]. The reason is that the arterial occlusion pressure is related to a wide range of individual characteristics (e.g., size of the limb, individual's blood pressure, or tourniquet shape, width, and length) [16, 46, 47]. However, this range of 40 to 80% of arterial occlusion pressure would make more sense for BFR with exercise and the total occlusion pressure (i.e., 100%) may be more closely related to BFR for recovery. In addition, a previous systematic review observed that some of the studies analyzing the effect of BFR on recovery did not clearly describe the characteristics of the participants and expressed concern about the statistical analysis [15]. Consequently, these limitations have a significant effect on understanding the benefits of BFR as a post-exercise recovery strategy.

Another main finding of this literature review was that some studies observed beneficial effects of BFR on the recovery process while others found no positive or detrimental effects of BFR as a post-exercise recovery strategy in comparison with the control/SHAM group. A total of 5 studies highlighted some beneficial effects of BFR on recovery [25, 33, 37, 38, 40], but unclear or detrimental effects were observed in 6 studies [34–36, 39, 41, 42]. In this regard, a previous investigation concluded that BFR interventions could lead to overall faster performance recovery, lower creatine kinase increase, and lower muscle soreness over 24 hours [15]. In addition, it has been suggested that the effectiveness of this intervention may be more specific to low/moderate fitness level individuals [15] and the mechanisms that explain the benefits of BFR for improving recovery and performance are unclear, but likely involve changes in both vascular and metabolic pathways [48]. This inconsistency among studies might be also due to the fact that recovery may be understood from multiple perspectives (e.g., changes in physiological parameters such as creatine kinase or modifications of perceived recovery and neuromuscular performance-related variables).

This review has several limitations to acknowledge. For example, the lack of studies, heterogenous methodologies, and the discrepancy between the results on the benefits of BFR as a post-exercise recovery strategy make it difficult to draw solid conclusions. For example, specification of cuff width and material should be included by each study as these variables may impact the effectiveness of BFR interventions [16]. Also, studies on BFR for recovery were mainly focused on passive strategies, so future research is not only necessary in this direction but also considering active strategies [16]. In this regard, the authors from a previous study recommended using BFR combined with various forms of exercise (e.g., resistance or aerobic) [16].

CONCLUSIONS

BFR could be a potential post-exercise recovery strategy, but practitioners should use caution when applying this a method of recovery for their athletes and clients. Only 11 studies investigated BFR as a post-exercise recovery strategy and there is not any significant amount of evidence in team or individual sports (especially in female populations). Some studies showed beneficial effects while others found unclear or detrimental effects of passive BFR as a post-exercise recovery strategy in comparison with the control/SHAM groups. Also, a lack of consistency in BFR protocols (e.g., number of cycles or duration of the occlusion-reperfusion periods) for recovery was observed.

In addition, this study has implications for practice and future research. Although limited data are available, the BFR protocols that

have shown potential positive effects on recovery markers may be beneficial for specific populations [25, 33, 37, 38, 40]. These protocols may be found in Table 1. For example, soccer players may adopt a supine position, use bilateral BFR (i.e., cuff placed on the proximal portion of the thigh: 77.0 cm length × 21.5 cm width) for 3 cycles of 5-minute occlusion and 5-minute reperfusion at a pressure of 50 mmHg above the systolic blood pressure and 0 mmHg during the reperfusion. Moreover, athletes from cyclic sports such as cycling may use BFR (i.e., cuff applied unilaterally to the sub-inguinal region of the upper thigh: 77.0 cm length × 21.5 cm width) in a supine position for 2 cycles of 5 min occlusion and 5 min reperfusion or 2 min occlusion and 2 min reperfusion at a pressure of 50 mmHg above systolic blood pressure.

Future studies need to analyze the benefits of BFR for recovery including sport-specific protocols (e.g., after participation in a full game or competition), and considering contextual variables (e.g., congested fixture periods) and actual protocols (e.g., pressures individualized to arterial occlusion pressure). In addition, it would be of interest for high performance-related practitioners to have a better understanding of the benefits of BFR interventions combined with either active or passive forms of exercise as a post-exercise recovery strategy. Another thing to consider is that passive BFR and BFR with exercise influences pain so could be used to help those recover if players have pain and niggles post exercise [49–51].

The use of BFR as a recovery strategy may be considered by practitioners, but the level of applicability to each specific context needs to be analyzed as well. For example, the timing of the intervention in high performance sports is very important, especially when there is travel involved after the competition. Also, further research is neeed to understand if it is likely that a single bout of restriction can improve recovery for the next days based on the initial change in blood flow. Furthermore, knowing the estimated duration of the effect of a BFR intervention would help understand the evolution of the recovery process. Nonetheless, it is necessary to gain a better understanding of the mechanisms of BFR for recovery. For instance, if the potential beneficial effects of BFR on exercise performance and recovery can be linked to post occlusion increases in blood flow associated with elevated adenosine levels and activation of ATP-sensitive potassium channels, which may lead to increased blood flow and improved skeletal muscle contractile function [39, 40]. In this regard, future research will be necessary to understand the effects of BFR on recovery markers.

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REFERENCES

1. Borresen J, Ian Lambert M. The quantification of training load, the training response and the effect on performance. Sports Med. 2009; 39(9):779–95.
2. Gabbett TJ, 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(20):1451–2.
3. Doherty R, Madigan SM, Nevill A, Warrington G, Ellis JG. The sleep and recovery practices of athletes. Nutrients. 2021; 13(4):1–25.
4. 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. 2023; 31(3):201–13.
5. Spencer M, Bishop D, Dawson B, Goodman C. Physiological and metabolic responses of repeated-sprint activities. Sports Med. 2005; 35(12):1025–44.
6. Pons E, Ponce-Bordón JC, Díaz-García J, López del Campo R, Resta R, Peirau X, García-Calvo T. A longitudinal exploration of match running performance during a football match in the Spanish La Liga: a four-season study. Int J Environ Res Public Health. 2021; 18(3):1133.
7. de Souza DB, González-García J, López-Del Campo R, Resta R, Martínez Buldú J, Wilk M, Coso J. Players' physical performance in LaLiga when the competition resumes after COVID-19: insights from previous seasons. Biol Sport. 2021; 38(1):3–7.
8. 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.
9. Harper DJ, 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(12):1923–47.
10. De Hoyo M, Cohen DD, Sañudo B, Carrasco L, Álvarez-Mesa A, del Ojo JJ, Domínguez-Cobo S, Mañas V, Otero-Esquina C. Influence of football match time–motion parameters on recovery time course of muscle damage and jump ability. J Sports Sci. 2016; 34(14):1363–70.
11. 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.
12. 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.
13. Ispirlidis I, Fatouros IG, Jamurtas AZ, Nikolaidis MG, Michailidis I, Douroudos I, Margonis K, Chatzinikolaou A, Kalistratos E, Katrabasas I, Alexiou V, Taxildaris K. Time-course of changes in inflammatory and performance responses following a soccer game. Clin J Sport Med. 2008; 18(5):423–31.
14. Nédélec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in soccer. Sports Med. 2012; 42(12):997–1015.
15. Arriel RA, Rodrigues JF, Souza HLR de, Meireles A, Leitão LFM, Crisafulli A, Marocolo M. Ischemia–reperfusion intervention: from enhancements in exercise performance to accelerated

performance recovery – A systematic review and meta-analysis. Int J Environ Res Public Health. 2020; 17(21):1–16.
16. Patterson SD, Hughes L, Warmington S, Burr J, Scott BR, Owens J, Abe T, Nielsen JL, Libardi CA, Laurentino G, Neto GR, Brandner C, Martin-Hernandez J, Loenneke J. Blood flow restriction exercise: considerations of methodology, application, and safety. Front Physiol. 2019; 10:1–15.
17. Scott BR, Loenneke JP, Slattery KM, Dascombe BJ. Exercise with blood flow restriction: an updated evidence-based approach for enhanced muscular development. Sports Med. 2015; 45(3):313–25.
18. Larkin KA, Macneil RG, Dirain M, Sandesara B, Manini TM, Buford TW. Blood flow restriction enhances post–resistance exercise angiogenic gene expression. Med Sci Sports Exerc. 2012; 44(11):2077–83.
19. Manini TM, Clark BC. Blood flow restricted exercise and skeletal muscle health. Exerc Sport Sci Rev. 2009; 37(2):78–85.
20. Lorenz DS, Bailey L, Wilk KE, Mangine RE, Head P, Grindstaff TL, Morrison S. Blood flow restriction training. J Athl Train. 2021; 56(9):937–44.
21. Wortman RJ, Brown SM, Savage-Elliott I, Finley ZJ, Mulcahey MK. Blood flow restriction training for athletes: a systematic review. Am J Sports Med. 2021; 49(7):1938–44.
22. Caru M, Levesque A, Lalonde F, Curnier D. An overview of ischemic preconditioning in exercise performance: A systematic review. J Sport Health Sci. 2019; 8(4):355–69.
23. Murry CE, Jennings RB, Reimer KA. Preconditioning with ischemia: a delay of lethal cell injury in ischemic myocardium. Circulation. 1986; 74(5):1124–36.
24. Loenneke JP, Wilson GJ, Wilson JM. A mechanistic approach to blood flow occlusion. Int J Sports Med. 2010; 31(1):1–4.
25. Page W, Swan R, Patterson SD. The effect of intermittent lower limb occlusion on recovery following exercise-induced muscle damage: A randomized controlled trial. J Sci Med Sport. 2017; 20(8):729–33.
26. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R, Glanville J, Grimshaw JM, Hróbjartsson A, Lalu MM, Li T, Loder EW, Mayo-Wilson E, McDonald S, McGuinness LA, Stewart LA, Thomas J, Tricco AC, Welch VA, Whiting P, Moher D. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021; 372(71):1–9
27. Rico-González M, Pino-Ortega J, Clemente F, Los Arcos A. Guidelines for performing systematic reviews in sports science. Biol Sport. 2022; 39(2):463–71.
28. de Morton NA. The PEDro scale is a valid measure of the methodological quality of clinical trials: a demographic study. Aust J Physiother. 2009; 55(2):129–33.
29. Slim K, Nini E, Forestier D, Kwiatkowski F, Panis Y, Chipponi J. Methodological index for non-randomized studies (MINORS): development and validation of a new instrument. ANZ J Surg. 2003; 73(9):712–6.
30. Sánchez M, Sanchez-Sanchez J, Nakamura FY, Clemente FM, Romero-Moraleda B, Ramirez-Campillo R. Effects of plyometric jump training in female soccer payer's physical fitness: a systematic review with meta-analysis. Int J Environ Res Public Health. 2020; 17(23):1–23.
31. Stojanović E, Ristić V, McMaster DT, Milanović Z. Effect of plyometric training on vertical jump performance in female athletes: a systematic review and meta-analysis. Sports Med. 2017; 47(5):975–86.
32. Huang J, Zhong M, Wang J. Effects of exercise-based interventions on functional movement capability in untrained populations: a systematic review and meta-analysis. Int J Environ Res Public Health. 2022; 19(15):1–16.
33. Daab W, Bouzid MA, Lajri M, Bouchiba M, Rebai H. Brief cycles of lower-limb occlusion accelerate recovery kinetics in soccer players. Phys Sportsmed. 2021; 49(2):143–50.
34. Williams N, Russell M, Cook CJ, Kilduff LP. The effect of lower limb occlusion on recovery following sprint exercise in academy rugby players. J Sci Med Sport. 2018; 21(10):1095–9.
35. Garcia C, da Mota G, Leicht A, Marocolo M. Ischemic preconditioning and acute recovery of performance in rugby union players. Sports Med Int Open. 2017; 1(3):107–12.
36. Castilla-López C, Romero-Franco N. Blood flow restriction is not useful as soccer competition recovery in youth male national-level soccer payers: a crossover randomised controlled trial. Sports. 2023; 11(5):1–12.
37. Arriel RA, de Souza HLR, da Mota GR, Marocolo M. Declines in exercise performance are prevented 24 hours after post-exercise ischemic conditioning in amateur cyclists. PLoS One. 2018; 13(11):1–12.
38. Ceylan B, Taşkın HB, Šimenko J. Effect of ischemic preconditioning on acute recovery in elite judo athletes: a randomized, single-blind, crossover trial. Int J Sports Physiol Perform. 2023; 1–7.
39. Northey JM, Rattray B, Argus CK, Etxebarria N, Driller MW. Vascular occlusion and sequential compression for recovery after resistance exercise. J Strength Cond Res. 2016; 30(2):533–9.
40. Beaven CM, Cook CJ, Kilduff L, Drawer S, Gill N. Intermittent lower-limb occlusion enhances recovery after strenuous exercise. App Physiol Nutr Metab. 2012; 37(6):1132–9.
41. Wong V, Dankel SJ, Spitz RW, Bell ZW, Viana RB, Chatakondi RN, Abe T, Loenneke JP. The effect of blood flow restriction therapy on recovery after experimentally induced muscle weakness and pain. J Strength Cond Res. 2022; 36(4):1147–52.
42. Lillquist T, Mahoney SJ, Kotarsky C, McGrath R, Jarajapu Y, Scholten SD, Hackney KJ. The effect of direct and remote postexercise ischemic conditioning on muscle soreness and strength 24 hours after eccentric drop jumps. J Strength Cond Res. 2023; 37(9):1870–6.
43. Nicholas CW, Nuttall FE, Williams C. The Loughborough Intermittent Shuttle Test: A field test that simulates the activity pattern of soccer. J Sports Sci. 2000; 18(2):97–104.
44. Magalhães J, Rebelo A, Oliveira E, Silva JR, Marques F, Ascensão A. Impact of Loughborough Intermittent Shuttle Test versus soccer match on physiological, biochemical and neuromuscular parameters. Eur J Appl Physiol. 2010; 108(1):39–48.
45. O'Brien L, Jacobs I. Methodological variations contributing to heterogenous ergogenic responses to ischemic preconditioning. Front Physiol. 2021; 12:1–12.
46. McEwen JA, Owens JG, Jeyasurya J. Why is it crucial to use personalized occlusion pressures in blood flow restriction (BFR) rehabilitation? J Med Biol Eng. 2019; 39(2):173–7.
47. Jessee MB, Buckner SL, Dankel SJ, Counts BR, Abe T, Loenneke JP. The Influence of cuff width, sex, and race on arterial occlusion: implications for blood flow restriction research. Sports Med. 2016; 46(6):913–21.
48. Incognito A V., Burr JF, Millar PJ. The effects of ischemic preconditioning on human exercise performance. Sports Med. 2016; 46(4):531–44.
49. Slysz JT, Burr JF. Ischemic preconditioning: modulating pain sensitivity and exercise performance. Front Physiol. 2021; 12:1–7.
50. Hughes L, Patterson SD. The effect of blood flow restriction exercise on exercise-induced hypoalgesia and endogenous opioid and endocannabinoid mechanisms of pain modulation. J Appl Physiol. 2020; 128(4):914–24.
51. Hughes L, Grant I, Patterson SD. Aerobic exercise with blood flow restriction causes local and systemic hypoalgesia and increases circulating opioid and endocannabinoid levels. J Appl Physiol. 2021; 131(5):1460–8.

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Variations in strength-speed-power performance across the season: do true changes occur in elite rugby players?

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ABSTRACT: This study aimed to determine, through the use of a highly sensitive statistical tool, whether real changes in performance were present; and compare the rates of meaningful variations in strength, speed, and power parameters at different time-points during the competitive season in national team rugby players. Thirty-two players were assessed 5 times across the season using the following tests: squat jump and countermovement jump tests; 30-m sprint velocity; and one-repetition maximum (1RM) in the half-squat and bench-press exercises. A repeated-measures analysis of variance was conducted to test for differences between successive time-points. Individual coefficients of variation values were used to set target scores for post-measurements and examine whether changes in performance parameters were greater than the natural test variance, thus providing an indication of whether "true changes" occurred. No significant changes were detected in the vertical jump height, 1RM measures, and sprint velocity and momentum throughout the 11-month period ($P > 0.05$). True changes occurred much more frequently for strength-power measures than for sprint velocity and momentum. Elite rugby union players did not exhibit significant variations in neuromuscular performance across the competitive period, when a group-based analysis was conducted. However, at the individual level, "true changes" in strength-power- (but not in speed-) related qualities were consistently observed over the competitive season.

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INTRODUCTION

In elite sports, resistance training programs are designed to improve the physical performance of athletes, and hence, their ability to effectively execute technical and tactical actions [1, 2]. Relevant reviews have addressed this issue, concluding that there is sufficient evidence to encourage the frequent use of these strategies in athletes' preparation [1, 2]. The importance of strength and power for athletic development may also be supported by a range of cross-sectional studies showing close associations between strength-power-related variables and various performance measures (e.g., sprint time, top-speed, and jump height), as well as their potential to discriminate between athletes from distinct competitive levels [1–5]. Whereas correlational and comparative investigations can be complementary in many respects, the lack of long-term interventions in team-sports, precludes robust conclusions about the actual effects of resistance training on athletic performance (or even in strength-power development itself) [1, 2].

Specifically in rugby union, a team-sport that relies heavily on maximum strength and power [3, 6–8], the implementation of effective strength-power training programs has a critical impact on player and team performance [3, 9, 10]. Accordingly, short-term studies (4 weeks) conducted during the competitive phase have reported increased strength (i.e., bench-press [BP] and squat 1RM) and jumping performance following different resistance training methods in rugby union players (i.e., "full-body vs. split-body resistance training" and "contrast strength-power vs. contrast speed-power training", respectively) [9, 11]. Despite the absence of clear differences

between training protocols, in both studies [9, 11], the authors highlighted and described the crucial role played by strength-power training volume (i.e., exposure to high volume-load stimuli) in modulating training-induced adaptations (specifically those related to power production).

As an additional attempt to examine the effects of resistance-based interventions and map strength-power changes across the season, studies dealing with seasonal variations are widely performed in rugby union [7, 12–14]. In a 45-week study on strength-power development in rugby union players from an English premiership team, Gannon et al. [7] observed worthwhile (i.e., estimated by magnitude-based inferences), but not statistically significant, differences in peak force and power output (i.e., assessed using isometric squat and "explosive hack-squat" exercises, respectively) throughout the competitive season. Zabaloy et al. [15] observed a similar pattern (i.e., lack of significant changes) in the evolution of measures of relative strength (squat- and BP-1RM) and squat peak force in a 10-month study in elite young rugby union players. Notably, these two studies also found small and significant decreases in rapid force production (-6.3% and -8.8% for peak force at 50 and 100 ms, respectively) [7] and sprint velocity (+4%, on average, for sprint time at 30-m) [15] in the latter stages of the season, which certainly compromise rugby-specific performance.

The lack of positive changes in sprint velocity and power-related capabilities across the season is commonplace in many sports and may be related to a number of factors [13, 15–18]. High exposure to match loads throughout the season, concurrent training effects, limited trainability for speed qualities, and low frequency and volume of sprint-specific and strength-power training are usually cited as the main barriers to adequate speed-power development [6, 17, 19–22]. The low level of transference from strength improvements to sprinting speed is another critical factor that may affect the enhancement of speed qualities throughout the season – an issue that seems even more pronounced in highly-trained rugby players (and well-trained athletes of other sports) [10, 17, 23]. Indeed, it is likely that the complexity of sprinting technique, associated with the minimal remaining trainability in athletes with an extensive training background, may further reduce the transfer potential of strength training to sprinting performance [10, 17, 23]. However, it should be emphasized that when applied to small and highly-specialized samples (i.e., elite athletes), more conventional statistical approaches may not be sensitive enough to assess meaningful changes in speed- and power-related capabilities [17, 24, 25]. In this sense, even when "real changes" occur (i.e., when variations in post-test scores are greater than pre-test variance) [17, 24, 25], they can be undetected if assessed by traditional inferential methods (e.g., null hypothesis significance testing). Thus, specifically when small (and non-significant) changes in performance are expected, the use of more sensitive statistical techniques (e.g., "true changes") [17, 24, 25] could serve as a guide for decision-making regarding training progression, especially when aiming to adjust programming and make decisions at the individual level [24, 25].

Considering previous studies that analyzed the evolution, and confirmed the stability, of strength, speed, and power parameters in elite rugby union players across the season [7, 12–14], we believe it is important to investigate whether true changes in these measures occur at the individual level. Therefore, the objectives of this study were to: 1) determine, through the use of a more sensitive statistical tool (i.e., true changes calculation), whether real changes in strength-speed-power-related performance were present; and 2) compare the rates of meaningful changes between strength, speed, and power measures at different time-points during the competitive season in national team rugby players.

MATERIALS AND METHODS

Participants

Thirty-two male rugby union players from the Brazilian national team (backs: n = 13; age: 24.8 ± 2.4 years; body-mass [BM]: 91.3 ± 10.1 kg; height: 1.78 ± 0.07 m; forwards: n = 19; age: 25.7 ± 3.2 years; BM: 112.1 ± 9.3 kg; height: 1.84 ± 0.08 m) participated in this study. Players were assessed during the 2022 annual season, from January to November, and participated in a total of 19 matches, during three international tournaments (comprising 17 matches) and 2 international friendly-matches. The study was approved by the local Ethics Committee and all athletes signed an informed consent form before participating in the study.

Study Design

This longitudinal comparative study analyzed the variations in the neuromuscular performance of national team rugby union players over an 11-month period. Athletes were assessed on 5 occasions: at the beginning of the preseason period (week 1, T1); at the end of the preparatory period and approximately 10 days before the first official match of the season (week 8, T2); after the first tournament of the year ("Super Rugby Americas") (week 21, T3); at the end of the inter-season period (week 29, T4); and at the end of the competitive season (week 44, T5), as part of their regular physical testing routine. The testing procedures followed the schedule set by the national team's coaching staff. All testing sessions were performed in the morning, between 09:00 and 12:00 hours, prior to the first training session of the day. During all testing sessions athletes performed on the same day and in the following order: squat jump (SJ) and countermovement jump (CMJ) tests, 30-m sprint velocity (assessed in all sessions, with the exception of T2, due to a decision of the national team coaching staff), and one-repetition maximum (1RM) in the half-squat (HS) and BP exercises. Before performing the tests, players completed a 10-min standardized warm-up, comprising 5-min of running at a moderate self-selected pace followed by 5-min of dynamic stretching for both upper- and lower-limbs. Prior to the actual measurements, athletes performed 5 submaximal trials of each specific test with a 30-s interval between each trial. The average number of weekly training sessions as well as the typical strength-power training programs followed by the national rugby players (i.e.,

TABLE 1. Average number of training sessions for backs and forwards and total number of matches played during the different phases of the annual training season.

		Training Phase			
		T1–T2 Preseason	**T2–T3 CP1**	**T3–T4 Inter-Season**	**T4–T5 CP2**
Strength-power training	*Backs*	3.2 ± 1.1	1.8 ± 1.9	4.0 ± 1.1	3.4 ± 0.6
	Forwards	2.8 ± 1.3	2.2 ± 0.4	3.0 ± 1.4	3.7 ± 1.3
Anaerobic and aerobic power	*Backs*	2.4 ± 0.5	1.0 ± 0	0.5 ± 0.5	0.4 ± 0.5
	Forwards	1.6 ± 0.9	1.0 ± 0	0.5 ± 0.5	0.4 ± 0.5
Game-based training	*Backs*	0.8 ± 0.4	0.9 ± 0.7	1.5 ± 0.5	1.7 ± 0.5
	Forwards	1.0 ± 0	1.2 ± 0.4	1.5 ± 0.5	1.7 ± 0.5
Speed training	*Backs*	0.4 ± 0.4	0.9 ± 0.9	1.0 ± 0	1.0 ± 0
	Forwards	0.6 ± 0.5	1.0 ± 0	1.0 ± 0	1.0 ± 0
Technical-tactical training	–	5 (90–120')	4 (60–90')	4 (90–120')	4 (60–90')
Official matches	–	0	10	0	9

Note: CP1 (Competitive phase 1): comprised the "Super Rugby Americas Tournament"; CP2 (Competitive phase 2): comprised the "South America Rugby Championship" and the international matches; Strength-power training sessions involved traditional (e.g., half-squat, bench-press, prone row, etc.), ballistic (e.g., jump squat, medicine ball throw, etc.), and plyometric (e.g., drop and hurdle jumps, and bounding) exercises; Anaerobic and aerobic power training sessions involved small-sided games and high-intensity interval training; Game-based training involved sessions designed to improve physical and technical skills according to playing positions; Speed training sessions involved traditional and resisted sprints (sled pushing and sled pulling), and technical drills (e.g., skipping and high-knee running); Technical-tactical training sessions involved simulated rugby matches and specific tactical tasks. For technical-tactical training, the numbers in parenthesis correspond to total volume of training sessions in minutes.

TABLE 2. Typical strength-power training programs prescribed for backs and forwards during the preseason period.

	Backs				**Forwards**			
	Exercise*	**Sets**	**Reps**	**Load#**	**Exercise***	**Sets**	**Reps**	**Load#**
Day 1	Jump squat	4	6	60–70%	Isometric mid–thigh pull	3–4	10"	–
	Drop jump	4	4	45 cm	Hang high pull	4	8	70–80%
	Hurdle jump	4	3	75 cm	Drop jump	3	4	45 cm
	Snatch	4	6	60–70%	Jump squat	4	4–6	80%
	Power clean	4	6	60–70%	Push press	4	8	70–80%
	Push press	4	6	60–70%				
Day 2	Overhead squat	2	8–10	70–80%	Isometric squat	4	10"	–
	Unilateral row	2	8–10	70–80%	Half squat	5–6	3–4	85–95%
	Half squat	3	4–6	80–90%	Pull up	5	3–4	85–95%
	Pull up	3	4–6	80–90%	Prone row	4	3–4	85–95%
	Prone row	3	6–8	75–85%	Lunges	4	4–6	80–90%
	Lunges	3	6–8	75–85%				
Day 3	Reverse fly	2	10	70–80%	Push press	5	6–8	80–90%
	Biceps curl	2	10	70–80%	High pull	5	6–8	80–90%
	Push press	3	6	60–70%	Parallel dips	4	8	+25% BM
	High pull	3–4	6	60–70%	Reverse fly	4	10	70–80%
	Lateral raises	3	6–8	75–85%	Shoulder press	3–4	8–10	70–80%
Day 4	Bench press	2–3	8–10	75–80%	Isometric bench press	4	5"	–
	Stiff	3	4–6	80–90%	Nordic	4	4	BM
	Push up	3	4–6	80–90%	Bench press	5	3–4	85–95%
	Bench press 45°	3	4–6	80–90%	Deadlift	5	3–4	85–95%
	Nordic	3	6–8	BM	Prone row	4	6–8	80–90%
					Hip thrust	5	6–8	80–90%

Note: *In general, 2–3 minutes were provided between exercises and sets. #Percentage of one-repetition maximum (i.e., mean values reported by the technical staff); BM: body-mass.

TABLE 3. Typical strength-power training programs prescribed for backs and forwards during the competitive period.

	Backs				Forwards			
	Exercise*	**Sets**	**Reps**	**Load#**	**Exercise***	**Sets**	**Reps**	**Load#**
Day 1	Jump squat	3–4	6	45%	Jump squat	4	6–8	70–80%
	Drop jump	3	4	45 cm	Box jump	3	4–6	45–60 cm
	Hurdle jump	3	4	75 cm	Isometric mid–thigh pull	3–4	10"	–
	Clean and jerk	4	6	60%	Drop jump	3	4–6	45 cm
	Med ball throw	4	4	10 kg	Push press	4	4–6	80–90%
	Push press	4	6	60%	Med ball throw	3	4–6	12–15 kg
Day 2	Bench press	3	4–6	80–90%	Bench press	4	2–3	> 90%
	Unilateral stiff	3	4–6	80%	Deadlift	4	2–3	> 90%
	Incline fly	3	4–6	80%	Bench press 45º	3	4–6	85–90%
	Med ball throw	4	4–6	10 kg	Med ball throw	3	4–6	12–15 kg
	Nordic	3	4–6	BM	Hip thrust	4	4–6	80–90%
	Hip thrust	3	6	60–70%	Leg curl	3–4	6–8	70–80%
Day 3	Pull-up	3	6	70%	Pull–up	3	4–6	> 80%
	Jump squat	3	4–6	60%	Half squat	4	2–3	> 90%
	Drop jump	3	6	> 45 cm	Jump squat	4	4–6	80–90%
	Bench press 45º	3	4–6	80–90%	Prone row	4	6–8	80–90%
	Bulgarian squat	3	6	60–70%	Lunges	3	4–6	> 85%
	Bounding	3	6	BM	Drop jump	3	5	45 cm

Note: *In general, 2–3 minutes were provided between exercises and sets. #Percentage of one-repetition maximum (i.e., mean values reported by the technical staff); BM: body-mass.

backs and forwards) during the different phases of the annual season are presented in Tables 1, 2, and 3. Resistance training intensity was constantly monitored and adjusted throughout the season, according to the actual variations in 1RM measurements. The 1RM values collected during the first control session (5–7 days after T1) were used to calculate the CVs for the 1RM measurements. During the study, nutrition and sleep habits of the athletes were monitored by the technical staff of the Brazilian national team.

Procedures

Vertical Jump Tests

Vertical jump height was assessed using the SJ and CMJ. In the SJ, a static position with a ~90° knee flexion angle was maintained for 2-s before a jump attempt without any preparatory movement. In the CMJ, players were instructed to perform a downward movement followed by complete extension of the lower limbs and the amplitude of the countermovement was freely determined to avoid changes in the jumping coordination pattern. All jumps were executed with hands on the hips. Five attempts at each jump were performed interspersed by 15-s intervals. The jumps were performed on a contact platform (Elite Jump System®; S2 Sports, São Paulo, Brazil) and the best attempt at each jump was used for data analysis purposes.

Sprint Velocity

Sprint testing was conducted on an indoor running track. Three pairs of photocells (Elite Speed System®; S2 Sports, São Paulo, Brazil) were positioned at the starting line and at the distances of 10- and 30-m. Players sprinted twice, starting from a standing position 0.5-m behind the starting line. Sprint velocity was calculated as the distance travelled over a measured time interval. A 5-min rest interval was allowed between trials and the fastest time was considered for analysis. Sprint momentum ($kg \cdot m \cdot s^{-1}$) was obtained by multiplying the athlete's BM by the respective velocity (i.e., 10- or 30-m) in the sprint test.

One-Repetition Maximum Tests in the Bench Press and Half-Squat Exercises

The 1RM test was performed using an Olympic barbell for the BP and HS exercises, as described previously [26, 27]. The testing protocol was adapted from the procedures proposed by Brown and Weir [28]. Prior to testing, athletes performed 3 specific warm-up sets. In the first set, subjects performed 4 repetitions with 50% of the estimated 1RM (i.e., based on prior assessments); in the second set they performed 3 repetitions with 60% of the estimated 1RM, and in the third set they performed 2 repetitions with 70% of the

estimated 1RM. A 3-minute rest interval was allowed between sets. Three minutes after the warm-up, participants were allowed up to 5 attempts (~ 80%, 90%, 95%, and [1–2 repetitions] > 95% of the estimated 1RM) to obtain the 1RM load (e.g., maximum weight that could be lifted once using the proper technique) [28], with a 3-minute interval between attempts. To account for differences in the BM of the rugby players, values were normalized by dividing the 1RM load value by the athlete's BM (i.e., relative strength, RS).

Statistical Analysis

Data are presented as mean ± standard deviation. Data were analyzed using the intention-to-treat approach, considering all observed data collected from the participants, according to their respective groups. The Shapiro-Wilk test was used to confirm the normality of the data. To analyze the differences in the physical tests executed across the time-points between backs and forwards, a two-way repeated-measures analysis of variance was conducted followed by the Bonferroni post hoc. Statistical significance was set as $P < 0.05$. Effect sizes were calculated using Cohens' *d* [29] with associated 95% confidence intervals (CI). All tests used demonstrated small errors of measurement, as evidenced by their high levels of accuracy and reproducibility (i.e., coefficient of variation < 10% and intraclass correlation coefficient [using an alpha 2-way mixed model] > 0.90; for all tests). Statistical power was calculated by using the G*Power software (v. 3.1.9.7), for the different comparisons performed in the tested variables. CV values were calculated for each athlete at the individual level, and utilized to establish "target scores" for comparisons with post-testing results (i.e., T2, T3, T4, and T5) [25]. This analysis aimed to determine whether fluctuations in strength, speed, and jump parameters were greater than their "natural variability" estimated at baseline (i.e., T1), thereby providing an indication of whether true changes occurred on an individual basis [17, 24, 25].

RESULTS

The statistical power achieved for the different comparisons, given the sample size of 32 rugby players, and considering an alpha level of 5%, was > 80%. Backs exhibited higher relative strength qualities, better sprint and jump performance, and lower sprint momentum compared to the forwards, across the 5 testing sessions (ES [95%CI] ranging from 0.66 [0.04; 1.25] to 1.69 [0.83; 2.46]; *P*-values ranging from < 0.001 to 0.043). Similar non-significant variations

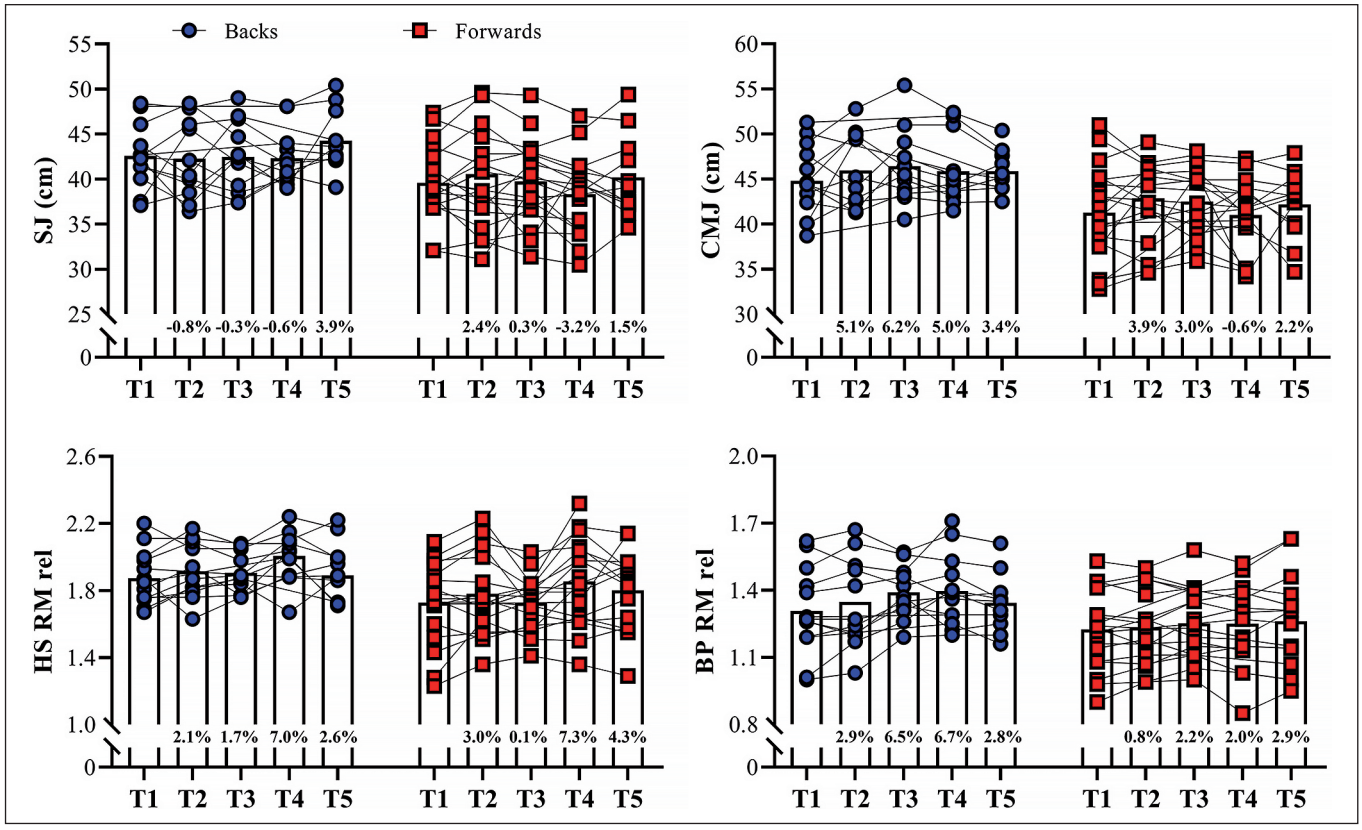


FIG. 1. Variations in squat and countermovement jump height (SJ and CMJ) and relative values of maximum strength in the half-squat (HS) and bench-press (BP) exercises across the different time-points. RM: repetition maximum. Bars represent mean values; symbols represent individual results. Percentage differences are shown in each column relative to the first assessment.

in the BM of backs and forwards were observed over the 11-month period (ES [95%CI] ranging from 0.05 [-0.73; 0.84] to 0.30 [-0.55; 1.13]; *P*-values ranging from 0.234 to 1.00, for backs; and ES [95%CI] ranging from 0.06 [-0.68; 0.79] to 0.38 [-0.33; 1.07]; *P*-values ranging from 0.105 to 1.00, for forwards, for main effect of time; $P = 0.347$ for group*time interaction). Figure 1 depicts the variations in vertical jump performance and relative strength in the HS and BP exercises across the 5 time-points. No significant changes were noticed for backs and forwards throughout the 11-month period in vertical jump measures and RS in both exercises tested (ES [95%CI] ranging from 0.01 [-0.84; 0.84] to 0.45 [-0.39; 1.27]; *P*-values ranging from 0.563 to 1.00, for backs; and ES [95%CI] ranging from 0.01 [-0.68; 0.68] to 0.45 [-0.25; 1.15]; *P*-values ranging from 0.168 to 1.00, for forwards, for main effect of time; $P = 0.921$, 0.657, 0.705, and 0.250 for SJ, CMJ, HS RS, and BP RS, respectively, for group*time interaction).

Figure 2 shows the variations in the sprint velocity and momentum over 4 testing occasions. No significant variations were observed for backs and forwards in these velocity-based measurements comparing the distinct assessments performed (ES [95%CI] ranging from 0.01 [-0.82; 0.81] to 0.55 [-0.29; 1.35]; *P*-values ranging from 0.113 to 1.00, for backs; and ES [95%CI] ranging from 0.02 [-0.74; 0.71] to 0.64 [-0.10; 1.34]; *P*-values ranging from 0.075 to 1.00, for forwards, for main effect of time; $P = 0.587$, 0.128, 0.499, and 0.416 for 10-m and 30-m sprint velocity and momentum, respectively, for group*time interaction). Figures 3–6 show the individual comparisons between the target scores, and the subsequent performance tests for the multiple variables analyzed. When a given athlete presented a test result higher than the target score in a specific variable, a "true change" occurred.

DISCUSSION

We analyzed the changes in physical performance of elite rugby union players at different time-points, during an annual training season. Overall, these athletes did not exhibit significant variations in their strength-, speed-, and power-related qualities, which reinforces previous findings indicating the long-term stability of these measures across the competitive period [7, 12–14, 17, 30]. On the other hand, this highlights the need to use more sensitive statistical techniques for the assessment and evaluation of highly-trained athletes, especially when the intention is to create more effective and tailored training programs.

The lack of significant changes in neuromuscular performance throughout the competitive phase is not novel, either in elite rugby

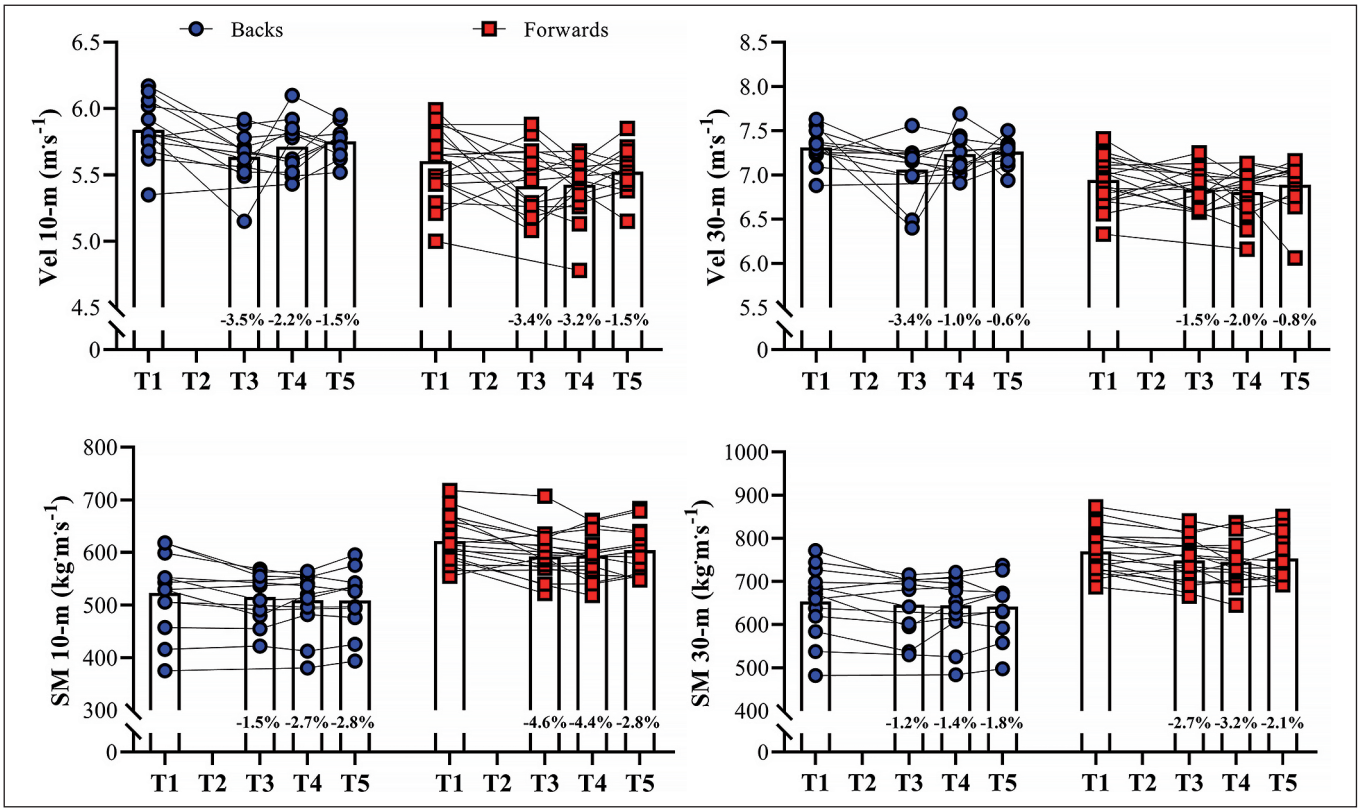


FIG. 2. Variations in sprint velocity (Vel) and momentum (SM) at 10- and 30-m across the different time-points. RM: repetition maximum. Bars represent mean values; symbols represent individual results. Percentage differences are shown in each column relative to the first assessment.

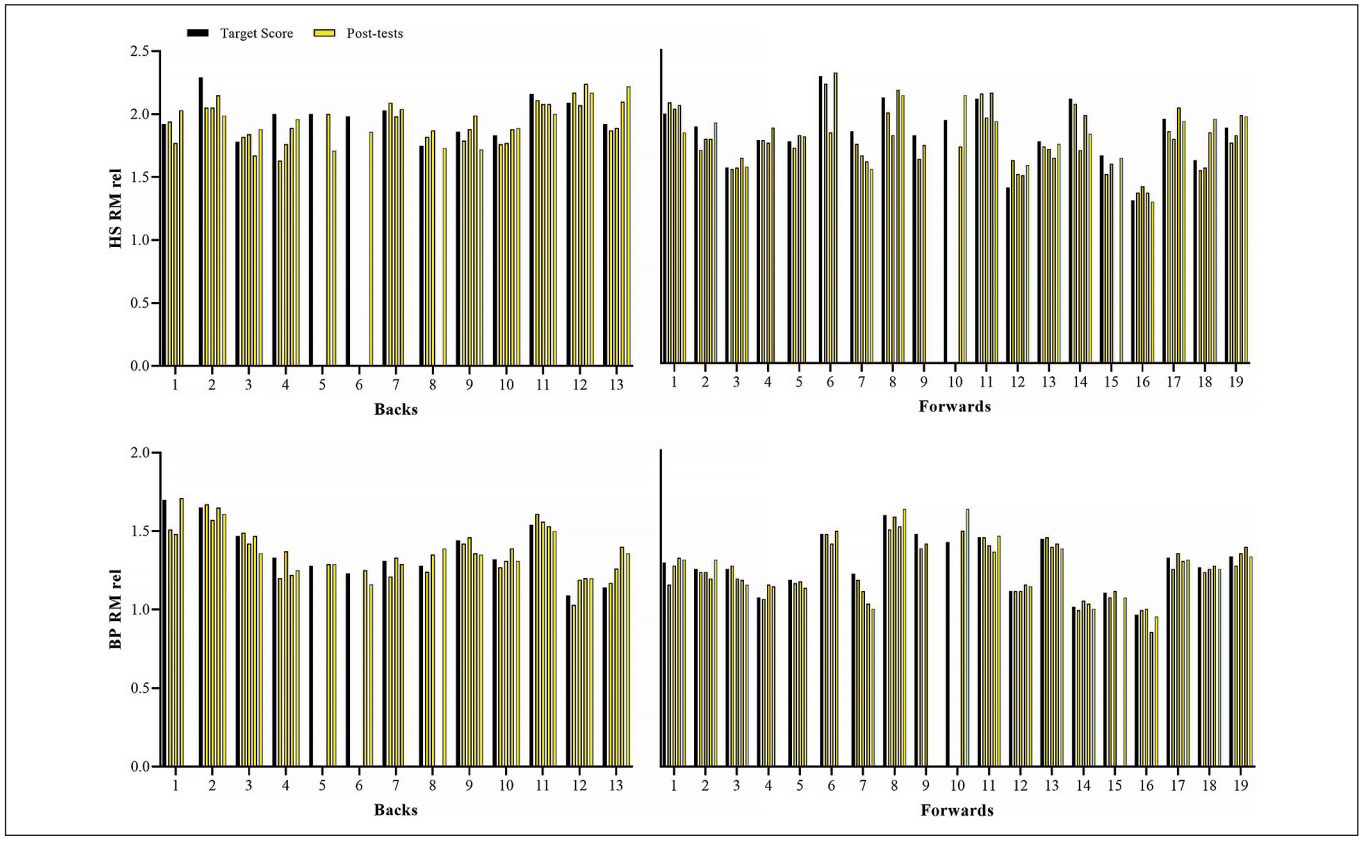


FIG. 3. Individual comparisons between target scores and subsequent performance scores for relative values of maximum strength in the half-squat (HS RM rel) and bench-press (BP RM rel) exercises.

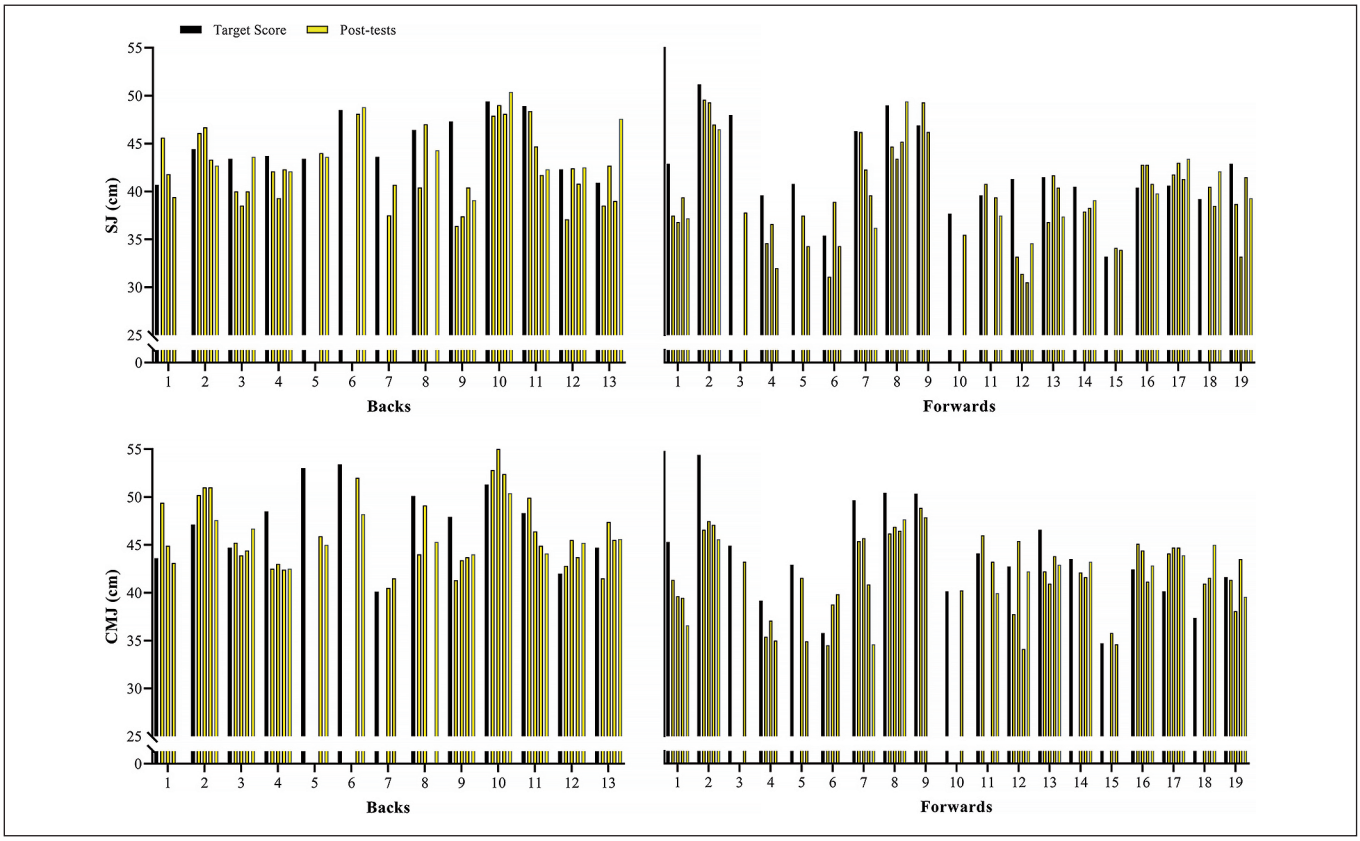


FIG. 4. Individual comparisons between target scores and subsequent performance scores for squat and countermovement jump height (SJ and CMJ).

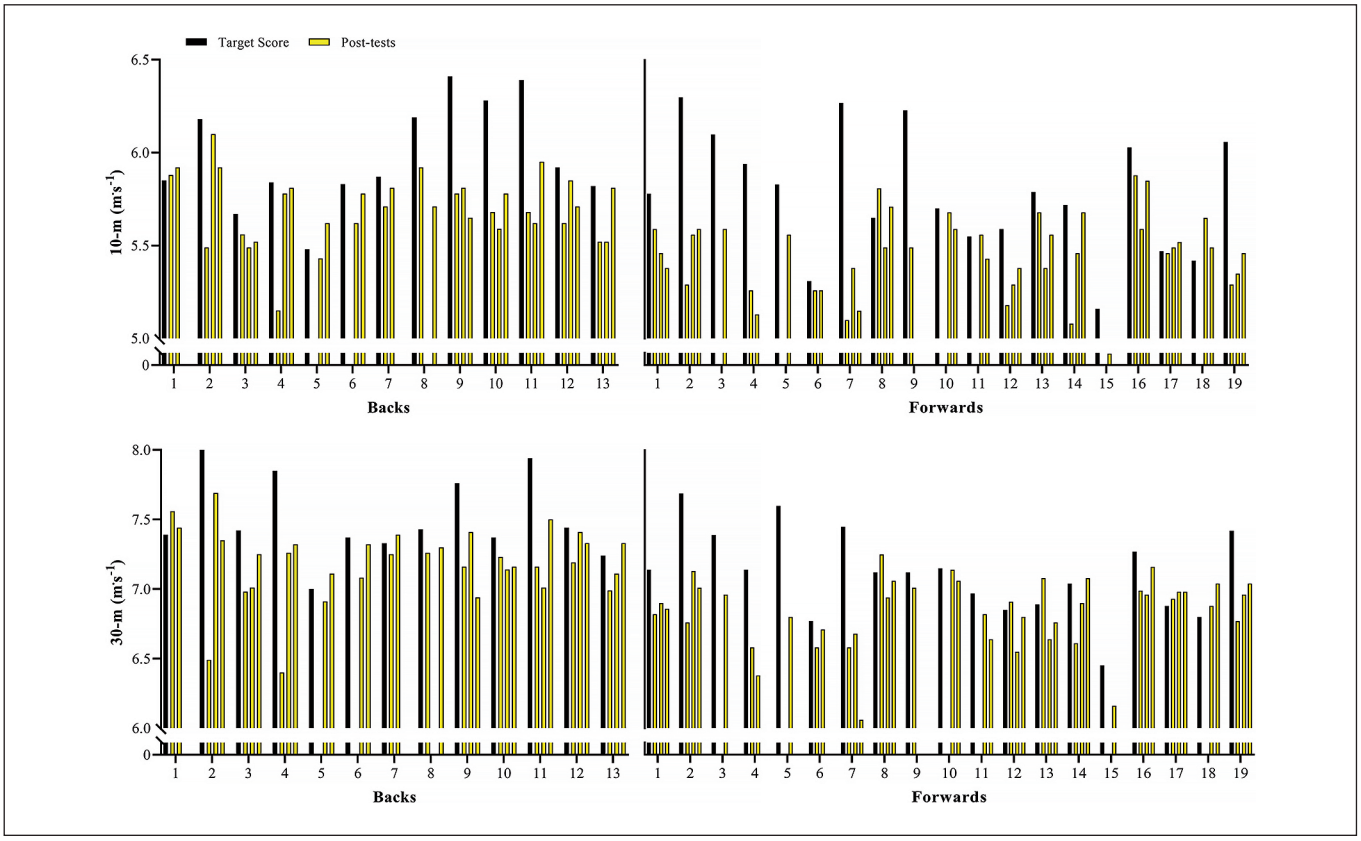


FIG. 5. Individual comparisons between target scores and subsequent performance scores for sprint velocity at 10- and 30-m.

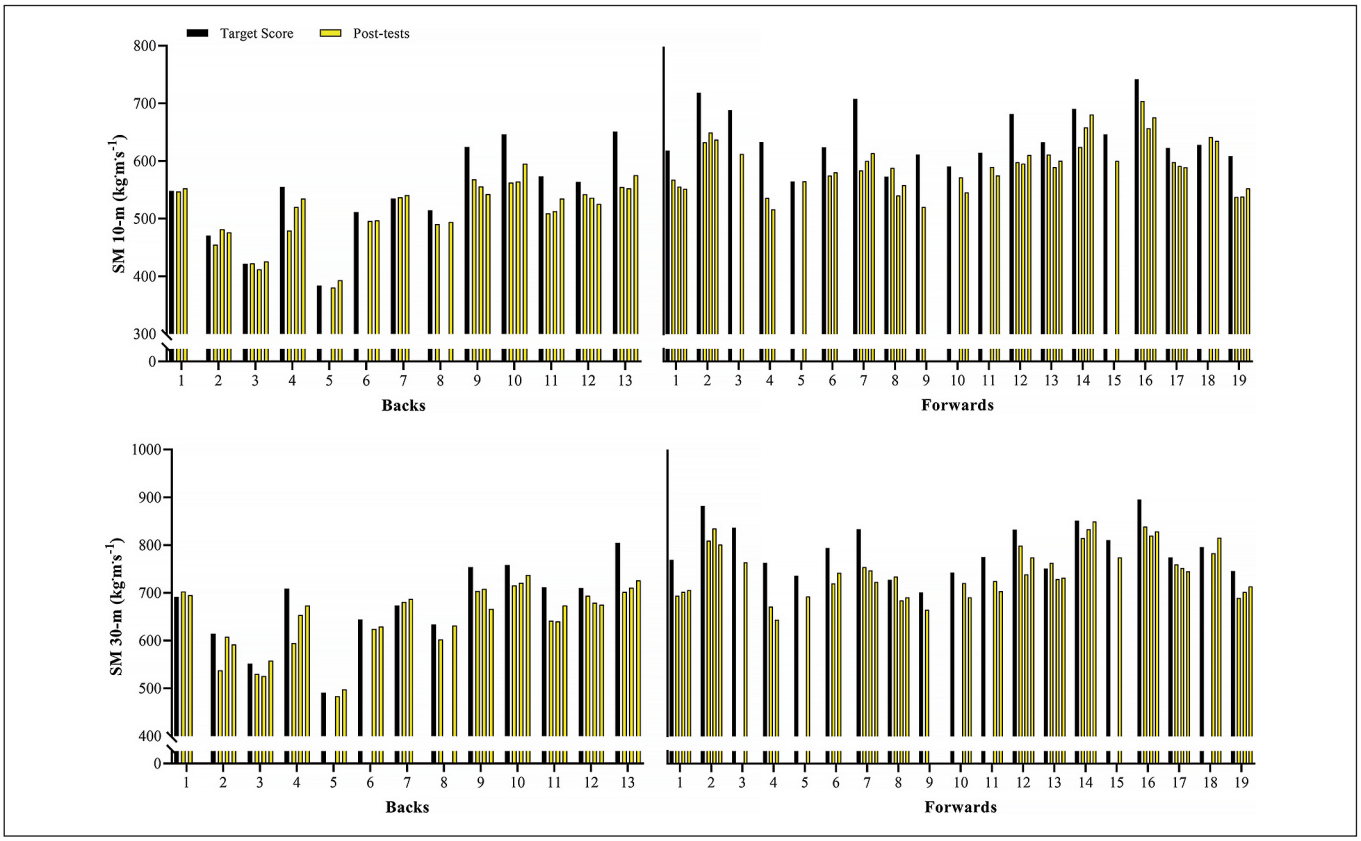


FIG. 6. Individual comparisons between target scores and subsequent performance scores for sprint momentum (SM) at 10- and 30-m.

union or other team-sports [6, 14, 30]. For example, studies in soccer [16, 31, 32] and cricket [30] showed that the high demands of the competitive period associated with a multitude of in-season training practices (e.g., technical-tactical preparation, match-recovery, and injury prevention strategies, etc.) do not provide an appropriate and effective stimulus to improve strength and power qualities. Indeed, even when adequate and feasible volumes of resistance training are completed within the training schedule (e.g., 2–3 sessions of 30–45 min per week), in-season variations in independent measures of strength and power tend to be marginal in elite rugby union players [6, 14]. Nevertheless, according to our results, these relatively small (and non-significant) differences can represent meaningful changes in performance, and therefore should be considered by coaches when preparing training programs and planning individual workouts in the context of high-performance sports. It is crucial to mention that these strategies could be further enhanced in terms of effectiveness and precision by incorporating the analysis of additional jump metrics (e.g., peak and time to peak power, peak force, propulsive impulse, etc.) when utilizing force platforms for data collection [25, 33, 34].

Notably, different from the vast number and relative frequency of true changes found in strength- (BP 1RM and HS 1RM) and power-related (SJ and CMJ) qualities, sprint velocity and momentum practically did not vary across the season. Specifically, whereas more than 75% and 60% of backs and forwards exhibited meaningful variations in 1RM strength and vertical jump height, only 15% and 25% of them presented real changes in 10- and 30-m sprint velocity (Figures 3, 4, and 5; respectively). As a consequence of the lack of meaningful increases in sprint velocity (and BM), only a small percentage of players (< 15%) displayed increased levels of sprint momentum, in both 10- and 30-m (Figure 6). This is also surprising, given that general and sport-specific training programs differ considerably between playing positions (Table 1). For example, backs typically execute more explosive and strength-power oriented training sessions, with forwards exposed to more maximum strength and hypertrophy-oriented loads across the season (Tables 2 and 3). Indeed, when it comes to the development of sprinting skills in highly-trained athletes during the competitive period, coaches should keep in mind two basic concepts: 1) the narrow "window of development" for speed-related abilities, and 2) the limited transference of strength-power training to sprint performance [10, 17, 30]. It is worth noting that this is an issue that affects not only team-sport players, but also highly-specialized and powerful track and field athletes (e.g., sprinters and jumpers) from different levels, who follow tailored training programs and compete under different circumstances [17, 35–37].

As part of a long-term study, elite rugby union players were tracked over a 1-year period to examine the potential transference of lower-body strength and power gains to sprinting kinematics [10]. After comparing pre- and post-test scores, the authors concluded that the evolution of strength, speed, and power qualities over the season tend to be minimal (or absent) in rugby union players with extensive training backgrounds [10]. Moreover, even when moderate improvements in certain strength measures occur and considerable levels of transference are achieved (e.g., increases in power clean strength corresponding to increases in stride length during the acceleration phase of sprint running), these athletes do not exhibit significant changes in sprint velocity [10]. On the basis of these findings, the authors suggested that highly-trained rugby players may reach a point of "diminishing returns", where high levels of strength do not necessarily result in positive transfer to sprinting ability [10]. Another possible explanation for the low degree of transference of strength to and lack of meaningful variations in sprint performance may be related to the high levels of physical and physiological strain that these athletes are exposed to throughout the competitive season [38, 39]. It is likely that the "excessive" training and match load accumulated during the season may negatively affect the magnitude of neuromuscular adaptations in senior rugby athletes, especially those associated with the development of complex sprint-specific skills. These excessive workloads, combined with inadequate recovery time and a gradual decrease in the relative volume and frequency of neuromuscular training, may not only hamper the proper development of speed-related capabilities within the season, but also preclude their progressive evolution across different age-categories (e.g., no differences in 10- and 40-m sprint times between junior and senior rugby players) [39, 40]. Importantly, this paradoxical finding (i.e., lack of evolution in sprint performance throughout the players' specialization process) has also been reported for other team-sports [41, 42], and certainly deserves further investigation. Together, these factors could help to explain why the vast majority of our athletes did not exhibit any meaningful variations (i.e., true changes) in sprint velocity and momentum over the course of the annual training cycle, even when a very sensitive statistical technique was used to test for differences across multiple time points.

In summary, we demonstrated that a large proportion of elite rugby union players involved in a supervised 11-month in-season training program presented real changes in maximum strength and power-related performance. In contrast, a small number of these players improved sprint velocity and sprint momentum at 10- and 30-m. As in other studies with a similar design, this research is limited by the impossibility of manipulating and controlling training variables and match schedules, as well as the difficulty of testing the effects of specific training components (e.g., resistance or sprint-specific training sessions). However, the present study highlights the need to consider new approaches for assessing variations in the neuromuscular performance of elite athletes throughout the annual training season. Specifically, while meaningful changes (i.e., when the improvement is greater than the individual target score [25]) in strength-power qualities are frequently observed, the same does not hold true for speed-related qualities during the annual training season. These findings have important implications not only for a more accurate assessment of seasonal variations in performance, but also for the development of more effective strength, speed, and power training

strategies for elite athletes. Future studies using the same statistical approach (i.e., true changes) and encompassing a larger number of jump metrics (e.g., comparing concentric and eccentric jumping parameters, asymmetries, etc.) are also needed to better understand how these parameters may fluctuate throughout the season.

CONCLUSIONS

During the annual training cycle, national team rugby union players usually exhibit meaningful increases in 1RM strength and power-related capabilities, but rarely present real changes in sprint velocity and sprint momentum. To detect these small but important variations, practitioners are advised to utilize the "true changes" calculation by setting "target scores" and examining whether fluctuations in performance metrics are greater than their "natural variability" (estimated by the individual CVs). This statistical procedure is extremely useful when non-significant differences in physical performance are highly expected, as is the case for changes associated with strength, speed, and power performance in elite rugby union players (or other team-sport athletes) over the competitive period [7, 12, 17, 30]. Under this realistic scenario, the use of this simple and applied statistical tool can help coaches and sport scientists to make well-informed decisions on individualized training prescription and training load management. This may be particularly relevant for the creation of more effective, customized, and realistic sprint-specific training programs. Practitioners from other team-sports (e.g., soccer, futsal, rugby sevens, and cricket) could also benefit from the application of the same statistical approach given the similar pattern of strength-power and, specifically, speed development throughout the season.

Conflict of interest

The authors declare no conflict of interest.

REFERENCES

1. McGuigan MR, Wright GA, Fleck SJ. Strength training for athletes: does it really help sports performance? Int J Sports Physiol Perform. 2012; 7(1):2–5.
2. Suchomel TJ, Nimphius S, Stone MH. The Importance of Muscular Strength in Athletic Performance. Sports Med. 2016; 46(10):1419–1449.
3. Alonso-Aubin DA, Picon-Martinez M, Chulvi-Medrano I. Strength and Power Characteristics in National Amateur Rugby Players. Int J Environ Res Public Health. 2021; 18(11):5615.
4. Furlong LM, Harrison AJ, Jensen RL. Measures of Strength and Jump Performance Can Predict 30-m Sprint Time in Rugby Union Players. J Strength Cond Res. 2021; 35(9):2579–2583.
5. Loturco I, Dello Iacono A, Nakamura FY, Freitas TT, Boullosa D, Valenzuela PL, Pereira LA, McGuigan MR. The Optimum Power Load: A Simple and Powerful Tool for Testing and Training. Int J Sports Physiol Perform. 2022; 17(2):151–159.
6. Baker D. The effects of an in-season of concurrent training on the maintenance of maximal strength and power in professional and college-aged rugby league football players. J Strength Cond Res. 2001; 15(2):172–177.
7. Gannon EA, Stokes KA, Trewartha G. Strength and Power Development in Professional Rugby Union Players Over a Training and Playing Season. Int J Sports Physiol Perform. 2016; 11(3):381–387.
8. Loturco I, McGuigan MR, Freitas TT, Valenzuela PL, Pereira LA, Pareja-Blanco F. Performance and reference data in the jump squat at different relative loads in elite sprinters, rugby players, and soccer players. Biol Sport. 2021; 38(2):219–227.
9. Argus CK, Gill ND, Keogh JW, McGuigan MR, Hopkins WG. Effects of two contrast training programs on jump performance in rugby union players during a competition phase. Int J Sports Physiol Perform. 2012; 7(1):68–75.
10. Barr MJ, Sheppard JM, Agar-Newman DJ, Newton RU. Transfer effect of strength and power training to the sprinting kinematics of international rugby players. J Strength Cond Res. 2014; 28(9):2585–2596.
11. Crewther BT, Heke T, Keogh J. The effects of two equal-volume training protocols upon strength, body composition and salivary hormones in male rugby union players. Biol Sport 2016; 33(2):111–116.
12. Appleby B, Newton RU, Cormie P. Changes in strength over a 2-year period in professional rugby union players. J Strength Cond Res. 2012; 26(9):2538–2546.
13. Gabbett TJ. Changes in physiological and anthropometric characteristics of rugby league players during a competitive season. J Strength Cond Res. 2005; 19(2):400–408.
14. Wade JA, Fuller JT, Devlin PJ, Doyle TLA. Senior and Junior Rugby League Players Improve Lower-Body Strength and Power Differently During a Rugby League Season. J Strength Cond Res. 2022; 36(5):1367–1372.
15. Zabaloy S, Gálvez González J, Giráldez J, Fink B, Alcaraz PE, Pereira L, Loturco I, Freitas TT. Changes in body composition and physical performance measures during a regular competitive season among young backs and forwards rugby players. Sports Biomech. 2022; In Press:1–18.
16. Freitas TT, Pereira LA, Reis VP, Fernandes V, Alcaraz PE, Azevedo P, Loturco I. Effects of a Congested Fixture Period on Speed and Power Performance of Elite Young Soccer Players. Int J Sports Physiol Perform. 2021; 16(8):1120–1126.
17. Loturco I, Fernandes V, Bishop C, Mercer VP, Siqueira F, Nakaya K, Pereira LA, Haugen T. Variations in Physical and Competitive Performance of Highly Trained Sprinters Across an Annual Training Season. J Strength Cond Res. 2023; 37(5):1104–1110.
18. Pecci J, Muñoz-López A, Jones PA, Sañudo B. Effects of 6 weeks in-season flywheel squat resistance training on strength, vertical jump, change of direction and sprint performance in professional female soccer players. Biol Sport. 2023; 40(2):521–529.
19. Haugen T. Sprint conditioning of elite soccer players: worth the effort or lets just buy faster players. Sport Perform Sci Rep. 2017; 1:1–2.
20. Zabaloy S, Tondelli E, Pereira LA, Freitas TT, Loturco I. Training and testing practices of strength and conditioning coaches in Argentinian Rugby Union. Int J Sports Sci Coach. 2022; 17(6):1331–1344.
21. 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):779–791.
22. Doering TM, Elsworthy N, Callaghan DE, Jones B, Teramoto M, Scanlan AT. A comparison of activity demands between trial matches and in-season matches across multiple teams and seasons in semi-professional, male rugby league players. Biol Sport. 2023; 40(4):1239–1247.
23. Young WB. Transfer of strength and power training to sports performance. Int J Sports Physiol Perform. 2006; 1(2):74–83.

24. Bishop C, Abbott W, Brashill C, Loturco I, Beato M, Turner A. Seasonal Variation of Physical Performance, Bilateral Deficit, and Interlimb Asymmetry in Elite Academy Soccer Players: Which Metrics Are Sensitive to Change? J Strength Cond Res. 2023; 37(2):358–365.
25. Bishop C, Jordan M, Torres-Ronda L, Loturco I, Harry J, Virgile A, Mundy P, Turner A, Comfort P. Selecting Metrics That Matter: Comparing the Use of the Countermovement Jump for Performance Profiling, Neuromuscular Fatigue Monitoring, and Injury Rehabilitation Testing. Strength Cond J. 2023; In Press
26. Loturco I, Kobal R, Moraes JE, Kitamura K, Cal Abad CC, Pereira LA, Nakamura FY. Predicting the Maximum Dynamic Strength in Bench Press: The High Precision of the Bar Velocity Approach. J Strength Cond Res. 2017; 31(4):1127–1131.
27. Loturco I, Pereira LA, Cal Abad CC, Gil S, Kitamura K, Kobal R, Nakamura FY. Using Bar Velocity to Predict the Maximum Dynamic Strength in the Half-Squat Exercise. Int J Sports Physiol Perform. 2016; 11(5):697–700.
28. Brown LE, Weir JP. ASEP procedures recommendation I: accurate assessment of muscular strength and power. J Exerc Physiol Online. 2001; 4(3):1–21.
29. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale (NJ): Lawrence Erlbaum Associates; 1988.
30. Carr C, McMahon JJ, Comfort P. Changes in Strength, Power, and Speed Across a Season in English County Cricketers. Int J Sports Physiol Perform. 2017; 12(1):50–55.
31. Arcos AL, Martínez-Santos R, Yanci J, Mendiguchia J, Méndez-Villanueva A. Negative Associations between Perceived Training Load, Volume and Changes in Physical Fitness in Professional Soccer Players. J Sports Sci Med. 2015; 14(2):394–401.
32. Casajus JA. Seasonal variation in fitness variables in professional soccer players. J Sports Med Phys Fitness. 2001; 41(4):463–469.
33. 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.
34. Spyrou K, Alcaraz PE, Marín-Cascales E, Herrero-Carrasco R, Cohen DD, Freitas TT. Neuromuscular Performance Changes in Elite Futsal Players Over a Competitive Season. J Strength Cond Res. 2023; 37(5):1111–1116.
35. Haugen T, Tønnessen E, Seiler S. 9.58 and 10.49: nearing the citius end for 100 m? Int J Sports Physiol Perform. 2015; 10(2):269–272.
36. Haugen TA, Solberg PA, Foster C, Morán-Navarro R, Breitschädel F, Hopkins WG. Peak Age and Performance Progression in World-Class Track-and-Field Athletes. Int J Sports Physiol Perform. 2018; 13(9):1122–1129.
37. Loturco I. Rethinking Sport Science to Improve Coach-Researcher Interactions. Int J Sports Physiol Perform. 2023, DOI: 10.1123/ijspp.2023-0367:1–2.
38. Arcos AL, Yanci J, Mendiguchia J, Gorostiaga EM. Rating of muscular and respiratory perceived exertion in professional soccer players. J Strength Cond Res. 2014; 28(11):3280–3288.
39. Gabbett TJ. Performance changes following a field conditioning program in junior and senior rugby league players. J Strength Cond Res. 2006; 20(1):215–221.
40. Kobal R, Nakamura FY, Moraes JE, Coelho M, Kitamura K, Cal Abad CC, Pereira LA, Loturco I. Physical Performance of Brazilian Rugby Players From Different Age Categories and Competitive Levels. J Strength Cond Res. 2016; 30(9):2433–2439.
41. Ayarra R, Nakamura FY, Iturricastillo A, Castillo D, Yanci J. Differences in Physical Performance According to the Competitive Level in Futsal Players. J Hum Kinet. 2018; 64:275–285.
42. Loturco I, Jeffreys I, Abad CCC, Kobal R, Zanetti V, Pereira LA, Nimphius S. Change-of-direction, speed and jump performance in soccer players: a comparison across different age-categories. J Sports Sci. 2020; 38(11–12):1279–1285.

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Napping and heart rate variability in elite athletes

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ABSTRACT: Sleep and autonomic nervous system (ANS) influence each other in a bidirectional fashion. Importantly, it has been proposed that sleep has a beneficial regulatory influence over cardiovascular activity, which is mostly controlled by autonomic regulation through the activity of sympathetic and parasympathetic pathways of the ANS. A well-established method to non-invasively assess cardiac autonomic activity is heart rate variability (HRV) analysis. We aimed to investigate the effect of a 40-min nap opportunity on HRV. Twelve professional basketball players randomly accomplished two conditions: 40-min nap (NAP) and control (CON). Nocturnal sleep and naps were monitored by actigraphic recording and sleep diaries. Total sleep time (TST), time in bed (TIB), sleep efficiency (SE), sleep onset latency (SOL), and wake after sleep onset (WASO) were analyzed. HRV was analyzed in 5-min segments during quiet wake before and after each condition with controlled breathing. Were analysed high (HF) and low frequency (LF) bands, the standard deviation of NN interval (SDNN), HRV index and stress index (SI). Wellness Hooper index and Epworth Sleepiness Scale (ESS) were assessed before and after both conditions. There was no significant difference in TIB, TST, SE, WASO, and VAS between NAP and CON. A significant increase in SDNN, HRV index, and LF and a significant decrease in HF, SI, ESS, and Hooper's stress and fatigue scores were observed from pre- to post-nap. In conclusion, napping reduces sleepiness, stress and fatigue, and might provide an advantage by preparing the body for a much-required sympathetic comeback following peaceful rest.

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INTRODUCTION

Sleep has been widely recognized as the most effective recovery strategy available to athletes [1, 2]. In the last decade, a growing body of evidence has proposed napping as a safe and non-invasive intervention to supplement night-time sleep and improve physical and cognitive performances [3–6]. In our previous research, we reported a beneficial effect of napping on physical and cognitive performances in athletes [7] as well as in older adults [8]. A 40 min daytime nap opportunity improved physical outcomes of elite basketball players and was deemed successful as a strategy to overcome the deterioration in shooting performance caused by the fatigue induced during exhaustive gameplay situations [9]. In another study, we reported a beneficial effect of napping on technical and tactical performance, physiological responses, and perceived exertion during a real game situation among elite athletes [10]. In addition, napping was an effective strategy for reducing sleepiness, stress, fatigue, anxiety, anger, and oral temperature [9, 10]. However, the mechanisms underlying the beneficial effects of napping remain unclear. According to Gupta, "Siesta is still an enigma" [11].

Furthermore, it has been reported that sleep and the autonomic nervous system (ANS) influence each other in a bidirectional fashion (for review see Trinder et al. [12]). Changes in the ANS modulate sleep onset as well as the transition between the different stages during nocturnal sleep [12, 13] but also during daytime naps [14, 15]. Importantly, it has been proposed that sleep has a beneficial regulatory influence over cardiovascular activity, a reciprocated influence that likely reflects a functional aspect of sleep [12]. A well-established method to non-invasively assess cardiac autonomic activity is heart rate variability (HRV) analysis [14, 15]. The cardiovascular system is mostly controlled by autonomic regulation through the activity of sympathetic and parasympathetic pathways

of the autonomic nervous system. Analysis of HRV permits insight into this control mechanism [16, 17].

Moreover, HRV represents a psychophysiological marker of mental and physical well-being [18–20]. Increased HRV reflects a healthy ANS that can respond to changing environmental circumstances [19, 21]. By contrast, decreased HRV is a marker of autonomic inflexibility [22] and has been linked to a very large number of physical [23, 24] and psychological [25, 26] diseases. Furthermore, several studies have shown that acute [27, 28] and chronic [29, 30] stresses lead to a decrease in HRV. In the area of sports, HRV has increasingly been used to examine training load and recovery state after training [31], to monitor changes in physical performance and individual adaptation to training [32], to assess ventilatory thresholds [33], etc…

Fundamentally, HRV consists of measuring the inter-beat time intervals between consecutive heartbeats and represents the variability of intervals between consecutive R-peaks (RR) on the QRS complex on the ECG [17]. HRV measures can be divided mainly into time domain measures, based on arithmetic calculations of RR intervals; and frequency domain measures, based on spectral analysis (see Malik et al. [34] for more information on methods of HRV analysis). Studies investigating the effect of daytime napping on HRV in healthy young individuals reported a reduction in cardiovascular output and a shift from sympathetic to parasympathetic (vagal) dominance from wakefulness into sleep [14, 35, 36]. Importantly, these circadian- and sleep-dependent shifts in the ANS are critical to the maintenance of autonomic balance between parasympathetic and sympathetic branches and are beneficial for health and cognition [37, 38]. Moreover, Suppiah et al. [39] reported that nap did not elicit any performance or physiological benefits as monitored by HRV among adolescents. Another study aimed to explore the relationship between HRV and napping duration and their impact on handball performance [40]. Although no significant difference was reported between the two nap opportunities (i.e., 20 and 60 min) on HRV, a significant correlation was showed only with long nap between HRV parameters and handball performance.

Given the pressing need to understand the role of napping on physiological and psychological health and the lack of studies investigating the effect of daytime sleep on HRV in athlete populations, the present study aimed to assess cardiac autonomic activity — through HRV analysis — before and following an afternoon nap in elite basketball players. We hypothesize that diurnal napping would (i) change the HRV profile of athletes following nap in order to prepare them for physical stress, and (ii) impact positively perceived variables including stress, sleepiness and fatigue.

MATERIALS AND METHODS

Participants

Twelve high-level professional male basketball players (26 ± 5 years; 193 ± 7 cm; 87 ± 11 kg; 13 ± 2 % body fat and 17 ± 6 years expertise) volunteered to participate in the study. They were fully informed about the study information, and written informed consent was obtained from each participant before the study. Athletes are classified as successful elite (eliteness' mean score = 9.0 ± 1.2), based on Swann et al. [41]' categories. Eight out of the twelve players have taken part in international tournaments and represented their country in international competitions. Seven of them have more than 8 years of experience at the highest level of competition. Players were part of the same team and they trained regularly 6–8 times per week and played 1–2 competitions per week since they signed a professional contract (*i.e.,* 8 ± 5 years). They were asked to stay away from tobacco, alcoholic, or caffeinated beverages. None was habitual napper or presented an extreme morning or extreme evening type (Morningness–Eveningness Questionnaire's mean score = 56 ± 3.1) [42]. The protocol of the present study was approved by the local Institutional Review Board (CPP SUD N° 0339/2021) and carried out according to the guidelines of the Helsinki Declaration for human experimentation. The sample size was a priori calculated using the G*power software [43], as strongly recommended [44], and based on an earlier study with a similar paradigm [45]. Statistical analysis indicated a minimum required sample size of twelve participants.

Procedure

To minimize the learning effects during the study, participants were familiarized with the experimenters, sleeping room, tests, and questionnaires during a familiarization session. In addition, to assess their maximal heart rate (HR_{max}), players carried out a Yo-Yo Intermittent Recovery test level-1; which is considered a valid basketball-specific test for the assessment of aerobic fitness [46]. The test consisted of 20-m shuttle runs performed at increasing velocities with 10-s active recovery between runs until exhaustion.

In experimental sessions, each participant completed randomly two test sessions, 72 hours apart. All sessions were performed after a reference night. Athletes had a standardized morning in the laboratory. They subjectively rated their last night's sleep, ate a standardized breakfast (8:00 h) then stayed awake doing passive activities (*e.g.,* watching television, reading). After eating an isocaloric lunch at 12:00 p.m., they were assigned to experience nap (NAP) and no-nap (CON) conditions. HRV was analyzed in 5-min segments during a quiet wake before and after each condition with controlled breathing in a supine position.

In NAP condition, participants entered the comfortably warm, fully dark, and quiet sleeping room at 12:50 h. After 10 min of acclimatization in bed, nap opportunity started at 13:00 h and lasted for 40 min. The visual analogue scale (VAS) was presented to participant following the nap opportunity to evaluate their subjective sleep quality. In the CON condition, participants spent the same amount of time seated in comfortable chairs watching television.

Measured Variables

Actigraphy and sleep diaries

Participants wore GT3X activity monitors (Actigraph, Pensacola, FL, USA) on their non-dominant arms the night before each experimental day (from 18:00 h) and took them off after the napping opportunities (at 15:00 h). Sleep parameters (TST, time in bed (TIB), sleep efficiency (SE), sleep onset latency (SOL), and wake after sleep onset (WASO)) were derived and analyzed using Actilife 6 (version 6.13.7) software. Actigraphy is a non-invasive device and was evaluated as a valid tool to assess sleep and wake behaviourbehaviours compared to the gold standard polysomnography [47].

Subjective sleep quality

The subjective sleep quality was evaluated using the visual analogueanalogue scale (VAS) [48]. The VAS is a 10-cm scale that shows "Very bad sleep quality" (left side) and "Very good sleep quality" (right side).

Heart rate (HR)

Heart rate was assessed using HR monitor chest belts (Team System 2, Polar, Kempele, Finland) provided with internal memory and recorded at 1-second intervals. The HR beats were exported and analyzed using Excel software (Microsoft Corporation, Redmond, WA, USA). HR data were expressed as mean (HR_{mean}), peak (HR_{peak}), and percentage of each subject's individual HR_{max} (%HR_{max}).

Heart rate variability (HRV) analysis

R-wave peaks were detected automatically by Kubios HRV Analysis Software 2.2 (Matlab, Kuopio, Finland), visually examined, and edited for artefacts [49]. The same software was employed to perform the HRV analysis of the R-wave series according to the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology guidelines [34]. Kubios HRV is a cutting-edge and simple-to-use freeware for coronary heart rate variability (HRV) analysis. It comprises an improvised QRS detection algorithm and tools for noise correction, trend removal, and analysis sample selection [50]. The two major components of the frequency domain, i.e., high frequency (HF, 0.15–0.4 Hz) and low frequency (LF, 0.04–0.15 Hz) bands, and for the time domain, the standard deviation of the NN interval (SDNN), an index of global variability, were analyzed. Moreover, HRV triangular index (HRV index) and stress index (SI) were also calculated. HRV index is a geometric measure that calculates the integral of the density of the RR interval histogram divided by its height and reflects the global HRV. A 5-min epoch is conventionally used to study the above-mentioned variables [51]. Normalized HRV values (LF nu, HF nu) were calculated from the raw values of either short-term frequency band (LF or HF) divided by the total spectral power (typically LF + HF), with the value of this expressed as a decimal [52]. Unlike raw power, normalized units allow direct comparison between frequency and autoregressive methods for calculating spectral power, between spectral power expressed as ms^2 or bpm^2, and between different algorithms for calculation.

Hooper scale

This is a validated psychological self-reporting scale of sleep quality, fatigue, stress, and muscle pain. Parameters were measured separately using a 7-point subjective rating scale ranging from 1 "very, very low" to 7 "very, very high". The total score indicates the athlete's form state or readiness to train [53].

Epworth Sleepiness Scale (ESS)

Daytime sleepiness was assessed using a scale of eight elements (*i.e.,* ESS). Participants assign a score of "0" to "3" for each situation where there is "no chance" for "0", a low chance for "1", "a moderate chance" for "2" and "a high chance" for "3" to fall asleep. The score obtained from the scale ranges from "0" to "24" [54].

Statistical analysis

Analyses were performed using Excel (Microsoft Office, v.2016) and SPSS Statistics (IBM, v.23) software. All data were expressed as means ± standard error of the mean (SEM). The Shapiro-Wilk W-test revealed that the normalized units of LF (LF nu) and HF (HF nu), SDNN, HRV index, ESS and Hooper's fatigue and total score were normally distributed. Analysis was performed using a two-way repeated measures ANOVA [2 conditions (CON and NAP) x2 times (pre and post)] for HR_{mean}, HR_{peak}, LF nu, HF nu, SDNN, HRV index, ESS, Hooper's fatigue, and the total score. ANOVA effect sizes were calculated as partial eta squared (*np2*). When significant main or interaction effects were observed, pairwise comparisons were performed using the Bonferroni post-hoc test. Sleep parameters, SI and Hooper's sleep, stress, and muscle soreness scores being not normally distributed, were analyzed using Friedman nonparametric analysis of variance, and pairwise comparisons were conducted using the Wilcoxon test.

RESULTS

Objective and subjective sleep Parameters

Statistical analysis showed no significant difference during the night before experimental days in objective (i.e., TIB, TST, SE and WASO) and subjective (i.e., VAS) sleep parameters between the CON and NAP conditions.

Heart rate

There was no significant effect of condition ($F_{(1,11)} = 2.7$, $p > 0.05$, $\eta p^2 = 0.19$) or time ($F_{(1,11)} = 0.002$, $p > 0.05$, $\eta p^2 = 0.005$) on HR_{mean}. Two-way repeated measures ANOVA showed a significant effect of time ($F_{(1,11)} = 6.1$, $p = 0.03$, $\eta p^2 = 0.35$) on HR_{peak}. Bonferroni post-hoc test revealed that HR_{peak} was significantly higher in post-nap wakefulness compared to pre-nap wakefulness ($p = 0.004$) (Figure 1).

HRV analysis

Frequency domain

Statistical results revealed a significant interaction (condition × time) ($F_{(1,11)}$ = 9.42, p = 0.01, ηp^2 = 0.46) on the normalized unit of LF (LF nu). There was no significant effect of time ($F_{(1,11)}$ = 3.22, p > 0.05, ηp^2 = 0.22) or condition ($F_{(1,11)}$ = 0.09, p > 0.05, ηp^2 = 0.008). Bonferroni post-hoc showed that LF nu was significantly higher after nap compared to before nap (P = 0.005) (Figure 2.a). Similarly, while no significant effect of time ($F_{(1,11)}$ = 3.92, p > 0.05, ηp^2 = 0.26) and condition ($F_{(1,11)}$ = 0.01, p > 0.05, ηp^2 = 0.001) was observed on the normalized unit of HF (HF nu), there was a significant interaction (condition × time) ($F_{(1,11)}$ = 4.91, p = 0.04, ηp^2 = 0.30). HF nu was significantly lower after nap compared to before nap (p = 0.005) (Figure 2.b).

Time-domain

Concerning SDNN, repeated measure ANOVA tests revealed a significant effect of time ($F_{(1,11)}$ = 5.03, p = 0.04, ηp^2 = 0.31). There was no significant effect of condition ($F_{(1,11)}$ = 0.46, p > 0.05, ηp^2 = 0.04) or interaction ($F_{(1,11)}$ = 1.04, p > 0.05, ηp^2 = 0.08).

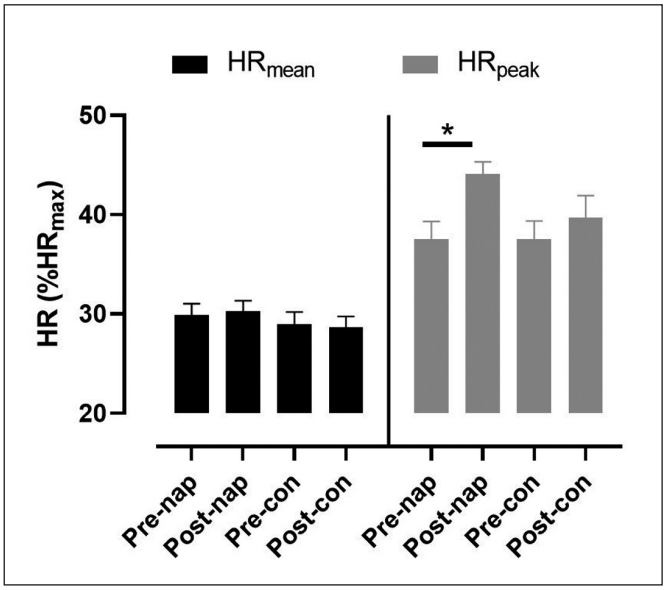


FIG. 1. Mean values (± SEM) for HR_{mean} and HR_{peak} before and after NAP and CON conditions. *: significant difference (p < 0.05). Abbreviations: CON, control condition; NAP, nap condition; Pre, before nap/rest period; Post, after nap/rest period.

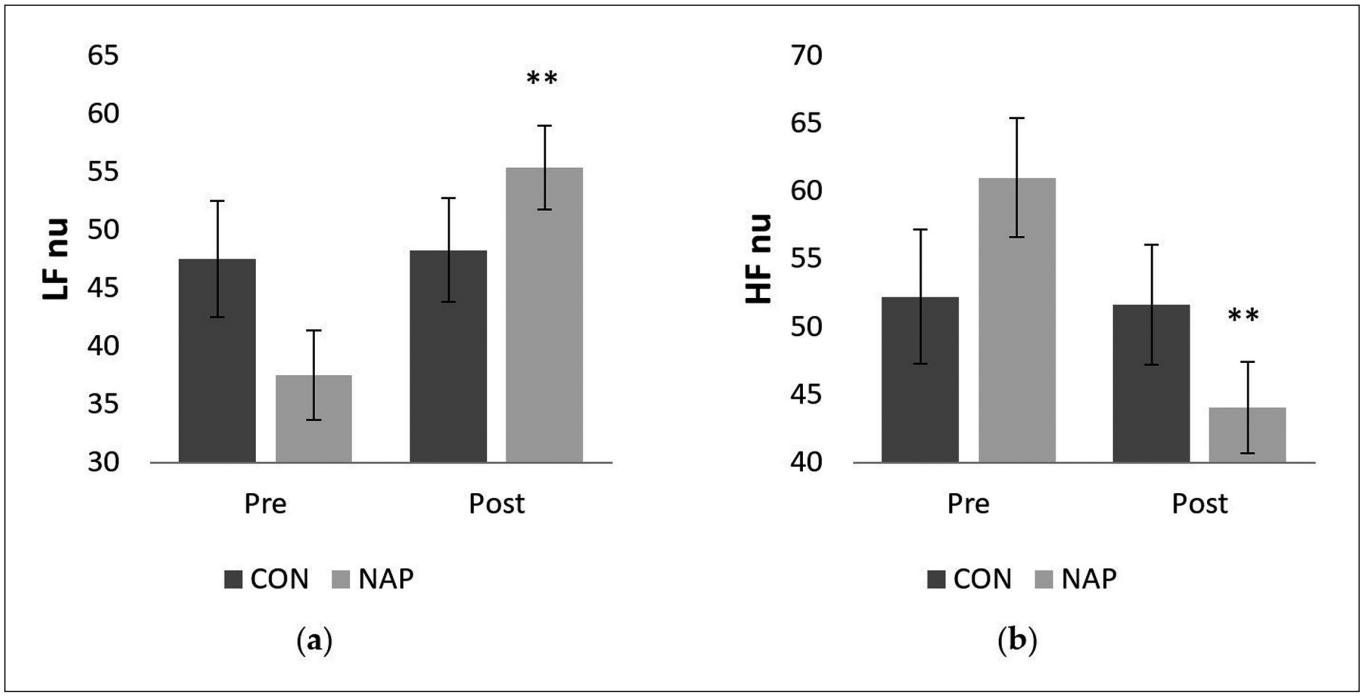


FIG. 2. Mean values (± SEM) for (a) LF nu, and (b) HF nu before and after nap/rest. ** p < 0.01 significant difference compared to pre nap/rest. Abbreviations: CON, control condition; HF, high frequency; LF, low frequency; NAP, nap condition; nu, normalized unit; Pre, before nap/rest period; Post, after nap/rest period.

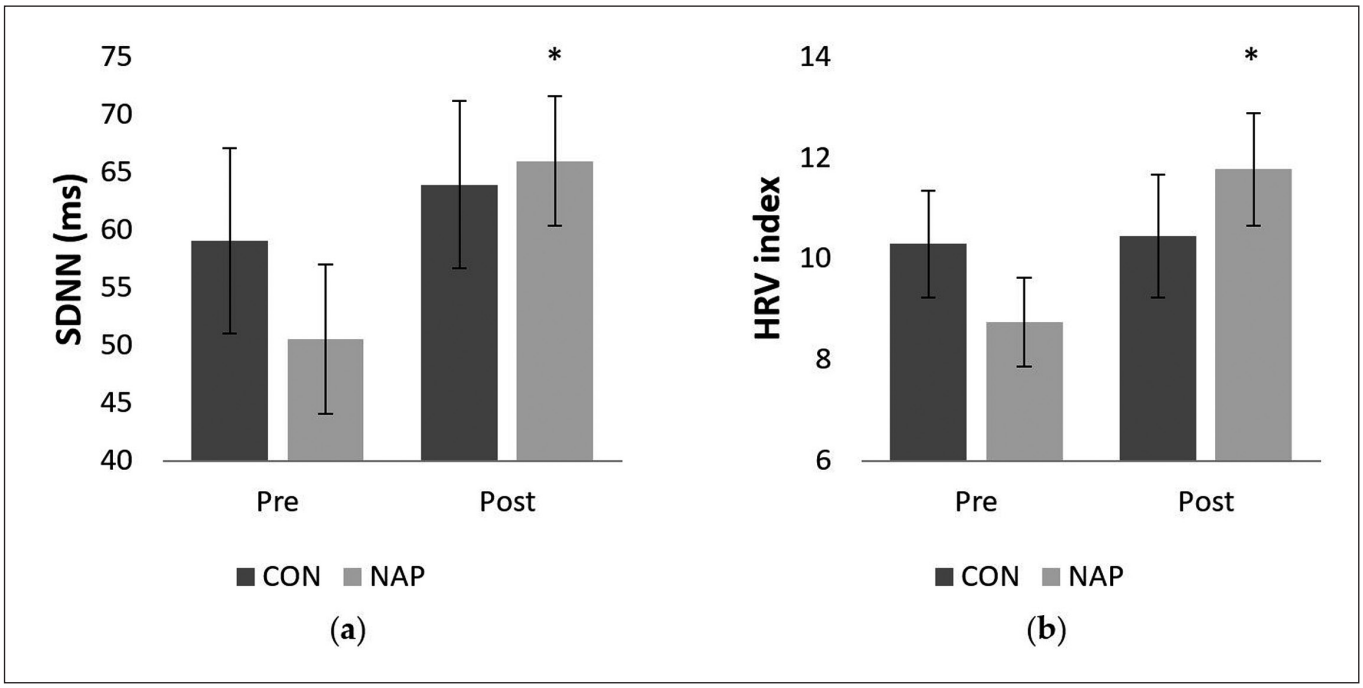


FIG. 3. Mean values (± SEM) for (a) SDNN, and (b) HRV index before and after nap/rest. * $p < 0.05$ significant difference compared to pre nap/rest. Abbreviations: CON, control condition; NAP, nap condition; Pre, before nap/rest period; Post, after nap/rest period.

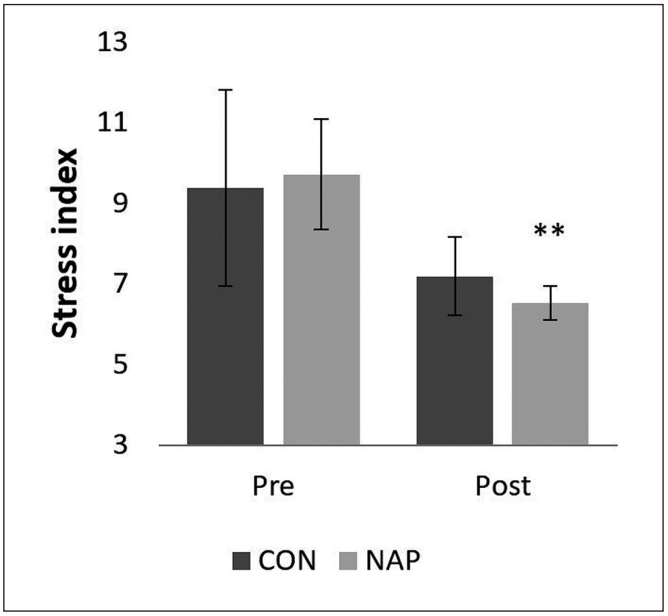


FIG. 4. Mean values (± SEM) for Stress Index before and after NAP and CON conditions. ** $p < 0.01$ significant difference compared to pre nap/rest. Abbreviations: CON, control condition; NAP, nap condition; Pre, before nap/rest period; Post, after nap/rest period.

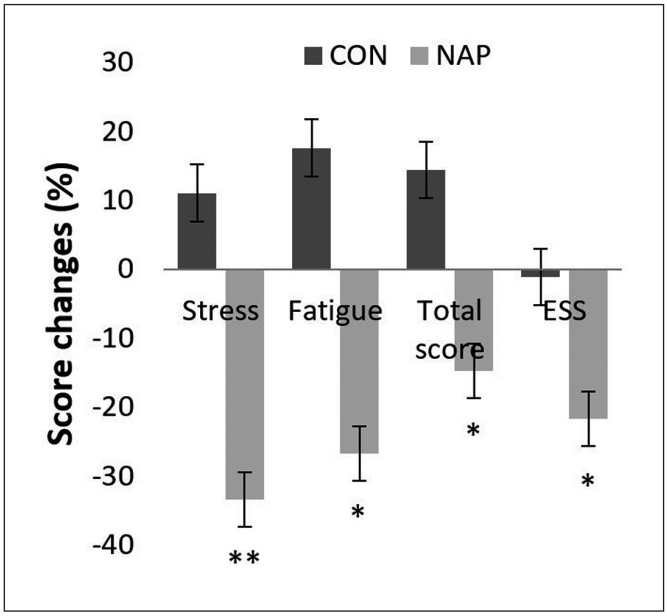


FIG. 5. Percentage of score changes (± SEM) from pre to post nap/rest for Hooper's stress, fatigue and total score, and ESS. * $p < 0.05$, ** $p < 0.01$ significant difference compared to pre nap/rest. Abbreviations: CON, control condition; ESS, Epworth sleepiness scale; NAP, nap condition; Pre, before nap/rest period; Post, after nap/rest period.

SDNN values increased significantly in post-nap wakefulness ($p = 0.04$ (Figure 3.a).

Regarding geometric analysis, the two-way repeated measures ANOVA revealed a significant interaction (condition × time) ($F_{(1,11)} = 5.55$, $p = 0.03$, $\eta p^2 = 0.33$) on the HRV index. No significant effect of condition ($F_{(1,11)} = 0.01$, $p = 0.8$, $\eta p^2 = 0.002$) or time ($F_{(1,11)} = 2.74$, $p = 0.12$, $\eta p^2 = 0.20$) was reported. Values were significantly higher after nap compared to before nap ($p = 0.03$). Interestingly, there were no significant changes for the CON condition (Figure 3.b).

Stress index

A significant decrease was noticed in stress index (SI) during post-nap wakefulness compared to pre-nap wakefulness ($p = 0.01$). Results showed no significant changes in CON condition (Figure 4).

ESS and Hooper scale

Repeated measure ANOVA tests showed a significant effect of time ($F_{(1,11)} = 6.19$, $p = 0.03$, $\eta p^2 = 0.36$) and a significant interaction (condition × time) ($F_{(1,11)} = 5.18$, $p = 0.04$, $\eta p^2 = 0.32$) on ESS. Bonferroni post-hoc test revealed that ESS was significantly lower after nap compared to before nap ($p = 0.03$). In the same way, a significant decrease was observed in Hooper's post-nap stress, fatigue and total score compared to pre-nap ($p = 0.009$, $p = 0.01$, $p = 0.04$, respectively) (Figure 5).

DISCUSSION

In this study, we aimed to investigate the impact of daytime sleep on cardiac autonomic activity (i) to fill the gap in the literature and (ii) to give insight regarding the beneficial effect of nap reported in our previous papers [7–10]. To our knowledge, this is the first study to investigate the effect of a 40-min daytime nap opportunity on HRV in elite basketball players. Our findings showed that the HRV profiles of participants changed after a daytime nap, while no significant changes were reported for the control condition. We noticed a significant increase in HR_{peak}, SDNN, HRV index, and LF nu and a significant decrease in HF nu and SI following the nap opportunity. Moreover, daytime napping decreased Hooper's stress, fatigue, total score, and subjective sleepiness according to ESS.

It is well established that changes in LF and HF reflect specific changes in cardiac autonomic regulation. There is wide consensus regarding the significance of the HF component, which reflects cardiac parasympathetic nerve activity [13, 24, 34]. In contrast, the LF band was assumed to reflect a dominant sympathetic effect [17, 34]. It is worth mentioning that the meaning of the LF component is still debated. Some researchers consider LF as a marker of sympathetic activity, while other investigators believe that the LF component of HRV is a reflection of fluctuations in both sympathetic and parasympathetic activity [13, 17, 34, 55]. The current study showed a significant increase in HR_{peak} and time-domain parameters of HRV (i.e., SDNN and HRV index) after NAP. In addition, we noticed a significant decrease in HF from pre- to post-nap wakefulness, accompanied by a simultaneous increase in LF. Interestingly, there were no significant changes in the CON condition. Taken together, these results suggest a sympathetic dominance following the nap opportunity.

Importantly, previous studies reported significant changes in HRV profile from wakefulness into sleep and across different sleep stages during nocturnal sleep [12, 13] as well as daytime naps [14, 15]. The limited number of studies investigating the effect of daytime napping on HRV using various experimental protocols reported a shift of the ANS from sympathetic to parasympathetic dominance from wakefulness into sleep [14, 15, 35, 36, 56]. This vagal dominance is characterized by a reduced heart rate coupled with increased HF activity and a marked reduction of LF bands. Throughout the progression of non-rapid eye movement (NREM) sleep, HF activity remains elevated, with higher vagal modulation compared to rapid eye movement (REM) sleep, suggesting an overall reduction in cardiovascular output and dominance of parasympathetic/vagal activity during NREM sleep [14, 15, 35, 36, 56]. Importantly, these fluctuations and dynamic changes in the autonomic profile are similar to those seen during nocturnal sleep [35], are associated with significant benefits for the cardiovascular system, and may be responsible for the homeostatic regulatory balance between sympathetic and vagal activity [12]. This balance has been correlated with reduced risk for cardiovascular disease, diabetes, and all-cause mortality [24], suggesting a cardioprotective function of sleep [12] which has led some researchers to describe normal sleep as a "cardiovascular holiday" [12].

Interestingly, only one study compared the impact of daytime napping on the ANS from pre- to post-nap wakefulness [56]. The study of AlQatari et al. [56] showed an increase in LF during post-nap wakefulness compared with that during pre-nap wakefulness. The current study showed significant changes regarding HRV profile from pre- to post-nap wakefulness, including a marked increase in LF. This result is in line with the previous report [56], indicating relative sympathetic dominance. Similar to the results of AlQatari et al. [56], we noticed a significant decrease in HF, which also supports the above-mentioned statement regarding the restoration of sympathetic dominance during post-nap wakefulness. Moreover, a significant increase in the LF/HF ratio has been measured after- compared to pre-nap wakefulness [56]. Although the LF/HF ratio was proposed as an index describing the balance between the two branches of the ANS, in which an increased ratio reflects sympathetic dominance and a reduction in this ratio indicates parasympathetic dominance [57], this index has not been taken into account in the present study due to the several limitations described in previous research [55]. According to Billman [55], the complex nature of LF power (i.e., the LF component of HRV is a reflection of fluctuations in both sympathetic and parasympathetic activity) and the non-linear interactions between sympathetic and parasympathetic nerve activity that are confounded by the mechanical effects of respiration and prevailing heart rate, make it impossible (i) to delineate the physiological basis for

LF/HF with any degree of certainty and (ii) to quantify cardiac "sympathovagal balance".

The current investigation revealed a significant decrease in SI during post-nap compared to pre-nap wakefulness. This result was confirmed by Hooper's stress scores, which decreased significantly following the nap opportunity. In addition, the decrease in sleepiness and fatigue and the improvement of Hooper's total score suggest a better readiness of athletes and could explain the enhancement of performance reported in previous studies with NAP [9, 10]. It is important to mention that these studies included sedentary, inactive participants (i.e., young [14, 15, 35, 36, 56] or older adults [36]). One study compared daytime nap to nocturnal sleep [35]. Another study aimed to investigate changes in HRV during daytime naps in young and older adults [36]. Unlike the abovementioned studies, the present investigation aimed to evaluate the effect of nap on ANS regulation in an elite athlete population. Furthermore, it is noteworthy to mention that moderation of sympathetic activity – indicated by greater high-frequency HRV values – has been reported to be associated with improved basketball shooting, passing and dribbling performance in previous research [58].

Limitations

The present study presents some limitations. First, sleep was monitored using actigraphy, whereas, polysomnography provides more accurate results both in terms of quality and quantity and provides details regarding sleep stages [59]. Such information could have given us accurate information on the different changes in HRV profiles across sleep stages. Second, although this study was conducted on professional basketball players, only one basketball team was used, which could also lead to a lack of generalizability. Third, the selected participants were nonhabitual nappers. Given that non-habitual nappers display heavier sleep inertia at the awakening compared to habitual nappers [60], results could be different if habitual nappers were included instead of non-habitual nappers, especially regarding HRV indexes.

CONCLUSIONS

The results of the present study showed that a 40 min nap opportunity increased global heart rate variability, operationalized through an increase in LF nu and a decrease in HF nu. In addition, daytime napping might be a successful strategy for reducing stress since (i) the stress index decreased significantly during post-nap wakefulness and (ii) according to the Hooper scale, subjective stress scores were lower following nap. Overall, these findings suggest that napping reduces stress, sleepiness, and fatigue, and might provide an advantage by preparing the body for a much-required sympathetic comeback following peaceful rest and parasympathetic dominance during sleep. Our results support the notion that daytime napping is beneficial for cardiovascular health in basketball professional athletes.

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Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

1. Juliff LE, Halson SL, Peiffer JJ. Understanding sleep disturbance in athletes prior to important competitions. J Sci Med Sport. 2015; 18:13–18. doi: 10.1016/j.jsams.2014.02.007.
2. Walsh NP, Halson SL, Sargent C, et al. Sleep and the athlete: Narrative review and 2021 expert consensus recommendations. Br J Sports Med. 2020; bjsports-2020-102025. doi: 10.1136/bjsports-2020-102025.
3. Lastella M, Halson SL, Vitale JA, et al. To nap or not to nap? A systematic review evaluating napping behavior in athletes and the impact on various measures of athletic performance. Nat Sci Sleep. 2021; 13:841–862. doi: 10.2147/NSS.S315556.
4. Romyn G, Lastella M, Miller DJ, et al. Daytime naps can be used to supplement night-time sleep in athletes. Chronobiol Int. 2018; 35(6):865–868. doi: 10.1080/07420528.2018.1466795.
5. Blanchfield AW, Lewis-Jones TM, Wignall JR, et al. The influence of an afternoon nap on the endurance performance of trained runners. Eur J Sport Sci. 2018; 18:1177–1184. https://doi.org/10.1080/17461391.2018.1477180.
6. Brotherton EJ, Moseley SE, Langan-Evans C, et al. Effects of two nights partial sleep deprivation on an evening submaximal weightlifting performance; are 1 h powernaps useful on the day of competition? Chronobiol Int. 2019; 36:407–426. doi: 10.1080/07420528.2018.1552702.
7. Souabni M, Hammouda O, Romdhani M, et al. Benefits of Daytime Napping Opportunity on Physical and Cognitive Performances in Physically Active Participants: A Systematic Review. Sports Med. 2021; 1(10):2115–2146. doi: 10.1007/s40279-021-01482-1.
8. Souabni M, Souabni MJ, Hammouda O, et al. Benefits and risks of napping in older adults: A systematic review. Front Aging Neurosci. 2022; 14:1000707. doi: 10.3389/fnagi.2022.1000707.
9. Souabni M, Hammouda O, Souabni MJ, et al. 40-min nap opportunity attenuates heart rate and perceived exertion and improves physical specific abilities in elite basketball players. Res Sport Med. 2022; 1–14. doi: 10.1080/15438627.2022.2064221.
10. Souabni M, Hammouda O, Souabni M, et al. Nap improved game-related technical performance and physiological response during small-sided basketball game in professional players. Biol Sport. 2023; 40(2):389–397. https://doi.org/10.5114/biolsport.2023.116004.
11. Gupta R, Pandi-Perumal SR. Siesta: Still an Enigma. Sleep Vigil. 2019; 3:1–2. doi: 10.1007/s41782-019-00067-3.
12. Trinder J, Waloszek J, Woods MJ, et al. Sleep and cardiovascular regulation. Pflugers Arch. 2012;463(1):161-168. doi:10.1007/s00424-011-1041-3
13. Tobaldini E, Nobili L, Strada S, et al. Heart rate variability in normal and pathological sleep. Front Physiol. 2013; 4:294. doi: 10.3389/fphys.2013.00294.
14. Cellini N, Whitehurst LN, Mcdevitt EA, et al. Heart rate variability during daytime naps in healthy adults: Autonomic profile and short-term reliability. Psychophysio-logy. 2016; 53(4):473–81. doi: 10 .1111/psyp.12595.
15. Cellini N, Torre J, Stegagno L, et al. Cardiac autonomic activity during daytime nap in young adults. J Sleep Res. 2018; 27(2):159 –164. doi: 10 .1111/jsr.12539.

16. Aubert A, Seps B, Beckers F. Heart Rate Variability in Athletes. Sports Med. 2003; 33:889–919. doi: 10.2165/00007256 -200333120-00003.
17. Berntson GG, Thomas Bigger J, Eckberg DL, et al. Heart rate variability: Origins methods, and interpretive caveats. Psychophysiology. 1997; 34(6):623–48.
18. Ernst G. Heart-Rate Variability—More than Heart Beats? Front. Public Heal. 2017; 5:240. doi: 10.3389/fpubh .2017.00240.
19. Thayer JF, Hansen AL, Saus-Rose E, et al. Heart rate variability, prefrontal neural function, and cognitive performance: The neurovisceral integration perspective on self-regulation, adaptation, and health. Ann Behav Med. 2009; 37(2):141–53. doi: 10 .1007/ s12160-009-9101-z.
20. Kemp AH, Quintana DS. The relationship between mental and physical health: Insights from the study of heart rate variability. Int J Psychophysiol. 2013; 89(3):288–96. doi: 10.1016/j.ijpsycho .2013.06.018.
21. Beauchaine TP, Thayer JF. Heart rate variability as a transdiagnostic biomarker of psychopathology. Int J Psychophysiol. 2015; 98(2 Pt 2):338–350. doi: 10.1016/j.ijpsycho.2015.08.004.
22. Thayer JF, Lane RD. A model of neurovisceral integration in emotion regulation and dysregulation. J Affect Disord. 2000; 61(3):201–16. doi: 10 .1016/s0165-0327(00)00338-4.
23. Koenig J, Williams DP, Kemp AH, et al. Vagally mediated heart rate variability in headache patients – A systematic review and meta-analysis. Cephalalgia. 2016; 36(3):265–78. doi: 10.1177/033310 2415583989.
24. Thayer JF, Yamamoto SS, Brosschot JF. The relationship of autonomic imbalance, heart rate variability and cardiovascular disease risk factors. Int J Cardiol. 2010; 141(2):122–31. doi: 10.1016/j.ijcard .2009.09.543.
25. Chalmers JA, Quintana DS, Abbott MJA, et al. Anxiety disorders are associated with reduced heart rate variability: A meta-analysis. Front. Psychiatry. 2014; 5:80. doi: 10.3389/fpsyt.2014.00080.
26. Sgoifo A, Carnevali L, Pico Alfonso MDLA, et al. Autonomic dysfunction and heart rate variability in depression. Stress. 2015; 18(3):343–52. doi: 10.3109/1025 3890.2015.1045868.
27. Hamer M, Steptoe A. Association between physical fitness, parasympathetic control, and proinflammatory responses to mental stress. Psychosom Med. 2007; 69(7):660–6. doi: 10.1097/PSY .0b013e318148c4c0.
28. Sgoifo A, Braglia F, Costoli T, et al. Cardiac autonomic reactivity and salivary cortisol in men and women exposed to social stressors: Relationship with individual ethological profile. Neurosci. Biobehav. Rev. 2003; 27(1–2):179–88. doi: 10 .1016/s0149-7634(03)00019-8.
29. Chandola T, Heraclides A, Kumari M. Psychophysiological biomarkers of workplace stressors. Neurosci. Biobehav. Rev. 2010; 35(1):51–7. doi: 10.1016 /j.neubiorev.2009.11.005.
30. Zanstra YJ, Schellekens JMH, Schaap C, et al. Vagal and sympathetic activity in burnouts during a mentally demanding workday. Psychosom Med. 2006; 68(4):583–90. doi: 10.1097/01.psy .0000228012.38884.49.
31. Buchheit M, Simon C, Piquard F, et al. Effects of increased training load on vagal-related indexes of heart rate variability: A novel sleep approach. Am J Physiol – Hear Circ Physiol. 2004; 287(6):H2813–8. doi: 10.1152 /ajpheart.00490.2004.
32. Buchheit M, Simpson MB, Al Haddad H, et al. Monitoring changes in physical performance with heart rate measures in young soccer players. Eur J Appl Physiol. 2012; 112(2):711–23. doi: 10 .1007/ s00421-011-2014-0.
33. Ramos-Campo DJ, Rubio-Arias JA, Ávila-Gandía V, et al. Heart rate variability to assess ventilatory thresholds in professional basketball players. J Sport Heal Sci. 2017; 6(4):468–473. doi: 10.1016/j.jshs.2016.01.002.
34. Malik M, John Camm A, Thomas Bigger J, et al. Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. Circulation. 1996; 93(5):1043–65. PMID: 8598068.
35. Whitehurst LN, Naji M, Mednick SC. Comparing the cardiac autonomic activity profile of daytime naps and nighttime sleep. Neurobiol Sleep Circadian Rhythm. 2018; 5:52–57. doi: 10.1016 /j. nbscr.2018.03.001.
36. Chen PC, Sattari N, Whitehurst LN, et al. Age-related losses in cardiac autonomic activity during a daytime nap. Psychophysiology. 2021; 58(7):e13701. doi: 10.1111/psyp.13701.
37. Boudreau P, Yeh WH, Dumont GA, et al. Circadian variation of heart rate variability across sleep stages. Sleep. 2013; 36(12):1919–28. doi: 10.5665/sleep .3230.
38. Whitehurst LN, Chen PC, Naji M, et al. New directions in sleep and memory research: the role of autonomic activity. Curr Opin Behav Sci. 2020; 33:17–24. https://doi.org/10.1016/j.cobeha .2019.11.001.
39. Suppiah HT, Low CY, Choong G, et al. Effects of a short daytime nap on shooting and sprint performance in high-level adolescent athletes. Int J Sports Physiol Perform. 2019; 14:76–82. https://doi.org/10.1123/ijspp .2018-0107;
40. Nishida M, Yamamoto K, Murata Y, et al. Exploring the Effect of Long Naps on Handball Performance and Heart Rate Variability. Sport Med Int Open. 2021; 5(3):E73–E80. doi: 10.1055 /a-1551-8054;
41. Swann C, Moran A, Piggott D. Defining elite athletes: Issues in the study of expert performance in sport psychology. Psychol Sport Exerc. 2015; 16:3–14. https://doi.org/10.1016/j.psychsport .2014.07.004.
42. Horne JA, Ostberg O. A self assessment questionnaire to determine Morningness Eveningness in human circadian rhythms. Int J Chronobiol. 1976; 4(2):97–110. PMID: 1027738.
43. Faul F, Erdfelder E, Lang AG, et al. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007; 39(2):175–91. doi: 10 .3758/bf03193146.
44. Beck TW. The importance of a priori sample size estimation in strength and conditioning research. J Strength Cond Res. 2013; 27(8):2323–37. doi: 10 .1519/JSC.0b013e318278eea0.
45. Romdhani M, Dergaa I, Moussa-Chamari I, et al. The effect of post-lunch napping on mood, reaction time, and antioxidant defense during repeated sprint exercice. Biol Sport. 2021; 38(4):629–638. doi: 10.5114 /biolsport.2021.103569.
46. Castagna C, Impellizzeri FM, Rampinini E, et al. The Yo-Yo intermittent recovery test in basketball players. J Sci Med Sport. 2008; 1(2):202–8. doi: 10 .1016/j.jsams.2007.02.013.
47. Slater JA, Botsis T, Walsh J, et al. Assessing sleep using hip and wrist actigraphy. Sleep Biol Rhythms. 2015; 13(2):172–180. https://doi.org/10.1111 /sbr.12103;
48. Monk TH. A visual analogue scale technique to measure global vigor and affect. Psychiatry Res. 1989; 27(1):89–99. doi: 10.1016/0165 -1781(89)90013-9.
49. Tarvainen MP, Niskanen JP, Lipponen JA, et al. Kubios HRV – Heart rate variability analysis software. Comput Methods Programs Biomed. 2014; 113(1):210–20. doi: 10.1016/j.cmpb .2013.07.024.
50. Brennan M, Palaniswami M, Kamen P. Do existing measures of Poincaré plot geometry reflect nonlinear features of heart rate variability?. IEEE Trans Biomed Eng. 2001;48(11):1342-1347. doi:10.1109/10.959330.
51. Jovic A, Bogunovic N. Electrocardiogram analysis using a combination of statistical, geometric, and nonlinear heart rate variability features. Artif Intell Med.

2011; 51(3):175–86. doi: 10.1016/j.artmed.2010.09.005.
52. Heathers JAJ. Everything Hertz: Methodological issues in short-term frequency-domain HRV. Front Physiol. 2014; 7; 5:177. doi: 10.3389/fphys.2014.00177.
53. Hooper SL, Mackinnon LT. Monitoring Overtraining in Athletes: Recommendations. Sport Med. 20(5):321–7. doi: 10.2165/00007256-199520050-00003.
54. Johns MW. A new method for measuring daytime sleepiness: The Epworth sleepiness scale. Sleep. 1991; 14(6):540–5. doi: 10.1093/sleep/14.6.540.
55. Billman GE. The LF/HF ratio does not accurately measure cardiac sympatho-vagal balance. Front Physiol. 2013; 4:26. doi: 10.3389/fphys.2013.00026.
56. Alqatari AA, Alturki JA, Abdulali KA, et al. Changes in heart rate variability and baroreflex sensitivity during daytime naps. Nat Sci Sleep. 2020; 12:661–669. doi: 10.2147/NSS.S270191.
57. Malliani A, Pagani M, Lombardi F, et al. Cardiovascular neural regulation explored in the frequency domain. Circulation. 1991; 84(2):482–92. doi: 10.1161/01.cir.84.2.482.
58. Paul M, Garg K. The effect of heart rate variability biofeedback on performance psychology of basketball players. Appl Psychophysiol Biofeedback. 2012; 37(2):131–44. doi: 10.1007/s10484-012-9185-2.
59. Hirshkowitz M. Polysomnography Challenges. Sleep Med Clin. 2016; 11(4):403–411. doi: 10.1016/j.jsmc.2016.07.002.
60. Dinges DF. Adult Napping and Its Effects on Ability to Function. In: Stampi, C. (eds) Why We Nap. Boston; Birkhäuser; 1992. https://doi.org/10.1007/978-1-4757-2210-9_9.

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Analyzing soccer match sprint distances: A comparison of GPS-based absolute and relative thresholds

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ABSTRACT: This study compared the most common absolute sprint threshold (> 25.2 km/h) with relative and individualized thresholds (> 70%, > 75%, > 80%, > 85% and > 90% of peak match speed). Twenty elite soccer players, competing in the first division of the Portuguese League, were monitored using GNSS equipment during thirty-four official matches. Peak match speed was retrieved as the individual maximal speed reached during the full season. Distances were registered when speed overcame the absolute and the relative thresholds. Mean ± SD of peak speeds and distances covered were calculated, and Pearson correlation (*r*) and mean paired differences were performed to analyze relationships and differences between thresholds. The peak match speed was 32.9 ± 1.4 km/h. Correlations between distances covered using the absolute and relative thresholds varied from very strong (> 70%: $r = 0.84$, $p < .001$; > 75%: $r = 0.89$, $p < .001$; and > 80%: $r = 0.88$, $p < .001$), strong (> 85%: $r = 0.79$, $p < .001$), to moderate (> 90%: $r = 0.59$, $p < .001$). Overall, the > 75% (ES: 0.23 [95% CI: 0.16, 0.31]) and the > 90% (ES: -1.65 [95%CI: -1.85, -1.48]) relative thresholds presented the smallest and largest differences, respectively, with the absolute threshold. Differences were also found when considering the playing positions. While the distances covered by central midfielders were similar between the absolute and > 80% thresholds (-0.03 [-0.16, 0.10]), fullbacks covered largely more distance -1.88 [-2.42 -1.50]) in the absolute threshold than in the > 80% threshold. The distances covered by players varied based on the selected threshold, affecting the distances covered by different playing positions. Being the highest speed threshold within displacements thresholds, the absolute sprint threshold showed greater similarity to lower rather than higher relative thresholds.

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INTRODUCTION

With the advances in technological equipment (i.e., global positioning systems [GPS]) during the 1990's, coaches and sport scientists began directing their attention to the analysis of athletes' movements and efforts in training and competition [1]. Therefore, interesting data have been obtained regarding physical, physiological, and technical demands across technical-tactical training sessions and matches [2]. For example, it is known that soccer players usually cover between 9 and 14 km per match [3]. However, most of this distance (~35%) is covered at low speeds (< 7.2 km/h), with only 2–3% being covered at very-high speeds (> 25 km/h) [3]. Although practitioners continue to include total distance during match load monitoring [4], recent scientific research has focused on examining high-intensity efforts such as sprint distance (distance covered above a specific threshold) [1]. This happens due to the characteristics of soccer, especially due to the high intermittency of match activities [2] that allows reaching multiple peaks of speed along the match. Sprint efforts has also gained a particular importance because these actions usually precede goal situations in official soccer matches [5]. On the other hand, these explosive actions are regularly associated with a high risk of injury, especially when players perform maximal sprints in a fatigued state [6, 7]. However, players constantly exposed to these efforts might be better prepared for specific match demands, thus reducing the injury risk [8].

When analyzing sprint efforts, researchers can provide interesting information regarding match demands. For instance, maximal sprint speeds (> 30 km/h) occur more often at the beginning and

end of the match (i.e., 0'–15' and 75'–90'; compared to the rest of the match) [9], with players covering between 30 and 55 meters at those speeds per match [10]. However, an important point should be raised when discussing this issue: a maximal effort is always related to the player's aptitude and the context in which it occurs has critical implications. That is, maximal efforts might have distinct classifications and present a great variability among players of different fitness levels [11, 12]. In this regard, two interesting findings were recently reported. First, a study showed higher peak speeds in the 30-m sprint test compared to matches and sided games [13]. Secondly, arbitrary thresholds underestimated the distances covered when compared to relative thresholds (obtained using the 30–15 Intermittent Fitness Test, with peak speeds collected during training sessions and matches) [14]. Nevertheless, near-maximal efforts are usually classified according to arbitrary thresholds, without considering the individual characteristics of players and their respective playing positions [15]. For example, previous research has monitored sprint displacements with different absolute thresholds (i.e., distances covered > 19.8 km/h [8], > 21 km/h [16], > 24 km/h [17] and > 25.2 km/h) [18]. With these fixed ranges, two main issues arise: first, since speed thresholds differ between studies, comparisons between players' efforts are difficult to be made; second, players with different physical and physiological capacities are evaluated under the same criteria. In practical terms, for example, whereas the 25 km/h threshold represents an intensity of ~71% for a player who reaches a maximum speed of 35 km/h, the same threshold represents an intensity of ~83% for another player who sprints at a maximum speed of 30 km/h.

To address these issues, some authors have proposed the use of a more individualized approach, with individual efforts being classified according to the maximum values obtained during field tests [16]. However, during matches, players rarely achieve speeds > 90% of individual maximum speed registered during tests [19]. Furthermore, field tests protocols may have limitations, such as underestimating peak speed when measuring average speed in 10 meters or 20 meters splits [20]. Hence, using peak match speed (i.e., the highest speed registered during the match) as the reference value for determining and classifying players' efforts could provide a more realistic view of individual match demands. This strategy would benefit from analyzing the actual game context, accounting for players' capacities and tasks, thereby overcoming the limitations of relying on speed values collected during sprint speed tests, which are usually higher to those attained during matches, as well as from using data collected during the pre-season period [13, 21]. Regarding the use of relative thresholds, a recent study revealed that the assessment of distances covered at speeds superior to 80% of match and training peak speeds allowed to differentiate between starters and non-starters [22]. Furthermore, distances covered at speeds > 25 km/h and > 80% of players' maximum speeds differ, with players covering shorter distances while monitored with relative thresholds in comparison with absolute thresholds (i.e., starters and non-starters monitored with relative thresholds: ~940 m vs. ~550 m; starters and non-starters monitored with absolute thresholds: ~1300 m vs. ~970 m). Specifically, the 80% relative threshold has been recommended to ensure higher accuracy while monitoring sprinting activities [23]. However, the application of relative thresholds remains limited, as different relative intervals (> 80% and > 90%) are equally classified as sprints [20]. Therefore, the aim of this study was to analyze the relationships and differences between the distances covered during sprinting efforts of different intensities, classified according to the most commonly used absolute speed threshold for determining sprint efforts (> 25.2 km/h) [21] along with five relative and individualized speed thresholds (> 70%, > 75%, > 80%, > 85% and > 90% of peak match speed). Additionally, this study aims to compare the distances covered within each threshold based on the players' positions. It was hypothesized that most of the individualized speed thresholds would result in significantly different sprinting distances compared to the absolute threshold, although the correlations among the distances covered would be significant. In addition, we also hypothesized that such differences (distances covered sprinting) would vary across playing positions.

MATERIALS AND METHODS

Study design

This retrospective study analyzed the relations and differences between distances covered during official matches of the Portuguese first division, according to specific thresholds, defined as absolute (> 25.2 km/h) (the most commonly used absolute threshold) and relative thresholds (> 70%, > 75%, > 80%, > 85% and > 90% of peak match speed), separated by 5% intervals. Data were collected across thirty-four matches (full season), from August 2021 to May 2022, following the standard procedures established by the soccer club. Data was retrieved as raw data, collecting speed (km/h) and distance (m) for each player and for each match.

Subjects

Twenty elite-level soccer players [24] (age: 24.9 ± 4.0 years, height: 182.1 ± 7.5 cm, and body-mass: 75.1 ± 8.3 kg) competing in the first division of the Portuguese League were monitored during all matches of the League during the 2021/22 season. Matches from national cups and from the European competition were excluded. Data from goalkeepers and players who failed to complete at least one match were excluded. Only data for completed matches were considered, resulting in a total of 173 files. An a-priori power analysis was calculated using the G-Power software, which required 111 observations [25], to a respective power of 0.95. The number of completed matches per player ranged from 2 to 25. Importantly, since only full matches were included, the data were not influenced by potential noise from short (but intense) participation and performance of substitutes. Considering playing positions, were included: central defenders (CD) (n = 6), fullbacks (FB) (n = 3), central midfielders (CM)

(n = 5), wide midfielders (WM) (n = 4), and forwards (FW) (n = 2). Ethics Committee clearance was obtained (35/2021) and the study was conducted in accordance with the Declaration of Helsinki.

Procedures

Players were monitored with a 10-Hz global positioning system (Catapult Vector S7 – Catapult Sports, Melbourne, Australia) that encompassed a double constellation system (GNSS and GPS). This model has been certified by FIFA [26] and has demonstrated good reliability for peak speeds [27]. The horizontal dilution of precision (HDOP) for all observations was 1.02 ± 0.34, with an average of 12 ± 2 satellites acquired. Devices were positioned between the upper scapulae, at approximately the T3–4 junction, being activated 15 minutes before use, in accordance with the manufacturer's instructions. Raw data regarding distance and speed (km/h) were retrieved from the proprietary software (OpenField Console, Catapult Sports, Melbourne, Australia).

Peak match speed was defined as the highest value attained by each player across the thirty-four matches. Individual relative thresholds were individually calculated as > 70%, > 75%, > 80%, > 85%, and > 90% of the individual peak match speed. Covered distances were counted for every 0.1 seconds if velocity surpassed the established thresholds (> 25.2 km/h, > 70%, > 75%, > 80%, > 85% and > 90% of peak match speed).

Statistical Analysis

All analysis were performed using Microsoft Excel and Jamovi (Version 2.3.19.0; JAMOVI project, 2022) with the ESCI package [28, 29]. Means ± SD and coefficient of variation (%CV) of peak match speeds were calculated for each playing position and for all players. Means ± SD of distances covered by players according to the specific threshold (> 25.2 km/h and > 70%, > 75%, > 80%, > 85% and > 90% of peak match speed) were calculated for each playing position and for all players. Pearson (r) correlation (with 95% Confidence Intervals) analyzed the relationships between absolute and relative thresholds. Magnitudes of correlations were classified as very weak (0–0.19), weak (0.20–0.39), moderate (0.40–0.59), strong (0.60–0.79), and very strong (0.80–1) [30], and statistical significance was established at $p < .05$. Differences between measurement thresholds were analyzed via mean paired differences, with intra-individual comparisons for each threshold. For example, the distances covered within the absolute threshold by player A in match 1 were compared with the distances covered within the selected relative threshold by the same player in the same match. This analysis was performed with all players, divided according to playing positions. Effect sizes were established as trivial (< 0.2), small (0.2 < 0.6), moderate (0.6 < 1.2), large (1.2 < 2.0), very large (2.0 < 4.0), and huge (> 4.0), and presented along with 95% confidence intervals [31]. An unclear effect size was established if the CI crossed zero [32].

RESULTS

FW, FB, and WM reached higher peak match speeds across the full season and covered higher distances per match independent of the threshold (Table 1). Peak match speeds exhibited a %CV ranging from 0.9% (FW) to 4.9% (WM). Additionally, the intra-individual %CV of peak match speeds across the matches ranged from 0.9% to 7.7%, while the %CV of the team's peak match speeds was 4.3%. Distances covered using the absolute threshold were longer than the > 80% threshold for CD, CM, and WM, and the 75% threshold for FB and FW (Table 1). Overall, distance covered decreased when considering the following thresholds: > 70%, > 75%, > 25.2 km/h, > 80%, > 85% and > 90% (Figure 1).

Very strong correlations were found between the absolute threshold and > 70% (r = 0.84, $p < .001$), > 75% (r = 0.89, $p < .001$), and > 80% (r = 0.88, $p < .001$) relative thresholds (Figure 2).

TABLE 1. Mean ± SD of peak match speed and distances covered per match according to the threshold, for each playing position and for all players.

	Peak Match Speed (km/h)	Distances covered (m)					
		> 25.2 km/h	> 70% peak match speed	> 75% peak match speed	> 80% peak match speed	> 85% peak match speed	> 90% peak match speed
CD	32.3 ± 1.0	92.7 ± 47.8	211.8 ± 68.2	121.9 ± 52.2	63.5 ± 36.0	29.9 ± 22.2	8.7 ± 10.5
FB	34.1 ± 0.7	258.0 ± 72.9	371.40 ± 77.1	231.9 ± 65.4	134.3 ± 52.4	63.5 ± 32.3	22.9 ± 19.8
CM	31.7 ± 0.7	44.7 ± 30.8	205.9 ± 83.1	102.1 ± 51.4	43.9 ± 28.0	15.4 ± 15.0	4.4 ± 7.1
WM	33.4 ± 1.6	185.8 ± 115.6	361.5 ± 109.2	212.7 ± 82.0	111.6 ± 54.0	49.6 ± 34.3	15.4 ± 19.8
FW	34.3 ± 0.3	244.7 ± 105.1	349.2 ± 119.8	204.6 ± 81.8	109.2 ± 44.1	46.0 ± 24.6	15.7 ± 11.7
All	32.9 ± 1.4	134.5 ± 103.5	270.3 ± 113.2	156.4 ± 80.8	82.0 ± 52.6	36.4 ± 30.1	11.7 ± 15.2

Note: CD = central defenders; FB = fullbacks; CM = central midfielders; WM = wide midfielders; FW = forwards

Strong and moderate correlations were found between the absolute threshold and > 85% ($r = 0.79$, $p < .001$), and > 90% ($r = 0.59$, $p < .001$) relative thresholds, respectively (Figure 2).

Table 2 presents the mean differences according to the different thresholds and for each playing position and all players. Overall, the > 75% relative threshold presented the smallest difference (ES: 0.23 [90% CI: 0.16, 0.31]) when compared with the absolute threshold. Actually, on average, the 25.2 km/h threshold represented 76.8% of the peak match speed, ranging from 70.4% to 81.8%. However, for CM, the > 80% relative threshold presented unclear differences (ES: -0.03 [90% CI: -0.16, 0.10]) with the absolute threshold. The absolute threshold differed largely to hugely from the > 70% (except forwards which differed moderately) and the > 90% relative thresholds.

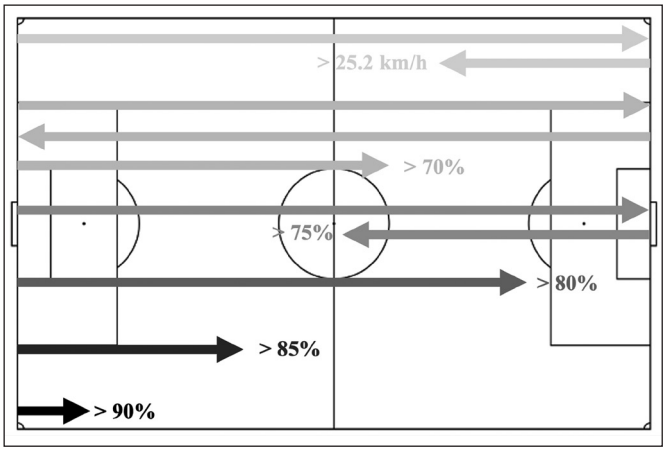


FIG. 1. Distances covered per match according to the absolute threshold (> 25.2 km/h) and the relative thresholds (70%, > 75%, > 80%, > 85% and > 90% of match peak speed).

TABLE 2. Mean differences [90% CI] with effect sizes [90% CI] of distances covered per match between the absolute and relative sprint thresholds (> 70%, > 75%, > 80%, > 85% and > 90% of peak match speed) for each playing position and for all players.

	Distances covered (m)				
	> 70% peak match speed	**> 75% peak match speed**	**> 80% peak match speed**	**> 85% peak match speed**	**> 90% peak match speed**
CD	119.06 [107.69, 130.42]	29.19 [22.17, 36.22]	-29.22 [-34.88, -22.57]	-63.79 [-72.20, -55.38]	-84.04 [-94.07, -74.00]
	2.00 [1.73, 2.32]^{VL}	0.58 [0.43, 0.74]^{S}	-0.68 [-0.86, -0.53]^{M}	-1.69 [-1.98, -1.45]^{L}	-2.40 [-2.79, -2.08]^{VL}
FB	113.36 [96.86, 129.86]	-26.09 [-42.41, -9.78]	-123.74 [-141.80, -105.68]	-194.58 [-218.57, -170.60]	-235.18 [-263.66, 206.71]
	1.46 [1.15, 1.89]^{L}	-0.36 [-0.61, -0.15]^{S}	-1.88 [-2.42, -1.50]^{L}	-3.33 [-4.24, -2.71]^{VL}	-4.25 [-5.42, -3.44]^{H}
CM	161.19 [138.35, 184.04]	57.40 [47.51, 67.29]	-0.80 [-4.87, 3.28]	-29.30 [-37.94, -20.66]	-40.24 [-50.57, -29.92]
	2.50 [2.07, 3.10]^{VL}	1.32 [1.08, 1.65]^{L}	-0.03 [-0.16, 0.10]^{U}	-1.18 [-1.57, -0.86]^{M}	-1.75 [-2.29, -1.34]^{L}
WM	175.71 [146.84, 204.58]	26.92 [3.13, 50.72]	-74.23 [-101.36, -47.09]	-136.14 [-169.13, -103.16]	-170.36 [208.26, -132.46]
	1.52 [1.20, 1.94]^{L}	0.26 [0.06, 0.48]^{S}	-0.80 [-1.07, -0.59]^{M}	-1.55 [-1.97, -1.24]^{L}	-2.00 [-2.54, -1.59]^{VL}
FW	104.45 [78.12, 130.78]	-40.07 [-62.21, -17.93]	-135.48 [-184.71, -86.24]	-198.70 [-264.16, -133.25]	-228.97 [-306.43, -151.51]
	0.84 [0.59, 1.30]^{M}	-0.39 [-0.62, -0.25]^{S}	-1.53 [-2.30, -1.11]^{L}	-2.36 [-3.60, -1.70]^{VL}	-2.78 [-4.41, -1.84]^{VL}
All	135.75 [126.38, 145.12]	21.82 [14.42, 29.23]	-52.51 [-61.91, -43.12]	-98.11 [-110.44, -85.78]	-122.87 [-137.22, -108.53]
	1.25 [1.13, 1.38]^{L}	0.23 [0.16, 0.31]^{S}	-0.64 [-0.73, -0.55]^{M}	-1.28 [-1.43, -1.15]^{L}	-1.65 [-1.85, -1.48]^{L}

Note: CD = central defenders; FB = fullbacks; CM = central midfielders; WM = wide midfielders; FW = forwards; when the value is negative, it indicates that players covered greater distances at speeds exceeding the absolute sprint threshold (> 25.2 km/h); U = unclear effect size; S = small effect size; M = moderate effect size; L = large effect size; VL = very large effect size; H = huge effect size.

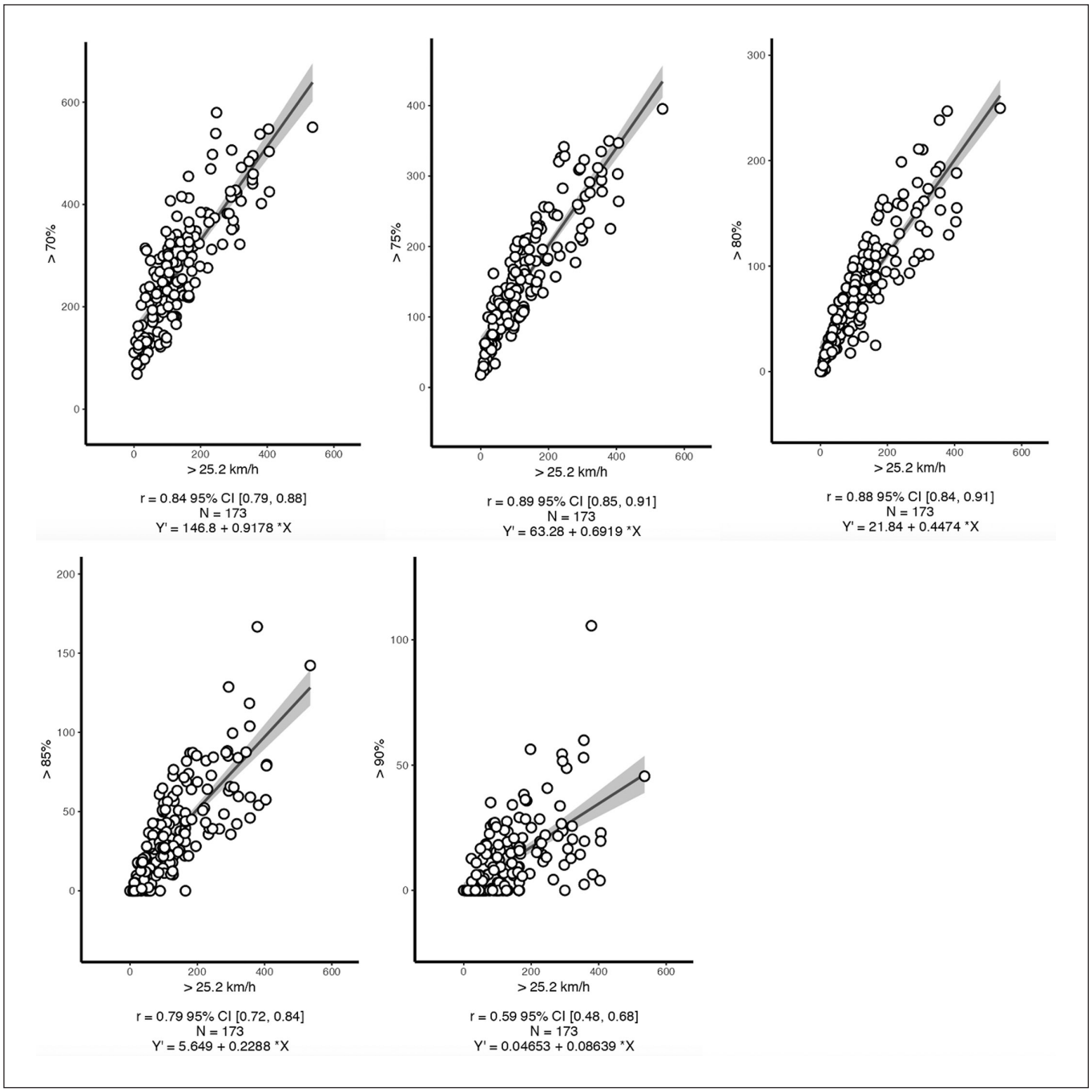


FIG. 2. Pearson correlations (*r*) between the absolute threshold (> 25.2 km/h) and the relative thresholds (70%, > 75%, > 80%, > 85% and > 90% of peak match speed).

DISCUSSION

The aim of this study was to compare distances covered by soccer players, per match, according to the most commonly used speed threshold for determining sprint efforts (> 25.2 km/h) with five other relative speed thresholds (> 70%, > 75%, > 80%, > 85% and > 90% of peak match speed). Our main finding agreed with our hypothesis, showing that sprint distances differ greatly according to the selected threshold, and with players covering more than one soccer field (i.e., 134.5 ± 103.5 m) per match at speeds > 25.2 km/h. This is longer than the distances covered at speeds > 80% of the individual peak match speed (i.e., +64%) but shorter than the distances covered at speeds > 75% (i.e., -14%) of the individual peak match speed (Figure 1).

Absolute speed thresholds allow comparisons within and between players and teams [33]. However, these thresholds are arbitrarily defined, with authors reproducing previous research and practitioners adopting the speed thresholds (i.e., speed zones) as determined by the proprietary GPS software [15]. Furthermore, although absolute thresholds consider that all displacements above a specific speed represent a similar level of effort for all players, the use of this

method does not provide an individually tailored and precise characterization of match load [22, 34]. To address this issue, individualized speed thresholds have been proposed, by calculating the percentage of effort according to the maximum speed test [34] or using the peak running speed recorded during matches or training sessions [22]. Considering that during matches players fail to achieve the maximum speed obtained during tests [13], the latter method can reflect a more realistic and applied scenario. Our findings relate to and expand the findings reported by Gualtieri et al. [22], with players, in general, covering shorter distances at individualized "speed thresholds" (> 80% peak match speed) compared to the absolute sprint threshold (> 25.2 km/h) (Figure 1). In contrast, Abbot et al. [34] reported lower percentages of sprint distances covered by players with the individualized threshold (> 30% of the anaerobic speed reserve [the difference between the maximum sprint speed and maximum aerobic speed score]), except for players with superior performance during the "maximum aerobic speed test" (i.e., > 1 standard deviation from mean). However, the latter study defined relative thresholds using test results and not using data collected during official matches.

Another potential issue when using absolute speed thresholds to map and monitor external load relates to how and to what extent the specific match demands differ across different playing positions. For instance, previous research has reported that CD (186 ± 82 m) and CM (167 ± 87 m) cover shorter sprint distances compared to FB (265 ± 121 m), WM (314 ± 123 m) and FW (345 ± 29 m) when using fixed and standardized speed thresholds [35]. Despite the similarity with our results, the magnitude of these differences decreases substantially when individualized speed thresholds are considered. For example, considering our findings, FB covered 5.8 × more sprint distance than CM when considering the absolute threshold (> 25.2 km/h) but only 3.1 × more sprint distance than CM when considering the > 80% relative threshold (Table 1).

Selecting the adequate speed threshold is important to ensure that data is being correctly analyzed and interpreted, according to its purposes. For example, the 80% relative threshold provided the closest speed (0.1 km/h of difference) compared to the absolute threshold (> 24.9 km/h), but more importantly, this relative threshold was more associated with risk of injury in comparison to the absolute speed threshold in Australian football rules players [23].

Increasingly, we found very close correlations between the absolute speed threshold (> 25.2 km/h) and the > 70% (r = 0.84, p < .001), > 75% (r = 0.89, p < .001), and > 80% (r = 0.88, p < .001) relative thresholds (Figure 2). However, it does not mean that they can be used interchangeably. As previously discussed, the absolute threshold represented an intensity of 70.4% to 81.8% of the peak match speed, highlighting why the higher correlations were found within these intervals. Although distances covered above absolute and arbitrary thresholds correlated very strongly with those covered above relative thresholds, player individuality is not considered by the former. Hence, absolute and relative thresholds can be used for different purposes. As aforementioned, absolute thresholds might be used to compare teams and playing positions. On the other hand, the relative thresholds are able to track changes in peak speed during training/matches over the season and provide a more accurate sprint training/match load.

During high-speed displacements monitoring process, the sprint threshold (i.e., > 25.2 km/h) is the highest absolute threshold used [21]. Therefore, it is crucial to consider players capabilities while assessing intense efforts such as sprints. In order to establish the maximal speed to determine the relative thresholds, we considered the peak speed achieved during matches instead of using data collected through standard speed tests (e.g., a 30-m linear sprint speed test). Although match context influences player performance [36], which limits our findings, field tests also present their inherent limitations. As previously discussed, field tests do not necessarily reproduce actual match situations [13] and are primarily performed during preseasons (which may compromise the use of these data across the competitive season). In this regard, to account for peak match speed variation across the season [37], we used the highest value of peak match speed recorded throughout the entire season during the competitive matches.

However, since sprint efforts refer to the highest threshold when assessing speed displacements, choosing a lower relative intensity (such as > 75% of the peak match speed) can overestimate players' loads. In contrast, choosing a high relative intensity (such as > 90% of the peak match speed) can result in the absence of sprints for some players, as the 90% intensity can even not occur during matches if one considers the maximum speed registered during field tests [19]. Considering that the > 80% has been previously recommended [22, 23], and can potentially increase the total displacement considered within the "actual" sprint threshold, this relative threshold may be used to improve the accuracy and efficacy of monitoring procedures, especially if the relation between this threshold and the risk of injury found Australian football rules [23] is replicated in future studies regarding soccer. Importantly, we only assessed one team and, to avoid potential noise in data, we only considered full matches. This strategy intended to avoid potential changes in data caused by short and intense appearances of substitutes. Additionally, it is worth noting that even when considering that peak match speed can vary across the season, field tests are typically conducted during the pre-season, which might increase this potential limitation.

CONCLUSIONS

In conclusion, we found very strong correlations between distances covered above the absolute threshold and above three relative thresholds (> 70%, > 75% and > 80%). This is probably explained because the absolute threshold represented an intensity ranging from 70.4% to 81.8% of the peak match speed, but this does not mean that they can be used interchangeably. Sprint distances registered during matches differ according to the selected threshold, increasing

the importance of what threshold to use while monitoring match sprint demands. Finally, different playing positions covered different distances, but the relative thresholds reduced the magnitude of those differences.

These findings have a direct impact on the load monitoring of soccer players. First, the absolute threshold neglects the players' individual capacities, although it allows comparison within teams and players. For instance, practitioners may wish to determine whether a player can reach a specific speed or assess if that player covers longer/shorter distances at or above that particular speed. However, for meaningful and real comparisons between players, individualizing players' capacities and demands could be a more effective strategy. Although faster players (assessed during field tests) achieved higher match speeds [38], a tactical strategy from the team or from the opposition can limit the expression of those sprint test speeds. For this reason, it makes sense recording peak speeds during matches since they better express the competitive demands. Considering the differences found between the distances covered according to the absolute or relative thresholds, the match load would vary according to the chosen strategy, which can impact how practitioners prepare the following training sessions. Finally, the relative threshold reduces the magnitude of the differences found between playing positions, highlighting the players' individual capacities and matches' context.

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Conflict of interest declaration

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REFERENCES

1. Cummins C, Orr R, O'Connor H, West C. Global positioning systems (GPS) and microtechnology sensors in team sports: A systematic review. Sports Med. 2013; 43(10):1025–42.
2. Stølen T, Chamari K, Castagna C, Wisløff U. Physiology of soccer: An update. Sports Med. 2005; 35(6):501–36.
3. Dolci F, Hart NH, Kilding AE, Chivers P, Piggott B, Spiteri T. Physical and Energetic Demand of Soccer: A Brief Review. Strength Cond J. 2020; 42(3):70–7.
4. 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.
5. 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):625–31.
6. Small K, McNaughton LR, Greig M, Lohkamp M, Lovell R. Soccer fatigue, sprinting and hamstring injury risk. Int J Sports Med. 2009; 30(8):573–8.
7. Schuermans J, Danneels L, van Tiggelen D, Palmans T, Witvrouw E. Proximal Neuromuscular Control Protects Against Hamstring Injuries in Male Soccer Players: A Prospective Study with Electromyography Time-Series Analysis during Maximal Sprinting. Am J Sports Med. 2017; 45(6):1315–25.
8. Malone S, Owen A, Mendes B, Hughes B, Collins K, Gabbett TJ. High-speed running and sprinting as an injury risk factor in soccer: Can well-developed physical qualities reduce the risk? J Sci Med Sport. 2018; 21(3):257–62.
9. Oliva-Lozano JM, Fortes V, López-Del Campo R, Resta R, Muyor JM. When and how do professional soccer players experience maximal intensity sprints in Laliga? Sci Med Footb. 2022; 7(3):288–296.
10. Oliva-Lozano JM, Fortes V, Muyor JM. When and how do elite soccer players sprint in match play? A longitudinal study in a professional soccer league. Res Sports Med. 2023; 31(1):1–12.
11. Djaoui L, Chamari K, Owen AL, Dellal A. Maximal sprinting speed of elite soccer players during training and matches. J Strength Cond Res. 2017; 31(6):1509–17.
12. Massard T, Eggers T, Lovell R. Peak speed determination in football: is sprint testing necessary? Sci Med Footb. 2018; 2(2):123–6.
13. Kyprianou E, Di Salvo V, Lolli L, Al Haddad H, Villanueva AM, Gregson W, Weston M. To Measure Peak Velocity in Soccer, Let the Players Sprint. J Strength Cond Res. 2022; 36(1):273–6.
14. 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; 1:153–61.
15. Sweeting AJ, Cormack SJ, Morgan S, Aughey RJ. When is a sprint a sprint? A review of the analysis of team-sport athlete activity profile. Front Physiol. 2017; 8(JUN):432.
16. Hennessy L, Jeffreys I. The current use of GPS, its potential, and limitations in soccer. Strength Cond J. 2018; 40(3):83–94.
17. Lorenzo-Martinez M, Kalén A, Rey E, López-Del Campo R, Resta R, Lago-Peñas C. Do elite soccer players cover less distance when their team spent more time in possession of the ball? Sci Med Footb. 2020; 28(3):351–9.
18. Carling C, Bradley P, McCall A, Dupont G. Match-to-match variability in high-speed running activity in a professional soccer team. J Sports Sci. 2016; 34(24):2215–23.
19. 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 Footb. 2021; 5(2):105–10.
20. 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):919–43.
21. 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(February):1–16.
22. 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):677–81.
23. O'Connor F, Thornton HR, Ritchie D, Anderson J, Bull L, Rigby A, Leonard Z, Stern S, Bartlett JD. Greater association of relative thresholds than absolute thresholds with noncontact lower-body injury in professional australian rules footballers: Implications for sprint monitoring. Int J Sports Physiol Perform. 2020; 15(2):204–12.

24. McKay AKA, Stellingwerff T, Smith ES, Martin DT, Mujika I, Goosey-Tolfrey VL, Sheppard J, Burke LM. Defining Training and Performance Caliber: A Participant Classification Framework. Int J Sports Physiol Perform. 2022; 17(2):317–31.
25. Lakens D. Sample Size Justification. Collabra Psychol. 2022; 8(1):1–31.
26. FIFA Resource Hub – Catapult. [cited 2022 Aug 1]. Available from: https://www.fifa.com/technical/football-technology/resource-hub?QualityProgram=6Sshn3qiYsRBq6muymEEtY& Category=21vlZTNlv31aveduLGFmDi& Provider=Catapult Sports
27. Cormier P, Tsai MC, Meylan C, Agar-Newman D, Epp-Stobbe A, Kalthoff Z, Klimstra M. Concurrent Validity and Reliability of Different Technologies for Sprint-Derived Horizontal Force-Velocity-Power Profiling. J Strength Cond Res. 2023; 37(6):1298–305.
28. Jamovi. the jamovi project [Internet]. Available from: https://www.jamovi.org
29. Team RC. R: A Language and environment for statistical computing. 2021. Available from: https://cran.r-project.org
30. BMJ. Correlation and regression. 2022. Available from: https://www.bmj.com/about-bmj/resources-readers/publications/statistics-square-one/11-correlation-and-regression
31. 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.
32. Batterham AM, Hopkins WG. Making Meaningful Inferences About Magnitudes. Int J Sports Physiol Perform. 2006; 1(1):50–7.
33. Hunter F, Bray J, Towlson C, Smith M, Barrett S, Madden J, Abt G, Lovell R. Individualisation Methods in Time-Motion Analysis. Int J Sports Med. 2015; 36(1):41–48.
34. 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):421–8.
35. Andrzejewski M, Chmura J, Pluta B, Strzelczyk R, Kasprzak A. Analysis of Sprinting Activities of Professional Soccer Players. J Strength Cond Res. 2013; 27(8):2134–40.
36. 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; 16(9):22–4.
37. Piñero JÁ, Chena M, Zapardiel JC, Roso-moliner A, Mainer-pardos E, Lampre M, Lozano D. Relative Individual Sprint in Most Demanding Passages of Play in Spanish Professional Soccer Matches. Sports. 2023; 11(72):1–12.
38. Mendez-Villanueva A, Buchheit M, Simpson B, Peltola E, Bourdon P. Does on-field sprinting performance in young soccer players depend on how fast they can run or how fast they do run? J Strength Cond Re. 2011; 25(9):2634–8.

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Reliability, interrelationships, and minimal detectable changes of strength and power metrics among well-trained rugby sevens players

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ABSTRACT: Despite the importance of strength and power in rugby skills and match outcomes, there exists a noticeable gap in the measurement consistency and estimation of a true change of typical assessments designed to assess these qualities. To address this gap, we investigated the between-session reliability, interrelationships, and minimal detectable changes (MDC) of commonly used strength and power measures in team sports. Sixteen national-level rugby 7 s players were tested on two occasions, one week apart. Both the best and average (of 2–3 trials) peak force, peak power, height, distance, and/or strength indices during countermovement jump (CMJ), drop jump (DJ), isometric mid-thigh pull (IMTP), plyometric push-up (PPU), and standing long jump (SLJ) were obtained. Furthermore, one-repetition maximum (1RM) strength for bench press and back squat, reactive strength index, and dynamic strength index were also determined. Reliability was assessed using intraclass correlation coefficients (ICC) and coefficients of variation (CV), and used for MDC calculations, and interrelationships between variables were determined using correlation coefficients. Reliability was *excellent* for bench press, back squat, and SLJ (ICCs > 0.91); *high to excellent* for IMTP peak force, all CMJ, and DJ (except best DJ height and contact time), and PPU peak force parameters (ICCs > 0.78), with $< 10\%$ CVs (except PPU peak power). MDCs were generally smaller for average than best values. *Large to very* large relationships ($r = 0.60$ to 0.85) were observed between bench press, back squat, and IMTP with selected parameters of CMJ and PPU ($p < 0.05$), but not in DJ and SLJ. In conclusion, selected measures of strength and power displayed *high to excellent* reproducibility, with average values (rather than best) offering more stable assessments, and "smaller" MDCs. Based upon the relationships, it can be inferred that maximising strength would likely contribute to enhanced explosive performance.

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INTRODUCTION

The capacity to generate force (strength) is seen as a "driving vehicle" to maximising sports performance [1, 2] as sufficient strength levels enhance the ability to sprint, jump, throw, and engage in rugby-specific movements (e.g., tackles, rucks, and mauls). In support of this, significant correlations have been reported between lower body strength (as measured through squats) with tackling [3] and sprinting [4] abilities among rugby players. Notably, sprint speed itself has been linked to game-changing outcomes like line breaks, tackle breaks, and tries scored in elite-level rugby [5] and rugby sevens [6]. As these qualities directly contribute to the likelihood of winning rugby matches, assessing strength and power has become a standard part of players' preparation. Indeed, these assessments facilitate the formulation of effective training regimens and allow for the monitoring of changes in an athlete's physical condition. However, despite the critical role of strength and power in influencing rugby skills and match outcomes there remains a substantial gap in understanding how coaches and athletes can fully benefit from the typical assessments that focus on these attributes, especially for well-trained rugby players.

Currently, reliability and minimal detectable change (MDC) for common maximal strength assessments in rugby players, like bench press and back squat exercises, are scarce [7]. The MDC is defined as a valid change in score that is not due to chance. In sports, understanding MDC is crucial for accurately assessing the effectiveness of training programs, evaluating individual athlete progress, and distinguishing meaningful performance changes from random

variability. In non-athletic populations, moderate and good reliability was reported for dynamic strength (e.g., squat), with Intraclass Correlation Coefficients (ICC) ranging between 0.64 and 0.99 (median ICC = 0.97), and Coefficients of Variations (CV) ranging between 0.5 and 12.1% (median CV = 4.2%) for bench press, back squat, and other strength exercises [7].

In contact sports like rugby, critical elements for successful performance include athletes' stretch-shortening performance and musculotendinous unit capacity [8]. These are represented by tasks like plyometric push-up (for upper-body power), standing long jump (for horizontal power), drop jump (for reactive strength), and countermovement jump (CMJ, for vertical power) [9]. Development of these explosive qualities needs to consider maximal strength development [1, 10]. Maximal strength is defined as the highest load that can be lifted for one repetition (one-repetition maximum; 1RM). Even though it is practical, 1RM assessment may be difficult for new athletes owing to safety implications or when assessing a large group of athletes. In contrast, isometric strength assessment like the isometric mid-thigh pull (IMTP) appears more "realistic" for inexperienced athletes testing maximal strength, as it requires minimal technical advice [11]. Moreover, peak force during IMTP has been correlated with bench press and back squat exercises [12], and field-based tasks such as sprinting and change of direction [13]. When the IMTP is used in combination with the CMJ, it is possible to derive additional metrics, such as the dynamic strength index [14], which has been demonstrated to be a useful performance index in strength and conditioning training, research, and clinical settings [12, 14].

Even though essential, most of the previous studies assessing reliability and MDC have not considered well-trained athletes, like National-level rugby sevens players [14]. In addition, there are few studies that examine strength and power assessments (such as the IMTP, CMJ, and reactive strength index) by comparing the best to the average performance, particularly in well-trained cohorts [15]. Such information would ascertain whether the former or latter is more responsive or sensitive to changes in performance [15]. These limitations restrict team sport players and practitioners in the interpretation of whether or not the improvements from training are meaningful. Knowledge in the stability and precision of a measurement is fundamental to provide some level of confidence to practitioners (coaches, athletes), i.e., to effectively monitor training responses. For example, how much improvements in back squat is considered changes due to training effects? With this in mind, the present study aimed to investigate reliability, interrelationships, and MDCs for the typical strength and power assessments used in team and strength-power dependent sports in a National-level rugby sevens team. We hypothesised that maximum strength during dynamic and isometric tasks, as well as explosive power, and reactive strength, would exhibit high reliability and minimal MDCs, while the dynamic strength index would depend on the reliability of the CMJ and IMTP.

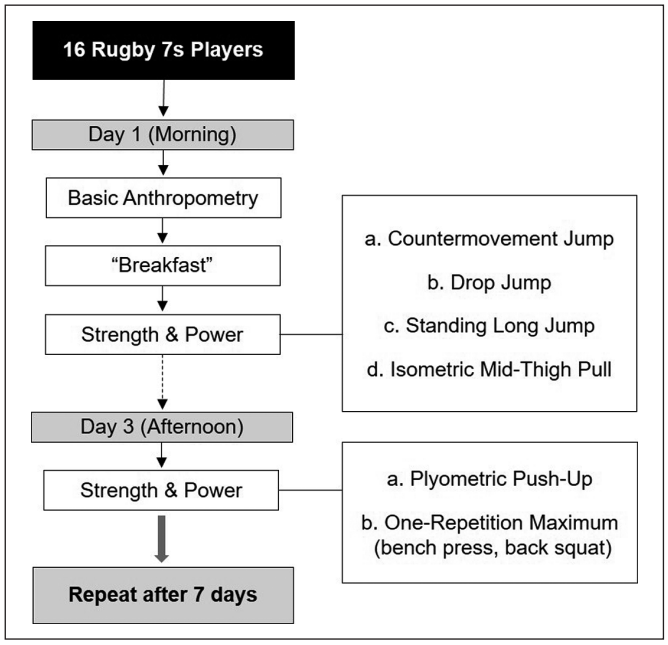


FIG. 1. Schematic representation of data collection.

MATERIALS AND METHODS

Participants

Sixteen (n = 16) male national rugby sevens players (height 175 ± 5.2 cm; body mass 82.6 ± 7.6 kg, age 21.2 ± 2.1 y) were recruited. Most of the players (75%) were new to the National squad but had competed regularly at national-level competitions (> 5 years). Due to missing attendance, a smaller subset of participants (n = 11) completed the morning re-test session (all attended the afternoon session). Before agreeing to participate in the study by completing an informed consent form, each participant was given information about the risks and benefits of the study. This study was conducted in accordance with the declaration of Helsinki and approved by an Institutional Review Board.

Study Design

Test-retest reliability was conducted. Athletes were tested twice (two sessions each), a week apart. The second re-test session was conducted at the same time of day to reduce the impact of the time of day (Figure 1).

Testing

The players had one full rest day prior to each testing session. Prior to testing, a standardised warm-up was conducted involving both general and specific warm-up [10]. The protocols used for the 1RM, IMTP, CMJ, drop jump, and plyometric push-up tests followed the recommendations and protocols from previous studies [16, 17, 18, 19, 20]. Except for the 1RM test (one attempt), the best and average performance of three attempts (two attempts for IMTP) were analysed for all assessments.

Countermovement jump, drop jump, and standing long jump

The CMJ, drop jump, and standing long jump were used to assess leg power and reactive strength. Three trials were given for each test, with ~30–60 seconds rest interval between trials. When performing the CMJ, the players were instructed to stand up straight with their hands on the waist (akimbo). Upon "jump" instruction, they squatted down to knee angles of ~80–90°, jumped upward, and landed around the same standing points [20]. The players were asked to "jump as high as possible". During the drop jump, the players were required to step-off (without sink down lower) a 40-cm box with their hands akimbo, land on both feet (forefeet area), and vigorously jump upwards [10]. The players were instructed to "minimise ground contact, and maximise jump height" while keeping upright body position (no tucking) during the jump, and landing with both feet on the same starting points [21].

Both CMJ and drop jump assessments were conducted using a force plate (400 series, Fitness Technology, Australia) sampling at 600 Hz, integrating the Ballistic Measurement System and software (BMS, Fitness Technology, Australia). The following variables were recorded (a) CMJ: concentric peak force, peak power, and jump height; (b) drop jump: contact time, jump height, and reactive strength index.

The reactive strength index was obtained during a drop jump using the ratio of jump height to ground contact time, (jump height / contact time). Flight time was utilised to calculate jump height, based on the equation of uniform acceleration, which stipulates that from the moment take-off was completed until subsequent ground contact upon landing, i.e., $JH = 9.81 \times (FT \times FT)/8$ [10, 20].

The standing long jump was conducted in a long jump pit. The standing long jump was initiated with both feet shoulder-width apart. The players were allowed to perform pre-stretch movement to a self-selected depth and swing their arms. A tape measure was used to record standing long jump distance (to the nearest 1 cm). The variable measures recorded were the absolute and relative (distance divided by stature) distance.

Plyometric push-up

The players were instructed to begin the plyometric push-up at the top push-up position with their hands and feet on their respective force platforms, with a self-selected hand placement width. To perform a maximum plyometric push-up, they were then instructed to bend their elbows to a self-selected countermovement depth, and rapidly push upwards until their hands left the force platform [16]. To obtain vertical ground reaction force data for the plyometric push-up, each hand was placed on a force plate (device, *see* above), and each foot was placed on another force plate positioned at the same height. Three trials were performed, with ~30–60 seconds rest interval between trials. The variable measures recorded for the plyometric push-up included absolute and relative (divided by body mass) peak force and peak power.

Maximum isometric strength

After the jump tests, the players performed a series of IMTPs, using a force plate (*see* above), with a custom-made rack designed to mount the bar at a specific height. For the warm-ups, the players performed IMTP once at ~50% effort, once at ~75% effort, and once at ~90% effort with 1 min rest interval. Subsequent to this, two IMTPs at maximum effort were performed, with a rest interval of 2–3 mins. During IMTP testing, the device was set to place the athlete in a typical power clean or pulling position that permits body position with the immovable bar around the mid-part of the thighs, while keeping the knee and hip angles at ~130–140° and ~145°, respectively [18, 19].

A 2D motion analysis software (Coach's Eye, TechSmith Corp) was used to establish appropriate knee and hip angles (during the warm-up trials) to determine the height of the IMTP bar. The players were instructed to pull the bar "as quickly and explosively as possible" for 3–4 seconds with the "legs exerting maximally (fast and hard) against force plates," after a countdown ("3, 2, 1, push") was given. Two trials were recorded, with ~2–3 mins rest intervals. The resultant force-time data on a computer screen (connected to the force plate) was visually monitored to confirm appropriate actions (e.g., no countermovement), or otherwise, the trial was repeated. The variable measures recorded during the IMTP were absolute and relative peak force. Dynamic strength index was also calculated by dividing absolute CMJ peak force with the absolute IMTP peak force [17, 18].

Maximum dynamic strength

Bench press and back squat exercises were used to conduct the 1RM strength test. For both exercises, the test was preceded by a warm-up set of 10 repetitions using an unweighted barbell (20 kg). Subsequent to this, the players performed 10 repetitions, 5 repetitions, and 1 repetition (respectively) at 50%, 70%, and 90% of the expected 1RM. Next, 2 (minimum) to 5 (maximum) single attempts were made by raising (2–10 kg for bench press, and 5–20 kg for squat) or reducing (2–5 kg for bench press, and 5–10 kg for squat) the weight until the largest load that could be lifted correctly (for both exercises) was identified [10]. A rest period of 2–5 minutes was provided between each attempt. For back squat, an acceptable method consisted of lowering a weighted barbell to a depth that corresponded to knee angles of 80–85° as determined by a 2D motion analysis (Coach's Eye, TechSmith Corp). Relative strength was also calculated for both exercises as 1 RM / body mass [10].

Statistical Analyses

We calculated both relative and absolute reliability metrics. Relative reliability was assessed using ICC, which focus on the rank order or position of individuals within a group across repeated measures. Absolute reliability was evaluated using the Standard Error of Measurement (SEM), CV, and MDC, which measure the consistency of scores for the same individual across repeated tests, irrespective of

their rank within the group. Relative reliability was rated as *poor*, *moderate*, *high*, and *excellent* based on ICC thresholds of < 0.50, 0.50, 0.75, and 0.90 [22]. For absolute reliability, CV values < 10% were considered to reflect acceptable absolute reliability. Absolute consistency was quantified using Bland–Altman statistics. The limits of agreement were calculated for both the lower (mean difference – (1.96 × SD)) and upper (mean difference + (1.96 × SD)) limit of agreement. MDC was calculated based on the ICC value, using an equation: MDC = 1.96 × SEMx√2. Relationships between explosive power and reactive strength variables with maximum dynamic strength, isometric strength, and dynamic strength index were determined using Pearson's correlation coefficients. Both the best and average (of two or three trials) values were considered in the analyses. The Holm–Bonferroni corrections were conducted to control for the family-wise error of the statistical significance ($p < 0.004$). The following criteria were adopted to interpret the magnitude of the correlation: trivial ($r < 0.1$), small ($0.1 \leq r < 0.3$), moderate ($0.3 \leq r < 0.5$), large ($0.5 \leq r < 0.7$), very large ($0.7 \leq r < 0.9$), nearly perfect ($0.9 \leq r < 1$), and perfect ($r = 1$) [23].

RESULTS

All players completed all tests without incident, with data summarised in Table 1 and Table 2. Briefly: **(a)** *maximum strength. Excellent* reliability was found for 1RM bench press and back squat (ICCs: > 0.96, and CVs: ≤ 3.6%). *High* reliability was observed for best IMTP peak force and average IMTP peak force (ICCs: > 0.78, and CVs: ≤ 8.4%); **(b)** *vertical explosive and reactive strength. High* to *excellent* reliability was observed for all CMJ parameters (ICCs: 0.893–0.943 and CVs: 2.9–3.9%), as well as for drop jump parameters (ICCs: 0.812–0.942 and CVs: 3.6–7.3%); **(c)** *horizontal explosive strength. Excellent* reliability was observed for standing long jump parameters (ICCs: > 0.91, and CVs: ≤ 3.7%); **(d)** *upper-body power. Excellent* reliability was observed for plyometric push-up peak force parameters (ICCs: > 0.92, and CVs: ≤ 3.6%) but *poor* to *moderate* reliability was observed for plyometric push-up peak power parameters; **(e)** *dynamic strength index. Poor* to *moderate* reliability was observed for the dynamic strength index parameters.

The CVs were acceptable for all assessments (< 10%) except for peak power metrics during the plyometric push-up (~30%). Average values produced relatively lower CVs than best values (Tables 1 and 2). Based on MDC results, average values consistently produced smaller MDCs as compared to best values (Tables 1 and 2).

Bland-Altman limits of agreement were employed to quantify the agreement between two paired variables, Day 1 and Day 2 assessments (Figure 2). Sub-figures show points (green squares) that are scattered and distributed (above and below zero), which suggests that there is no consistent bias or learning effect, except for the IMTP variables (Figure 2).

For the best value relationships, significant and *very large* relationships were detected between bench press (absolute or relative values) with CMJ peak force, and absolute and/or relative peak force

TABLE 1. Performance scores, reliability measures, and minimal detectable changes for maximum dynamic and isometric strength, and dynamic strength index. Data are from male national rugby 7 s players.

	Mean, SD	ICC, [D] (95% CI)	SEM (95% CI)	CV %, SD	$SWC_{0.5}$	MDC %	MDC
Dynamic Strength *(n = 16)*							
1RM bench press (kg)	92 ± 14	0.960[E] (0.882, 0.986)	1.0 (4.2, 0.2)	3.2 ± 3.0	6.8	2.6	2.9
1RM back squat (kg)	136 ± 21	0.957[E] (0.881, 0.985)	1.7 (5.9, −0.9)	3.6 ± 2.6	10.3	3.5	4.8
Isometric Mid-Thigh Pull *(n = 11)*							
Peak force, best (N)	2870 ± 336	0.809[H] (−0.139, 0.964)	56 (408, 190)	7.4 ± 3.1	169	5.4	155
Peak force, average (N)	2842 ± 332	0.785[H] (−0.038, 0.961)	34 (405, 273)	8.4 ± 1.6	166	3.3	94
Dynamic Strength Index *(n = 11)*							
Peak force, best (au)	0.73 ± 0.05	0.398[P] (0.369, 0.805)	0.05 (0.10, 0.03)	7.4 ± 4.6	0.02	19.2	0.14
Peak force, average (au)	0.71 ± 0.05	0.523[M] (0.290, 0.863)	0.04 (0.00, −0.14)	6.5 ± 4.8	0.02	13.8	0.10

Note: SD, standard deviation; ICC, intraclass correlation coefficient; CI, confidence interval (upper, lower); SEM, standard error measurement; CV, Coefficient of Variation; SWC, Smallest Worthwhile Change; MDC, minimal detectable change; [D] descriptor; [E] Excellent; [H] High, [M] Moderate; [P] Poor; 1RM, one-repetition maximum.

TABLE 2. Performance scores, reliability measures, and minimal detectable changes of explosive power and reactive strength variables. Data are from male national rugby 7 s players.

	Mean, SD	ICC, [D] (95% CI)	SEM (95% CI)	CV %, SD	$SWC_{0.5}$	MDC %	MDC
Countermovement Jump *(n = 11)*							
Peak force, best (N)	2073 ± 205	0.928[E] (0.747, 0.980)	40 (92, −22)	2.9 ± 2.5	102	5.3	111
Peak force, average (N)	2005 ± 169	0.893[H] (0.559, 0.972)	32 (125, −0.2)	3.2 ± 2.3	85	4.4	89
Peak power, best (W)	4724 ± 529	0.930[E] (0.295, 0.985)	69 (319, 122)	3.9 ± 1.8	264	4.0	191
Peak power, average (W)	4650 ± 532	0.933[E] (0.450, 0.985)	52 (305, 101)	3.9 ± 1.8	266	3.1	144
Jump height, best (cm)	44.5 ± 6.3	0.938[E] (0.769, 0.983)	1.0 (1.9, −1.3)	3.4 ± 4.0	3.1	5.0	2.2
Jump height, average (cm)	43.2 ± 5.9	0.943[E] (0.979, 0.985)	0.7 (2.0, −0.7)	3.7 ± 3.1	2.9	4.4	1.9
Drop Jump *(n = 11)*							
Contact time, best (s)	0.22 ± 0.02	0.817[H] (0.341, 0.950)	0.010 (0.2, 0.2)	4.5 ± 3.4	0.01	9.6	0.021
Contact time, average (s)	0.20 ± 0.02	0.828[H] (0.350, 0.954)	0.010 (0.2, 0.2)	3.6 ± 3.0	0.01	7.7	0.016
Jump height, best (m)	0.28 ± 0.04	0.821[H] (0.382, 0.951)	0.01 (0.01, −0.05)	7.3 ± 4.8	0.02	14.5	0.04
Jump height, average (m)	0.27 ± 0.04	0.857[H] (0.496, 0.961)	0.01 (0.01, −0.03)	6.2 ± 4.3	0.02	11.5	0.03
RSI, best (au)	1.41 ± 0.24	0.901[E] (0.600, 0.974)	0.04 (0.00, −0.16)	6.8 ± 3.4	0.12	8.2	0.12
RSI, average (au)	1.31 ± 0.23	0.942[E] (0.795, 0.984)	0.03 (0.01, −0.09)	5.0 ± 3.2	0.11	5.4	0.07
Plyometric Push-Up *(n = 13)*							
Peak force, best (N)	1260 ± 178	0.926[E] (0.768, 0.977)	26 (82, −20)	3.6 ± 3.6	54	5.7	72
Peak force, average (N)	1195 ± 173	0.961[E] (0.873, 0.988)	13 (52, 1)	3.0 ± 2.5	52	3.0	36
Peak power, best (W)	900 ± 329	0.074[P] (−2.673, 0.732)	610 (1179, −1214)	29.7 ± 38.6	164	188	1692
Peak power, average (W)	704 ± 276	0.541[M] (−0.589, 0.862)	258 (453, −557)	30.5 ± 34.4	138	101	714
Standing Long Jump *(n = 13)*							
Distance, best (cm)	242 ± 16	0.919[E] (0.738, 0.975)	3.7 (15.9, 1.5)	3.8 ± 2.8	8.3	4.2	10.2
Distance, average (cm)	238 ± 17	0.941[E] (0.790, 0.983)	2.7 (11.7, 1.2)	3.0 ± 2.6	8.5	3.1	7.4

Note: SD, standard deviation; ICC, intraclass correlation coefficient; CI, confidence interval (upper, lower); SEM, standard error measurement; CV, Coefficient of Variation; SWC, Smallest Worthwhile Change; MDC minimal detectable change; [D] descriptor; [E] Excellent; [H] High; [M] Moderate; [P] Poor; RSI, reactive strength index.

during plyometric push up; as well as between IMTP with peak force during plyometric push-up. No significant relationships were observed between the maximum strength parameters with any parameters in drop jump and standing long jump. Additionally, significant and *very large* relationships were detected for bench press and back squat with IMTP peak force; and bench press with absolute and relative peak force in IMTP (Table 3).

For the average value relationships, significant and *large* to *very large* relationships were observed for absolute and relative bench press with absolute peak force in plyometric push-up; and between absolute IMTP with CMJ peak force. No significant relationships were observed for the maximum strength parameters with any parameters in drop jump and standing long jump. Additionally, significant and *very large* relationships were observed for bench press with absolute back squat and IMTP peak force; between back squat and IMTP peak force (Table 4).

DISCUSSION

The findings of the current study indicate (i) *excellent* reliability for maximum strength in bench press, back squat, and standing long jump, all CMJ parameters (except average peak force, *high*), drop jump RSI, and peak forces during plyometric push-up; (ii) *high* reliability for peak force parameters during IMTP, and drop jump parameters (contact time and jump height); (iii) high levels of reliability can be achieved with one familiarisation session performed just prior to the actual assessment without inducing a systematic learning effect (except for IMTP) for these strength and power tests; (iv) acceptable levels of absolute reliability for all tests (CV < 10% except peak power during plyometric push-up); (v) average, rather than best values, optimised the stability of measurement, and provided a relatively smaller MDC; and (vi) significant and *large* to *very large* relationships between bench press and peak force during plyometric push-up and CMJ, but not in any parameters of drop jump and standing long jumps, for both best and average values. These findings

TABLE 3. Relationships of best scores in maximum strength, with explosive power and reactive strength performance. Data are from male national rugby 7 s players (n = 14).

BEST	[1]	[2]	[3]	[4]	[5[	[6]	[7]
[1] 1RM bench press							
[2] Relative 1RM bench press	**0.74****						
[3] 1RM back squat	**0.78****	0.47					
[4] Relative 1RM Back Squat	0.38	0.60*	**0.70****				
[5] IMTP peak force	**0.78****	0.39	**0.82****	0.35			
[6] IMTP relative peak force	**0.71****	**0.71****	0.63*	0.66*	0.69*		
[7] Dynamic strength index	-0.23	-0.09	-0.35	-0.21	-0.39	-0.27	
CMJ							
Peak force	**0.72****	0.42	0.67*	0.29	**0.82****	0.50	0.21
Relative peak force	0.28	0.38	0.30	0.33	0.38	0.46	0.59
Peak power	0.39	0.13	0.61*	0.39	0.63*	0.52	-0.23
Relative peak power	0.47	0.58	0.55	0.69*	0.49	0.62*	-0.01
Jump height	0.31	0.38	0.36	0.40	0.40	0.46	0.25
Drop Jump							
Contact time	0.04	0.33	-0.12	0.20	-0.47	-0.29	-0.10
Jump height	0.16	0.34	0.10	0.33	-0.11	0.14	0.48
Reactive strength index	0.02	0.07	0.02	0.10	0.05	0.24	0.43
Plyometric Push-Up							
Peak force	**0.84****	**0.79****	0.67*	0.36	**0.73****	0.66*	-0.25
Relative peak force	0.47	**0.81****	0.23	0.40	0.51	0.60	-0.35
Standing Long Jump							
Distance	0.08	-0.12	0.20	0.04	0.42	0.48	-0.13
Relative distance	0.14	-0.01	0.22	0.11	0.31	0.45	-0.06

*Significant at the 0.05 level (2-tailed); **Significant at the 0.004 level (2-tailed). *Note:* 1-RM, one-repetition maximum; IMTP, isometric mid-thigh pull; CMJ, countermovement jump.

TABLE 4. Relationships of average scores in maximum strength, with explosive power and reactive strength performance. Data are from male national rugby 7 s players (n = 14).

AVERAGE	[1]	[2]	[3]	[4]	[5[	[6]	[7]
[1] 1RM bench press							
[2] Relative 1RM bench press	**0.74****						
[3] 1RM back squat	**0.78****	0.47					
[4] Relative 1RM Back Squat	0.38	0.60*	**0.70****				
[5] IMTP peak force	**0.74****	0.41	**0.80****	0.33			
[6] IMTP relative peak force	0.45	0.52	0.49	0.62*	0.61*		
[7] Dynamic strength index	-0.30	-0.17	-0.37	-0.22	-0.48	-0.36	
CMJ							
Peak force	0.68*	0.36	0.67*	0.28	**0.83****	0.52	0.09
Relative peak force	0.25	0.42	0.12	0.34	0.15	0.57	0.54
Peak power	0.39	0.13	0.62*	0.38	0.60*	0.38	-0.28
Relative peak power	0.42	0.51	0.49	0.61*	0.26	0.46	-0.05
Jump height	0.39	0.39	0.40	0.44	0.3`	0.44	0.21
Drop Jump							
Contact time	0.13	0.37	0.00	0.27	-0.41	-0.29	-0.02
Jump height	0.16	0.33	0.07	0.28	-0.12	0.12	0.53
Reactive strength index	0.18	0.40	0.09	0.22	0.03	0.20	0.32
Plyometric Push-Up							
Peak force	**0.85****	**0.71****	0.60*	0.32	**0.70****	0.50	-0.23
Relative peak force	0.19	0.66*	-0.11	0.30	-0.31	0.32	0.30
Standing Long Jump							
Distance	0.01	-0.15	0.13	-0.01	0.32	0.39	-0.24
Relative distance	0.09	-0.03	0.17	0.09	0.20	0.34	-0.14

*Significant at the 0.05 level (2-tailed); **Significant at the 0.004 level (2-tailed). *Note:* 1RM, one-repetition maximum; IMTP, isometric mid-thigh pull; CMJ, countermovement jump.

offer practitioners with useful benchmarks to estimate whether the changes in performance (or progression) for strength and power variables can be interpreted as meaningful.

Dynamic and isometric strength are usually assessed in strength and conditioning setting. Between these two types of maximum strength tests, we found *excellent* reliability for the dynamic strength (bench press and back squat), whereas *high* reliability for the best and average peak force of IMTP. These findings might be attributed to the players' history of training with bench press and back squat exercises, as well as their exposure to actual testing protocols during earlier testing sessions. Grgic et al. [7] reviewed 32 studies investigating the reliability of one-repetition maximum, and found generally *excellent* reliability of dynamic strength (various exercises) from a range of populations, but only two included team-sport athletes and these were either adolescents aged ~16 [24] or defined as inexperienced [19]. More recently, Grgic et al. [25] reported that IMTP maximum strength assessment has *good to excellent* test-retest reliability based on a review of the literature [25]. Likewise, Aben et al. [26] reported acceptable between-day reliability for the IMTP peak force among professional male rugby players (n = 10). Based on the findings of the current study, it is possible to infer that dynamic and isometric strength may be used as reliable evaluations of maximal strength among athletes, albeit more familiarisation with IMTP is required if this exercise is not already part of athletes' training.

The current study also found *excellent* reliability of various measures of explosive power and reactive strength. CMJ and drop jump exercises are usually thought to represent slow (i.e., CMJ) and fast (i.e., drop jump) stretch-shortening cycle, which are decisive in high-speed, short-event performance such as sprinting [10, 27]. Supporting the current study's findings, earlier research has reported *excellent* reliability in CMJ variables (without specifying either best or average scores) among professional male rugby players [26]. Comparable to the current study [9], the authors found an acceptable level

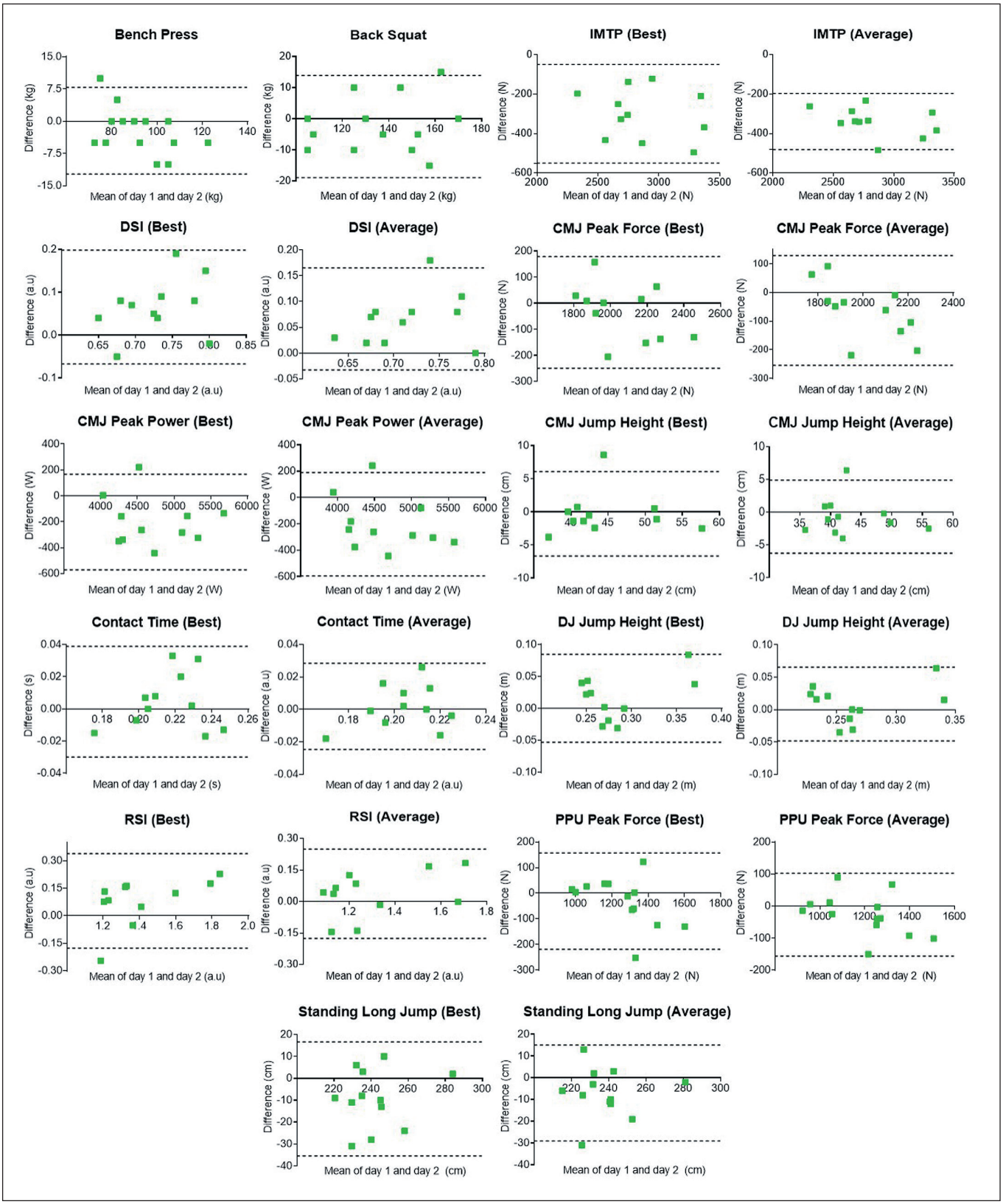


FIG. 2. Bland-Altman limits of agreement (bias ± 95%) for strength and power assessments including best and average values. Note: IMTP, isometric mid-thigh pull; CMJ, countermovement jump; DSI, dynamic strength index; DJ, drop jump; RSI, reactive strength index; PPU, plyometric push-up.

of reliability of the reactive strength index (ICC of 0.93, CV of 8.5%) among elite junior rugby players. CMJ height may lack sensitivity to detect neuromuscular changes in the context of Australian Rules football match [28], as compared to peak force and peak power [28]. As force plate CMJ analysis offers a greater range of kinetic and kinematic outputs including peak force, peak power, and flight time [10, 13], we assessed these parameters and found that specific metrics in CMJ (e.g., peak power and jump height) and drop jump (e.g., reactive strength index) were highly repeatable. Further, it is worth noting that the dynamic strength index showed relatively poor reliability among all the assessed variables in the current study. Dynamic strength index variables of IMTP and CMJ are assessed independently, and thus, subject to errors from different test occasions. Comfort et al. [14] stated that the dynamic strength index as derived from CMJ rather than squat jump is a more stable method of assessing the dynamic strength index. However, we observed that the dynamic strength index also depends on IMTP's reliability measures (Table 1, Figure 2). Additionally, the explosive measure of upper body (plyometric push-up) revealed similar (reliable) findings for the peak force variables, but not peak power. Taken together, CMJ and drop jump metrics have been widely used in athletes' monitoring and research, and these variables appear reliable. Nonetheless, the precision of the dynamic strength index can be limited as it relies on the collection of two reliable measurements for the data to be useful.

Practitioners should be aware that some assessments may be more sensitive when data are averaged rather than relying on best scores. Notably, we found that the reliability level was higher for average than best values, e.g., average reactive strength index (*excellent* vs *high*) and average IMTP peak force (*high* vs *moderate*). Roe et al. [15] suggest that CMJ mean power (taking maximal score from 2 or 3 attempts), peak force, or mean force and plyometric-push-up mean force (from 2 or 3 attempts) produced acceptable reliability (CV < 5%) and good sensitivity (CV < smallest worthwhile change) [15]. A lower CV for a test implies less random noise, and therefore a greater ability or likelihood of detecting a real change in performance [29]. Furthermore, an MDC greater than the CV of a test implies higher measurement error, which might limit the usefulness of specific tests [29]. Importantly, average results yielded relatively smaller MDCs compared to the best results. Comfort and McMahon [19] reported MDCs of approximately 5–6% in the back squat and power clean in inexperienced athletes, which is slightly larger than the current study (~3–5%). Thus, MDC calculation (best or average results) can help athletes and coaches set goals more appropriately. Employing MDC is necessary for athletes because any changes in strength and power measurements exceeding the MDC value can be deemed as real changes due to training rather than changes resulting from a random variation or errors in measurement.

High levels of reliability could be achieved in several strength and power tests with familiarisation sessions performed just prior to the actual assessment without inducing a systematic learning effect (confirmed by Bland-Altman plots). In this study, most players (> 75%) were new recruits in the national squad; and started to get exposure to typical tests in team sports. Importantly, the same test exercises (e.g., bench press, back squat, vertical jump) here were done regularly by the players during training, except for the IMTP and drop jump. The variation between trials may be considered to be intrinsic variation derived from independent sources of mistakes or random errors. Poor reliability might lead to different scores across two test administrations, and subsequent misinterpretation of change scores. Some exercises (e.g., vertical jump) can be performed without the need for familiarisation trials [30]. Given the challenge to conduct specific familiarisation sessions among elite athletes (usually, done only before the actual assessments as in the current study), high levels of reliability could be achieved in several strength and power tests, as noted. These findings agree with prior literature [14, 31]. However, additional familiarisation may be required for IMTP to improve the test-retest reliability.

The relationships between bench press with peak force during plyometric push-up and CMJ were *very large*. Training-induced increases in maximal strength can improve force generation and power production [2], with a transfer to greater athletic performance [2]. High levels of strength are often correlated with explosive performance, which may be linked to enhanced nervous system capacities e.g., rate of motor unit activation [1]. In the current study, *large* to *very large* relationships were found for dynamic and isometric strength with CMJ peak force, but not CMJ height. In accordance with Thomas et al. [32] who investigated team-sport athletes, absolute IMTP peak force does not necessarily correlate with CMJ height, but it does appear to correlate with absolute CMJ peak force and peak power. In the current study, this holds true especially for the best values observed. One possible reason for this observation is related to the overestimation of true flight time when using flight time to estimate jump height, as the jumps are not always performed uniformly with a consistent body position [20]. In contrast, McGuigan et al. [12] reported significant relationships between vertical jump height with bench press, back squat, and IMTP among recreational-level individuals, which indicates a discrepancy in findings due to different population, e.g., spread in dataset values and standard deviation [27]. There appears to be some unexplained variance between the maximum strength in back squat, IMTP, and bench press with drop jump, as well as standing long jump among this cohort. Plausibly, the aforementioned maximum strength exercises do not influence actions requiring more lower-limb muscles and joints (triceps surae and ankles) as stressed during drop jump, as well as force production in a horizontal manner (i.e., standing long jump). Meanwhile, biomechanical similarities (joint actions) in the upper body between the plyometric push-up and bench press, appear to be supported by the significant and *very large* correlation between both exercises. This observation may also be related to the similarity of muscle contractions [16]. These relationships between maximum strength and explosive tasks imply that, a concurrent strength and power training program, may be appropriate for improving performance in explosive exercises.

This study is not without limitations. It is possible that more specific familiarisation sessions would have altered the observed outcomes, (e.g., smaller MDCs). However, the current study represents the situation encountered by any teams performing testing and measurement at the beginning of their training preparation and can be considered to be ecologically valid. Secondly, the sample size can be considered *small-modest* and was affected by the missing attendance of players during the re-test sessions, which might have influenced how the conclusion was drawn. In particular, a proportional bias and non-uniform scatter may exist in several sub-plots (Figure 2), issues likely amplified by our small sample size. Additionally, we acknowledge that small sample size can adversely affect the SEM, thereby directly impacting MDC values. Moreover, the effects of timing of different variables must be noted; power variables assessed in the morning and dynamic strength variables measured in the afternoon (although being maintained during the retest), which could introduce "time of day" effects that may influence the outcomes. The results must also be considered in the context of limitations associated with correlations, which do not demonstrate causality and effect. Future research employing larger sample sizes are needed to replicate and validate our findings, and investigate covariance or the impact of performance changes (same players) over time (during early and late preparation, and competition periods) on test-retest reliability and MDC values.

CONCLUSIONS

In conclusion, a few commonly used tests in team sports, including bench press, back squat, standing long jump, and specific metrics (e.g., force, power) during IMTP, CMJs, drop jumps, and plyometric push-ups, showed *excellent* reproducibility, while exhibiting low variability (< 10% coefficient of variation). Furthermore, we found that dynamic strength index, and power metrics during plyometric push-ups presented *low* reproducibility. In evaluating the impacts of trials, we observed that the average score values, as opposed to the best score values, appeared to optimise measurement stability and produced comparatively lower MDCs. Furthermore, maximum strength was strongly associated with explosive performance, which suggests that muscular strength would markedly contribute to enhanced force and power output during explosive lower- (e.g., CMJ) and upper- (plyometric push-up) body.

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Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. Stone MH, Moir G, Glaister M, et al. How much strength is necessary? Phys Ther Sport. 2002; 3:88–96.
2. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. Sports Med. 2016; 46(10):1419–1449. doi: 10.1007/s40279-016-0486-0.
3. Speranza MJ, Gabbett TJ, Johnston RD, et al. Effect of strength and power training on tackling ability in semiprofessional rugby league players. J Strength Cond Res. 2016; 30(2):336–343. doi: 10.1519/JSC.0000000000001058.
4. Cunningham DJ, West DJ, Owen NJ, et al. Strength and power predictors of sprinting performance in professional rugby players. J Sports Med Phys Fitness. 2013; 53(2):105–111.
5. Smart D, Hopkins WG, Quarrie KL, Gill N. The relationship between physical fitness and game behaviours in Rugby Union players. Eur J Sport Sci. 2014; 14(S1), S8–S17. doi: 10.1080/17461391.2011.635812.
6. Sella FS, Hopkins WG, Beaven CM et al. The associations between physical-test performance and match performance in women's Rugby Sevens players. Biol Sport. 2023; 40(3):775–785. doi: 10.5114/biolsport.2023.119985.
7. Grgic J, Lazinica B, Schoenfeld BJ, et al. Test-retest reliability of the one-repetition maximum (1RM) strength assessment: a systematic review. Sports Med Open. 2020; 6(1):31. doi: 10.1186/s40798-020-00260-z.
8. Argus CK, Gill ND, Keogh JW, et al. Changes in strength, power, and steroid hormones during a professional rugby union competition. J Strength Cond Res. 2009; 23(5):1583–1592. doi: 10.1519/JSC.0b013e3181a392d9.
9. Beattie, K and Flanagan, EP. Establishing the reliability and meaningful change of the drop-jump reactive strength index. J Aust Strength Cond. 2015; 23:12–19.
10. Washif JA, Kok LY. Relationships between vertical jump metrics and sprint performance, and qualities that distinguish between faster and slower sprinters. J Sci Sport Exerc. 2022; 4:135–144. doi: 10.1007/s42978-021-00122-4.
11. Dos'Santos T, Jones PA, Comfort P, et al. Effect of different onset thresholds on isometric midthigh pull force-time variables. J Strength Cond Res. 2017; 31(12):3463–3473. doi: 10.1519/JSC.0000000000001765.
12. McGuigan MR, Newton MJ, Winchester JB, et al. Relationship between isometric and dynamic strength in recreationally trained men. J Strength Cond Res. 2010; 24(9):2570–2573. doi: 10.1519/JSC.0b013e3181ecd381.
13. Thomas C, Jones PA, Rothwell J, et al. An investigation into the relationship between maximum isometric strength and vertical jump performance. J Strength Cond Res. 2015; 29(8):2176–2185. doi: 10.1519/JSC.0000000000000866.
14. Comfort P, Thomas C, Dos'Santos T, et al. Comparison of methods of calculating dynamic strength index. Int J Sports Physiol Perform. 2018; 13(3):320–325. doi: 10.1123/ijspp.2017-0255.
15. Roe G, Darrall-Jones J, Till K, et al. Between-days reliability and sensitivity of common fatigue measures in rugby players. Int J Sports Physiol Perform. 2016; 11(5):581–586. doi: 10.1123/ijspp.2015-0413.

16. Bartolomei S, Nigro F, Ruggeri S, et al. Comparison between bench press throw and ballistic push-up tests to assess upper-body power in trained individuals. J Strength Cond Res. 2018; 32(6):1503–1510. doi: 10.1519/JSC .0000000000002571.
17. Thomas C, Dos'Santos T, Jones PA. A comparison of dynamic strength index between team-sport athletes. Sports. 2017; 5(3):71. doi: 10.3390 /sports5030071.
18. Comfort P, Dos'Santos T, Beckham GK, Stone MH, Guppy SN, Haff GG. Standardization and methodological considerations for the isometric midthigh pull. Strength Cond J. 2019; 41(2):57–79.
19. Comfort P, McMahon JJ. Reliability of maximal back squat and power clean performances in inexperienced athletes. J Strength Cond Res. 2015; 29(11):3089–3096. doi: 10.1519/JSC.0000000000000815.
20. Linthorne NP. Analysis of standing vertical jumps using a force platform. Am J Phys. 2001; 69(11):1198–1204.
21. Washif JA. Does whole-body vibration potentiate reactive strength performance in sprinters? J Aus Strength Cond. 2019; 27(07):14–22.
22. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J Chiropr Med. 2016; 15(2):155–163. doi: 10.1016/j.jcm.2016.02.012.
23. Hopkins WB, Marshall SW, Batterham AM, et al. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41:3–12. doi: 10.1249 /MSS.0b013e31818cb278.
24. Faigenbaum AD, McFarland JE, Herman RE, et al. Reliability of the one-repetition-maximum power clean test in adolescent athletes. J Strength Cond Res. 2012; 26(2):432–437. doi: 10 .1519/JSC.0b013e318220db2c.
25. Grgic J, Scapec B, Mikulic P, Pedisic Z. Test-retest reliability of isometric mid-thigh pull maximum strength assessment: a systematic review. Biol Sport. 2022; 39(2):407–414.
26. Aben HGJ, Hills SP, Higgins D, et al. The reliability of neuromuscular and perceptual measures used to profile recovery, and the time-course of such responses following academy rugby league match-play. Sports. 2020; 8(5):73. doi: 10.3390/sports8050073.
27. Washif JA, Kok LY. The reactive bounding coefficient as a measure of horizontal reactive strength to evaluate stretch-shortening cycle performance in sprinters. J Hum Kinet. 2020; 73:45–55. doi: 10.2478/hukin-2020-0003.
28. Cormack SJ, Newton RU, McGuigan MR. Neuromuscular and endocrine responses of elite players to an Australian rules football match. Int J Sports Physiol Perform. 2008; 3(3):359–374. doi: 10.1123/ijspp.3.3.359.
29. Hopkins WG. Measures of reliability in sports medicine and science. Sports Med. 2000; 30(1):1–15. doi: 10.2165/0000 7256-200030010-00001.
30. Nibali ML, Tombleson T, Brady PH, et al. Influence of familiarization and competitive level on the reliability of countermovement vertical jump kinetic and kinematic variables. J Strength Cond Res. 2015; 29(10):2827–2835. doi: 10.1519/JSC.0000000000000964.
31. Moir G, Button C, Glaister M, et al. Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. J Strength Cond Res. 2004; 18(2):276–280. doi: 10.1519/R-13093.1.
32. Thomas C, Comfort P, Chiang CY, et al. Relationship between isometric mid-thigh pull variables and sprint and change of direction performance in collegiate athletes. J Trainol. 2015; 4:6–10. doi: 10.17338/trainology.4.1_6.

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Effects of recreational team sports on the metabolic health, body composition and physical fitness parameters of overweight and obese populations: A systematic review

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ABSTRACT: This systematic review aims to provide a summary of the results from individual studies that specifically focused on overweight or obese populations, regardless of age or sex. The goal is to determine the effects of structured recreational team sports interventions (TSG) on metabolic health, body composition and physical fitness parameters when compared to passive or active control groups. This study adhered to the PRISMA guidelines for reporting a systematic review. A thorough examination of relevant literature was conducted on November 06, 2023, using three prominent databases: PubMed, Scopus, and the Web of Science. Inclusion criteria considered overweight (e.g., BMI 25.0–29.9 kg/m^2) and obese (e.g., BMI > 30 kg/m^2) populations exposed to training interventions using recreational team sports, while the comparator group consisted of the same populations not exposed to exercise (passive controls) or exposed to alternative training methods. The primary outcomes of interest were metabolic health parameters (glucose, waist circumference, blood pressure, cholesterol, triglycerides), body composition (e.g., fat mass, lean mass), as well as physical fitness parameters (e.g., aerobic fitness, muscular fitness). Only studies with two- or multi-arm designs, whether randomized or not, were eligible for inclusion. The PEDro scale was used to assess the methodological bias of the included studies. Out of the initial 275 titles retrieved, we deemed ten eligible for our study. In terms of body composition, TSG demonstrated a significant decrease in body mass index across three studies (−2.3 to −5.1%) and a significant reduction in waist circumference in four studies (−4.6% to −8.4%). Regarding blood pressure, TSG exhibited a significant decrease in systolic blood pressure in two studies (−3.9% to -8.3%), while diastolic blood pressure showed a significant decrease in only one study (−7.3%). Cholesterol levels saw a significant decrease in TSG in three studies (−7.0% to −9.7%), and triglyceride levels showed a significant reduction in four studies (−16.4% to −20.1%). In terms of aerobic fitness, TSG demonstrated within-group improvements in the field-based tests in three studies (8.1% to 79.0%), and within-group improvements in maximal oxygen uptake in four studies (6.5% to 31.0%), with significant favoring of TSG in most studies. Overall, TSG demonstrated significant benefits for overweight and obese populations compared to the control group, particularly in terms of improvements in body mass index, systolic blood pressures, cholesterol and triglyceride levels, and aerobic fitness. Future research ought to concentrate on tailoring responses to varying training volumes on an individualized basis.

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INTRODUCTION

Overweight and obesity represent a pervasive health concern in contemporary populations [1]. More than 1.9 billion adults aged 18 years and older are overweight, and of those, over 650 million adults are obese [2]. This prevalence represents a significant impact on both health [3] and physical fitness [4]. According to numerous scientific studies, the prevalence of overweight and obesity has risen steadily in recent decades, with an alarming increase in many parts of the world [5, 6].

While there are acknowledged limitations and concerns regarding the use of the Body Mass Index (BMI) as a surrogate for measuring body fat and determining overweight or obesity [7], it is worth noting that the Medical Subject Headings (MeSH) terms continue to

define overweight as having a BMI in the range of 25.0–29.9 kg/m^2, with obesity being characterized by a BMI exceeding 30 kg/m^2 (or 25% body fat percentage for men and 35% for women) [8].

The detrimental health effects of overweight and obesity are well-documented, and they encompass a wide range of conditions, including type 2 diabetes, cardiovascular disease, certain types of cancer, and musculoskeletal disorders [9, 10]. Physical exercise, when incorporated as part of comprehensive community programs, plays a pivotal role in mitigating the effects of overweight and obesity and its associated negative impact on health [11]. Scientific evidence underscores the effectiveness of physical exercise in combating overweight and obesity, not only by promoting weight loss but also by improving metabolic health and enhancing physical fitness [12].

Regular exercise contributes to energy expenditure [13], reduces body fat [14], and enhances insulin sensitivity [15], thereby addressing key components of the obesity problem. Furthermore, community-based programs, which offer structured and supportive environments for physical activity, hold the potential to bolster the impact of exercise interventions [16]. These programs often encompass educational components, social support networks, and opportunities for active recreation, fostering sustained adherence to physical activity [17]. In the fight against obesity, it is essential to recognize that physical exercise is just one facet of a multifaceted approach [18]. Non-pharmacological strategies for obesity management may also involve dietary modifications, behavioral therapy, and psychosocial support, as they can complement physical activity interventions to achieve more comprehensive and sustainable results [19]. Collaborative efforts within communities, incorporating various non-pharmacological approaches, are key to addressing the complex and multifactorial nature of obesity.

In the realm of physical exercise, scientific evidence supports the significant positive impact of aerobic exercise, particularly including intermittent forms and recreational sports, on metabolic health [20], physical fitness [21], and body composition [22] in overweight and obese populations. Numerous studies have shown that including intermittent forms of aerobic-based exercise and recreational sports has been shown to enhance insulin sensitivity [23], reduce fasting blood glucose levels [24], and improve lipid profiles [21], which are particularly relevant for individuals with overweight and obesity who often face heightened metabolic risks. Moreover, aerobic intermittent forms and recreational sports is highly effective in promoting physical fitness [25]. It has been associated with increased cardiorespiratory fitness [26] and muscle strength [27]. In terms of body composition, aerobic intermittent forms and recreational sports has demonstrated its ability to reduce body fat percentage while preserving lean muscle mass [21].

Participation in recreational team sports (e.g., soccer, basketball) presents a valuable strategy to combat sedentary behavior while offering numerous positive effects for such individuals, both physically and mentally [28]. Engaging in team sports not only provides an enjoyable and motivating alternative to traditional exercise but also fosters social interactions and a sense of community, which can be particularly beneficial for those dealing with isolation and self-esteem issues [29]. The engaging factors of team sports, such as competition, camaraderie, and the fun of the game, can enhance adherence to a physically active lifestyle among the obese and overweight.

In the context of a systematic review, summarizing the evidence regarding the effects of recreational team sports on overweight and obese individuals is essential and has been done [30]. Despite the abundance of systematic reviews and meta-analyses on physical activity and obesity [31, 32], there appears to be a notable gap: no review has exclusively focused on the benefits of recreational team sports for this specific population. Notably, several systematic reviews on recreational sports, such as soccer [33–36], have been disseminated, but without a targeted emphasis on a specific population or an assessment of its effects on particular outcomes.

Therefore, it is crucial to comprehend how metabolic health, encompassing variables such as waist circumference, fasting blood glucose, systolic and diastolic blood pressure, triglycerides, and high-density lipoprotein cholesterol, along with considerations of body composition (e.g., fat mass, lean mass, fat-free mass) and physical fitness (e.g., cardiorespiratory fitness, muscular strength and resistance), may be influenced by SSGs programs implemented in overweight and obese populations. This research may potentially alleviate the adverse effects of obesity on functional and health parameters.

A dedicated systematic review in this domain could significantly advance the state of the art by providing a comprehensive and evidence-based overview of the unique contributions of recreational team sports in metabolic health, body composition and physical fitness, shedding light on a currently underrepresented but promising area of research. As a result, the systematic review seeks to consolidate the primary findings concerning the effects of experimental programs utilizing recreational sports like basketball and soccer, when compared to control groups, on the metabolic health, body composition, and physical fitness of overweight and obese individuals, irrespective of age or sex.

MATERIALS AND METHODS

Design and protocol registration

Adhering to the criteria established by the PRISMA 2020 guidelines [37, 38], widely acknowledged as the leading standard for transparent reporting in systematic reviews, we executed our systematic review. Furthermore, the present systematic review adheres to the recommended guidelines for reporting systematic reviews in sports sciences [39]. A comprehensive protocol governing our review procedures has been formally recorded on the Open Science Framework (OSF) platform, and it is identified with the project number osf.io/ack4t, accompanied by a DOI: 10.17605/OSF.IO/ACK4T.

TABLE 1. Eligibility criteria based on PICOS.

	Inclusion criteria	Exclusion criteria
Population	Individuals of all age groups and sex who meet specific criteria for overweight (with a BMI of 25.0–29.9 kg/m^2, as defined in Medical Subject Headings terms) or obesity (with a BMI exceeding 30 kg/m^2, as defined in Medical Subject Headings terms). This criterion (or one based on fat mass as > 35% [61] or other reasonable criteria as BMI > +2 standard deviations above age- and sex-specific WHO reference medians or ≥ 85th percentile [62]) should be incorporated into the eligibility criteria of the study to ensure that participants who are non-overweight are not inadvertently mixed into the sample.	Individuals who are neither overweight nor obese or studies integrating mixed population that includes both overweight/obese individuals and those who are not overweight or obese. Studies that have presented BMI levels according to specific criteria but have not explicitly reported those criteria for participants fail to ensure the inclusion of other populations (i.e., non-overweight individuals) within the sample range.
Intervention/ exposure	Exclusively performing recreational team sports such as soccer or basketball, utilized as a form of exercise intervention for individuals who are overweight or obese.	Combined training programs, comprising recreational team sports and other training methods (e.g., running training, resistance training), or recreational team sports used alongside supplementary strategies like dietary modifications or medication.
Comparator	Comparators were considered for both cases: passive controls (a parallel group with similar characteristics not exposed to any exercise intervention) and/or active controls (a parallel group with similar characteristics exposed to a different form of exercise intervention unrelated to recreational team sports).	Combined training programs, comprising recreational team sports and other training methods (e.g., running training, resistance training), or other training interventions/control conditions in which a special dietary modification or medication was implemented.
Outcomes	We focused on parameters related to physical fitness (e.g., aerobic fitness, muscular fitness), metabolic health (glucose levels, waist circumference, blood pressure, cholesterol, triglycerides), and body composition (e.g., fat mass, lean mass), assessed at least in two time-points (baseline and post-intervention.	Immediate responses to a single session, or chronic adaptations encompassing outcomes beyond those delineated in the inclusion criteria (e.g., well-being and cognitive functioning).
Study design	The review will include studies that utilize either two-arm or multi-arm designs, irrespective of their randomization status.	Quasi-experimental studies, non-controlled studies, and observational studies will be excluded from consideration for inclusion.

Eligibility criteria

In our systematic review, we have encompassed all original articles that have been published in peer-reviewed journals, even those in "ahead-of-print" status. We intentionally refrained from imposing any language restrictions to ensure the inclusion of a comprehensive range of articles.

Our approach to establishing eligibility criteria adhered to the PICOS framework, and it is possible to find a comprehensive breakdown of these criteria in Table 1.

We assessed the suitability of the articles using the PICOS approach, as delineated in Table 1. This systematic method facilitated a meticulous examination of the content, enabling us to establish well-defined inclusion and exclusion criteria. In order to ensure a comprehensive evaluation, we conducted a thorough review of the full texts to determine their eligibility for inclusion in the review.

Information sources and search strategy

Our process for identifying relevant studies involved an extensive search conducted across several databases, including: (i) PubMed, (ii) Scopus, and (iii) Web of Science, up to the date of November 06, 2023. The searches were independently conducted by two authors, TW and FMC, on the same day. To augment the comprehensiveness of our methodology and minimize the potential of overlooking pertinent materials, we also conducted manual searches in the same day within the reference lists of the studies included in our review.

The search was systematically executed using Boolean operators AND/OR, with a deliberate decision to abstain from employing filters or constraints related to publication dates or language. This intentional approach was chosen to heighten the probability of discovering relevant studies. A comprehensive breakdown of the search strategy is meticulously documented in Table 2, conveniently presented below for reference.

Selection process

The screening process was meticulously carried out by two assigned authors, specifically TW and LY. They independently assessed the retrieved records, encompassing both titles and abstracts. Following this, they individually evaluated the full texts of the selected records. In cases where discrepancies in the evaluation surfaced, a collaborative reevaluation process was initiated to reach a consensus. If a consensus could not be reached, the final decision was entrusted to a third author, FMC.

For efficient record management, we utilized EndNote X9.3.3 software, developed by Clarivate Analytics in Philadelphia, Pennsylvania, USA.

Data collection process

The data collection process was conducted independently by the authors TW and LY. In instances where disagreements arose during this phase, FMC acted as a mediator to resolve any discrepancies. To enhance efficiency and maintain organization throughout this procedure, we utilized a dedicated Microsoft® Excel datasheet. This datasheet encompassed all pertinent data and essential information, ensuring a structured and effective approach to data management.

Data items

We carried out an exhaustive data collection process, capturing an extensive array of participant details and contextual factors. These variables encompassed essential information such as publication date, primary research objectives, sample size, country of origin, age distribution, sex composition, clinical conditions (e.g., diabetes, hypertension), study design, and the competitive level of the participants.

In terms of intervention-related details, we documented information related to the program's duration, training frequency, adherence to the training regimen, and various aspects of the training dosage. This included specific information on the duration, repetitions, rest intervals, intensity, frequency, and training density.

Additionally, we maintained comprehensive records of the comparison groups, which included details about both active and control groups. This encompassed specifics regarding the type of exercises, exercise intensity, and volume. In the case of passive control, we reported whether participants maintained their daily habits or were subjected to alternative approaches (e.g., receiving only documentation for lifestyle changes).

Our main emphasis in gathering primary outcome measures centered around parameters associated with physical fitness (e.g., aerobic fitness, muscular fitness), metabolic health (glucose levels, waist circumference, blood pressure, cholesterol, triglycerides), and body composition (e.g., fat mass, lean mass). These measures were collected both before and after the intervention, with a minimum of two time points for intervention study.

Study risk of bias assessment

To assess the risk of bias in the studies included in our review, we employed the Physiotherapy Evidence Database (PEDro) scale, a well-validated and reliable tool. This scale evaluates eleven specific criteria, with ten of them contributing to the overall score assigned to

TABLE 2. Full search strategy for each database.

Database	Specificities of the databases	Search Strategy	Number of articles
PubMed	Search for title and abstract also includes keywords	((“team sport*” [Title/Abstract] OR football* [Title/Abstract] OR soccer [Title/Abstract] OR futsal [Title/Abstract] OR handball* [Title/Abstract] OR volleyball* [Title/Abstract] OR basketball* [Title/Abstract] OR hockey [Title/Abstract] OR hurling [Title/Abstract] OR rugby [Title/Abstract] OR cricket [Title/Abstract] OR polo [Title/Abstract] OR lacrosse [Title/Abstract] OR softball [Title/Abstract] OR korfball [Title/Abstract] OR Gaelic* [Title/Abstract] OR netball [Title/Abstract] OR baseball [Title/Abstract] OR “sepak takraw” [Title/Abstract]) AND (Recreational [Title/Abstract] OR walk* [Title/Abstract])) AND (Obes* [Title/Abstract] OR overweight [Title/Abstract])	51
Scopus	Search for title and abstract also includes keywords	(TITLE-ABS-KEY (“team sport*” OR football* OR soccer OR futsal OR handball* OR volleyball* OR basketball* OR hockey OR hurling OR rugby OR cricket OR polo OR lacrosse OR softball OR korfball OR gaelic* OR netball OR baseball OR “sepak takraw”) AND TITLE-ABS-KEY (recreational OR walk*) AND TITLE-ABS-KEY (obes* OR overweight))	117
Web of Science	Search for title and abstract also includes keywords and its designated “topic”	“team sport*” OR football* OR soccer OR futsal OR handball* OR volleyball* OR basketball* OR hockey OR hurling OR rugby OR cricket OR polo OR lacrosse OR softball OR korfball OR Gaelic* OR netball OR baseball OR “sepak takraw” (Topic) and Recreational OR walk* (Topic) and Obes* OR overweight (Topic)	107

each article. Scores on the PEDro scale range from 0, representing the lowest quality, to 10, signifying the highest quality. Typically, predetermined score thresholds are utilized to categorize articles into qualitative categories, including 'poor' (< 4 points), 'fair' (4–5 points), 'good' (6–8 points), and 'excellent' (9–10 points).

The assessment process involved two authors independently evaluating and scoring the articles using the PEDro scale. Subsequently, these two authors (TW and LY) compared their individual scores and engaged in comprehensive discussions to resolve any discrepancies, criterion by criterion. In instances where a consensus could not be reached, a third author (FMC) was consulted to provide their score and ultimately make the definitive decision regarding the rating. The concordance between both authors (TW and LY) was assessed through the calculation of the kappa agreement rate between reviewers, yielding a k value of 0.96. Cohen's kappa coefficient (k) is employed to gauge inter-rater reliability for qualitative (categorical) items. A k value approaching 1 indicates greater inter-rater variability.

Data synthesis

Utilizing the data (mean ± standard deviation) obtained from pre-intervention (A) to post-intervention (B) within each group, we independently calculated the percentage of change for each individual study and outcome employing the following formula:

$$\left|\frac{B-A}{\frac{A+B}{2}}\right| \times 100$$

Furthermore, employing the data (mean ± standard deviation) derived from post-intervention for both the SSGs and control groups, we calculated Cohen's d using the following formula [40]:

$$Cohen's\ d = \frac{mean\ difference}{Pooled\ standard\ deviation}$$

RESULTS

Study Identification and Selection

In Figure 1, we present the results of our initial search, which yielded a total of 275 titles. Following this initial step, we embarked on a thorough curation process, combining both automated and manual methods, in order to eliminate duplicate entries. This process resulted in the removal of 81 titles, leaving us with a collection of 194 unique titles. Each of these titles then underwent a meticulous assessment, considering both their titles and abstracts, to determine their relevance. Following this assessment, 166 studies were deemed unsuitable and subsequently excluded from our review.

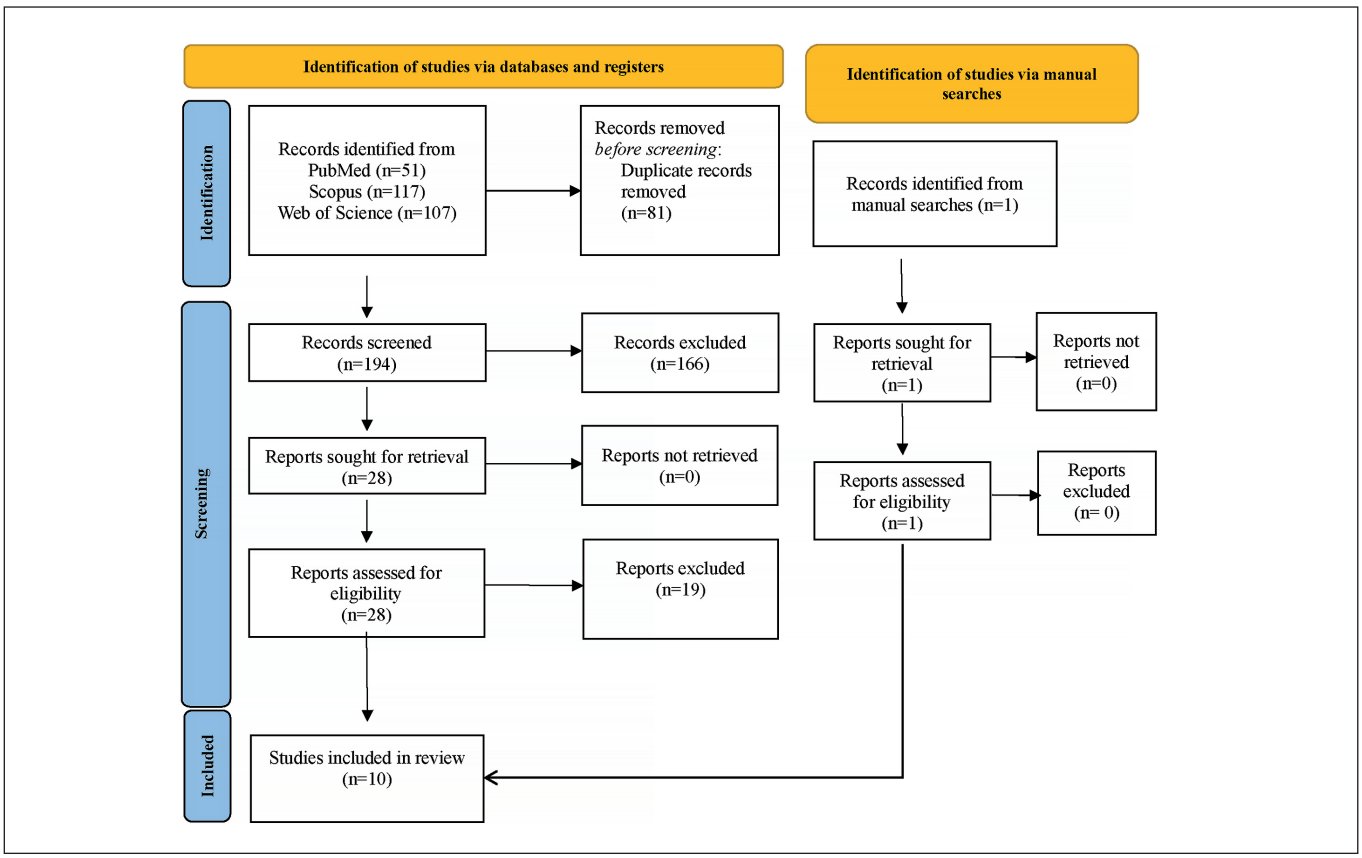


FIG. 1. PRISMA flow diagram.

The next stage of our investigation involved a comprehensive examination of the full texts of the remaining 28 studies. This systematic review ultimately identified 9 studies that met our predefined eligibility criteria. In addition to our database screening, we also conducted an extensive manual search within the references cited in the selected articles. This supplementary search uncovered one additional articles that satisfied our inclusion criteria. As a result, our systematic review incorporated a total of 10 articles. For a detailed breakdown of the full-text screening process and the rationale behind exclusions, we kindly refer you to Supplementary Material 1.

Assessment of the risk of bias

In the course of our systematic review, we conducted an extensive examination of a set of ten studies, as detailed in Table 3. Within this collection, we identified that three studies exhibited a quality rating in the range of 4 to 5 points, signifying a moderate level of quality. Conversely, the remaining seven studies were assigned quality scores between 6 and 8 points, indicating a notably higher level of quality. It is worth emphasizing a shared limitation present in all the studies under scrutiny, which pertained to the absence of reported information concerning blinding procedures for both study participants and the individuals responsible for conducting the investigation and assessment.

Characterization of the individual studies

The table 4 summarizes the individual studies investigating the effects of team sports interventions on overweight and obese populations. The age range across the studies varies, from 8 (Hansen et al. [41]) to 61 (Moller et al. [11]) years old, with the majority focusing on children and adolescents (Cvetkovic et al. [25]; Hansen et al. [41]; Seabra et al. [42]; Soares et al. [43]; Vasconcellos et al. [44]; Vasconcellos et al. [45]).

The number of participants ranges from 13 (Vasconcellos et al. [45]) to 88 (Seabra et al. [42]), with team sports like soccer and handball being common choices. The sex distribution is diverse, with some studies including both males and females (Hansen et al. [41]; Soares et al. [46]; Soares et al. [43]; Vasconcellos et al. [44]; Vasconcellos et al. [45]). The duration of interventions ranges from 12 to 24 weeks, with 12 weeks being the most common.

In the studies presented (Table 5), the total training sessions varied across experiments, with the highest number being 72 sessions in Seabra et al. [42] soccer training group and the minimum being 24 sessions in Cvetkovic et al. [25] and Moller et al. [47] soccer training groups. The training interventions in TSG were structured, involving warm-ups, technical exercises, small-sided games, and cool-downs. Notably, the control groups engaged in regular physical education classes or did not participate in specific training. The soccer training groups emphasized skill development, teamwork, and practical soccer play, utilizing various formats (e.g., 3v3 or 4v4) and pitch sizes.

Summary of the individual studies

In analyzing the statistical tendencies of using team sports groups (TSG) versus control groups (CG) across multiple studies (Table 6),

TABLE 3. Physiotherapy Evidence Database (PEDro) scale ratings.

Study	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Score
Cvetkovic et al. [25]	1	1	1	0	0	0	0	1	1	1	1	6
Hansen et al. [41]	1	0	0	0	0	0	1	1	1	1	1	5
Hornstrup et al. [48]	1	1	0	0	0	0	1	1	1	1	1	6
Mohr et al. [49]	1	1	0	1	0	0	0	1	1	1	1	6
Moller et al. [47]	1	0	0	1	0	0	0	1	1	1	1	5
Seabra et al. [42]	1	0	0	0	0	0	0	1	1	1	1	4
Soares et al. [46]	1	1	0	1	0	0	0	1	1	1	1	6
Soares et al. [43]	1	1	0	1	0	0	0	1	1	1	1	6
Vasconcellos et al. [44]	1	1	1	1	0	0	1	1	1	1	1	8
Vasconcellos et al. [45]	1	1	1	1	0	0	1	1	1	1	1	8

C1: eligibility criteria were specified; C2: subjects were randomly allocated to groups; C3: allocation was concealed; C4: the groups were similar at baseline regarding the most important prognostic indicators; C5: there was blinding of all subjects; C6: there was blinding of all therapists who administered the therapy; C7: there was blinding of all assessors who measured at least one key outcome; C8: measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; C9: all subjects for whom outcome measures were available received the treatment or control condition as allocated, or, where this was not the case, data for at least one key outcome were analyzed according to "intention to treat"; C10: the results of between-group statistical comparisons are reported for at least one key outcome; C11: the study provides both point measures and measures of variability for at least one key outcome. Score: The score is derived by summing the scores from C2 to C11, as recommended by the PEDro scale.

TABLE 4. Characteristics of the included studies

Study	N	Age (years old)	Sex	Team sport	Experimental groups (n)	Passive control groups (n)	Randomization	Study duration (w)	Outcomes extracted	Instruments/tests for measuring the outcomes
Cvetkovic et al. [25]	35	11–13	Male	Soccer	Soccer group (n = 10) HIIT group (n = 11)	Passive control (n = 14)	Yes	12	BMI (kg/m^2) Body fat mass (%) Lean body mass (%) Muscle mass (%) CMJ arm swing (cm) Agility T-test (s) Sit and reach (cm) YYIRT (m) Systolic and diastolic blood pressure (mmHg) BMI (kg/m^2)	Anthropometry (BMI) Bioelectrical impedance analyzer (for body fat mass, lean body mass, muscle mass) Agility t test Sit and reach test YYIRT Digital blood pressure monitor
Hansen et al. [41]	31	8–12	Both	Soccer	Soccer group (n = 20)	Passive control (n = 11)	No	12	BMI (kg/m^2) Systolic and diastolic blood pressure (mmHg) BMI (kg/m^2)	Anthropometry (BMI) Digital blood pressure monitor Anthropometry (BMI)
Hornstrup et al. [48]	32	41.8–46.3	Female	Handball	Handball experienced group (n = 13) Handball unexperienced group (n = 10)	Passive control (n = 9)	Yes	16	Systolic and diastolic blood pressure (mmHg) Gynoid fat mass (kg) BMI (kg/m^2) Total cholesterol (mmol/L) Triglycerid (mmol/L) $\dot{V}O_{2max}$ (ml/kg/min) YYIET (m)	X-ray absorptiometry (fat mass); Digital blood pressure monitor; Blood sample Incremental treadmill test ($\dot{V}O_{2max}$) YYIET
Mohr et al. [49]	41	35–50	Female	Soccer	Soccer group (n = 21)	Passive control (n = 20)	Yes	15	Systolic and diastolic blood pressure (mmHg) Total fat mass (kg) Lean body mass (kg) YYIET (m) Triglycerid (mmol/L) Total cholesterol (mmol/L)	Digital blood pressure monitor X-ray absorptiometry (fat and lean mass) YYIET Blood sample
Moller et al. [47]	68	58–61	Male	Multiple	Multiple sports group (n = 36) Aerobic training group (n = 32)	NA	No	12	Systolic and diastolic blood pressure (mmHg) Fat mass (kg) Lean body mass (kg) $\dot{V}O_{2max}$ (ml/kg/min) 6-minute walking test (m) Balance (s) Sit-to-stand (stand/30 s)	Digital blood pressure monitor X-ray absorptiometry (fat and lean mass) Incremental cycling test ($\dot{V}O_{2max}$) 6-minute walking test Tandem balance test Sit-to-stand test

TABLE 4. Continue

Study	N	Age (years old)	Sex	Team sport	Experimental groups (n)	Passive control groups (n)	Randomization	Study duration (w)	Outcomes extracted	Instruments/tests for measuring the outcomes
Seabra et al. [42]	88	8–12	Male	Soccer	Soccer group (n = 29) Traditional activity group (n = 29)	Passive control (n = 30)	No	24	BMI (kg/m^2) Waist circumference (cm) Body fat (%) Lean mass (kg) Systolic and diastolic blood pressure (mmHg) Glucose (mg/dl) Triglycerid (mmol/L) Total cholesterol (mmol/L) $\dot{V}O_{2max}$ (ml/kg/min)	Anthropometry (BMI; waist circumference) X-ray absorptiometry (fat and lean mass) Digital blood pressure monitor Blood sample Incremental treadmill test ($\dot{V}O_{2max}$)
Soares et al. [46]	39	60 ± 6	Both	Soccer	Soccer group* (n = 13) HIIT group* (n = 11)	Passive control* (n = 13)	Yes	12	BMI (kg/m^2) Waist circumference (cm) Body fat (%) Lean mass (%) Glucose (mg/dl) Triglycerid (mmol/L) Total cholesterol (mmol/L)	Anthropometry (BMI; waist circumference) X-ray absorptiometry (fat and lean mass) Blood sample
Soares et al. [43]	18	12–17	Both	Soccer	Soccer group (n = 10)	Passive control (n = 8)	Yes	12	BMI (kg/m^2) Waist circumference (cm) Fat mass (%) $\dot{V}O_{2max}$ (ml/kg/min)	Anthropometry (BMI; waist circumference) X-ray absorptiometry (fat mass) Ramp-incremented protocol on a cycle ergometer ($\dot{V}O_{2max}$)
Vasconcellos et al. [44]	30	12–17	Both	Soccer	Soccer group (n = 10)	Passive control (n = 10)	Yes	12	BMI (kg/m^2) Waist circumference (cm) Fat percentage (%) Systolic and diastolic blood pressure (mmHg) $\dot{V}O_{peak}$ (ml/kg/min) Triglycerid (mmol/L) Total cholesterol (mmol/L) Fasting glucose (mg/dl)	Anthropometry (BMI; waist circumference) X-ray absorptiometry (fat percentage) Digital blood pressure monitor Blood sample Incremented protocol on a cycle ergometer ($\dot{V}O_{2max}$) Blood sample
Vasconcellos et al. [45]	13	13–17	Both	Soccer	Soccer group (n = 6)	Passive control (n = 7)	Yes	12	BMI (kg/m^2) Waist circumference (cm) Waist circumference (cm) Systolic and diastolic blood pressure (mmHg) Triglycerid (mmol/L) Glucose (mg/dl)	Anthropometry (BMI; waist circumference) Digital blood pressure monitor Blood sample

BMI: body mass index; NA: not applicable; HIIT: high-intensity interval training; *these groups had dietary plan; CMJ: countermovement jump; YYIRT: yo-yo intermittent recovery test; YYIET: Yo-Yo Intermittent endurance test; LDL: low-density lipoprotein; HDL: high-density lipoprotein

TABLE 5. Characteristics of the experimental programs and the control groups

Study	Training frequency (n/w)	Total of training sessions (n)	Experimental groups (description of the training process)	Passive control groups (description)
Cvetkovic et al. [25]	2	24	Soccer training group: Frequency: Three times per week (Monday, Wednesday, and Friday); Duration: Each training session lasted approximately 60 minutes; Components: Included a 10-minute low-intensity warm-up, followed by 4 × 8-minute periods of play interspersed with 2 minutes of passive rest, and ended with a 10-minute cool-down; Activity: Participants engaged in five-to-seven-a-side matches on artificial grass with specific pitch area and aspect ratio; Warm-up: Included moderate-intensity jogging, static and dynamic stretching, and acceleration running; Rules: Matches were played without allocation of playing positions and followed the general rules of football. High-intensity interval training: Frequency: Three sets of high-intensity interval runs during each training session. Interval Distances: Individually adjusted based on each participant's maximal aerobic speed (MAS) determined by the Half-Cooper test; Training Volume Progression: Increased over three phases (weeks 0–4, weeks 5–8, and weeks 9–12). Intensity: Work intervals were at 100% MAS, interspersed with equivalent passive recovery at 0% MAS; The distance for each participant was individually calculated to maintain the same training intensity; Structure: Training sessions involved a warm-up, high-intensity interval runs, and a cool-down, similar to the football training group.	Participants in the control group continued their regular physical education (PE) classes twice per week during the study period. These classes were conducted under the guidance of the PE teacher according to the curriculum.
Hansen et al. [41]	4	48	Soccer training group: training sessions were administered 4 days per week during the school day. Each session included a warm-up, technical football exercises, small-sided football games, and a cool-down period. Exercise Intensity: The football training was designed to maintain the heart rate above 80% of the maximum heart rate.	Did not engage in formal sports activities during the study period, except for the compulsory sport curriculum at school (2 sessions of 45–90 minutes per week).
Hornstrup et al. [48]	2–3	32–48	Handball training group: The team handball training sessions involved a structured regimen, commencing with a 12 to 15-minute warm-up, followed by four sets of 10-minute match play periods, including 4v4 and 3v3 formats, conducted on a 14-meter wide and 19-meter long team handball pitch. These play periods were separated by 3-minute breaks, and it's noteworthy that no hard tackles were permitted during the training sessions. Additionally, the training balls were of a lightweight and soft material, emphasizing safety and skill development.	Not described
Mohr et al. [49]	2.3–3.5	40–52	Soccer training group: Small-sided football games, varying from 4v4 to 10v10, conducted in competitive settings, with 60-minutes per session. Supervision: A trained football coach oversaw all training sessions.	Did not engage in any specific training during the 15-week intervention period
Moller et al. [47]	2	24	Soccer training group: Training sessions included warm-ups, technical exercises, one-on-one (1v1) exercises, and small-sided games (up to six-a-side) with short intervals and breaks. The sessions also emphasized theories on physical exercise, healthy diet, and flexibility exercises.	Did not engage in any specific training

TABLE 5. Continue

Study	Training frequency (n/w)	Total of training sessions (n)	Experimental groups (description of the training process)	Passive control groups (description)
Seabra et al. [42]	3	72	Soccer training group: The soccer training program consisted of three sessions per week for a duration of 60–90 minutes each. The structure consisted into warm-Up (10–20 minutes): Each session began with a warm-up to prepare participants for physical activity; Technical Drills and Small-Sided Games (40–60 minutes): The core of the soccer training involved technical drills and small-sided games. This part of the session focused on skill development, teamwork, and practical soccer plan; cool-Down (10 minutes): At the end of each session, a cool-down period was implemented to gradually reduce heart rate and prevent injury. The training intensity for the soccer program was designed to maintain heart rates at approximately 70–80% of the maximum heart rate, as confirmed through monitoring. Traditional activity program: The traditional activity program for the AS group involved three sessions per week, with each session lasting 60–90 minutes. The structure of the AS group sessions was as follows: warm-Up (10–20 minutes): Each session started with a warm-up period to prepare participants for physical activity; generalized activities (40–60 minutes): The core of the session focused on general activities aimed at improving various aspects of fitness, including aerobic endurance, coordination, balance, flexibility, and strength. These activities included walking, running, gymnastics, games, and others; cool-Down (10 minutes): At the conclusion of each session, there was a cool-down period to gradually lower heart rates and reduce the risk of injury. Similar to the soccer training group, the training intensity for the traditional group was designed to maintain heart rates at approximately 70–80% of the maximum heart rate, as monitored throughout the sessions.	Not applicable
Soares et al. [46]	3	36	Soccer training group: These sessions were characterized by moderate-to-high intensity, lasting 40 minutes each, with a frequency of 3 sessions per week. During the training, participants maintained their heart rate above 60% of their maximum heart rate for approximately 70% of the total training time. The training sessions primarily involved ordinary small-sided friendly games (ranging from 3v3 to 7v7) and were conducted either outdoors on a natural grass pitch (30–40 meters wide and 45–60 meters long) or indoors on a wooden court in case of rainy weather. Notably, there were no goalkeepers involved in these sessions. Each training session followed a structured format, including a 10-minute low-intensity warm-up, followed by 3 minutes of passive rest, and then two 12-minute periods of play, with 3-minute passive rest intervals in between. High-intensity interval training: Each session initiated with a 10-minute warm-up designed to prepare participants for physical activity. Following the warm-up, the training sessions were divided into two distinct segments. First, participants engaged in a 12-minute session of high-intensity interval exercise, likely involving short bursts of intense physical activity interspersed with brief rest or lower-intensity intervals. Subsequently, the program transitioned into a 12-minute segment of continuous training performed at a moderate intensity level, similar to the average intensity of the soccer group. Before the commencement of each running session, all subjects participated in a 10-minute dynamic warm-up, which included activities like walking and running, progressively increasing in distance from 50 to 100 meters on a court. This comprehensive protocol aimed to deliver a structured and effective running training program.	Not described

TABLE 5. Continue

Study	Training frequency (n/w)	Total of training sessions (n)	Experimental groups (description of the training process)	Passive control groups (description)
Soares et al. [43]	3	36	Soccer training group: The exercise sessions had a duration of 60 minutes and followed a specific structure. They commenced with a 10-minute warm-up to prepare participants for physical activity. The core of each session consisted of 40 minutes of small-sided games, with variations like 2 vs. 2, 3 vs. 3, and 4 vs. 4. These small-sided games were played in confined pitch areas. The sessions concluded with a 10-minute cool-down period.	Not described
Vasconcellos et al. [44]	3	36	Soccer training group: Every session was structured with a 10-minute warm-up at the outset, followed by 40 minutes of engaging games conducted in compact pitch areas, including formats like 2 vs. 2, 3 vs. 3, and 4 vs. 4. The sessions then concluded with a 10-minute cool-down period.	Not described
Vasconcellos et al. [45]	3	36	Soccer training group: Each exercise session was structured to include a 10-minute warm-up, succeeded by 40 minutes of participation in small-sided games, featuring formats like 2 vs. 2, 3 vs. 3, and 4 vs. 4. These games were strategically played in smaller pitch areas, with the recognized benefits of enhancing aerobic fitness and honing technical and tactical skills. Notably, the sessions maintained an average percentage of maximal heart rate at 84.5 ± 4.1%, indicating a consistently high level of cardiovascular intensity throughout the games.	Not described

TABLE 6. Results of individual studies on anthropometry and body composition

Study	Variable	TSG pre	TSG post	%dif (post-pre)	Within-TSG (p-value)	CG pre	CG post	%dif (post-pre)	Within-CG (p-value)	Between groups (p-value)	ES between groups (post)
Cvetkovic et al. [25]	BMI (kg/m^2)	25.43 ± 4.05	24.65 ± 4.22	−3.1%ß	$p > 0.05$	25.29 ± 4.77	26.16 ± 4.49	3.4%Ý	$p > 0.05$	$p < 0.05$ favoring TSG	−0.356
Hansen et al. [41]	BMI (kg/m^2)	23.1 ± 2.9	22.9 ± 2.8	−0.9%ß	$p > 0.05$	28.0 ± 2.9	27.6 ± 3.3	−1.4%Ý	$p > 0.05$	$p > 0.05$	−1.320
Hornstrup et al. [48]#	BMI (kg/m^2)	28.4 ± 4.7	28.4 ± 4.5	0.0%Þ	ND	29.8 ± 5.5	30.3 ± 5.7	1.7%Ý	ND	$p > 0.05$	−0.603
Seabra et al. [42]	BMI (kg/m^2)	23.7 ± 2.8	23.5 ± 2.6	−0.8%ß	$p > 0.05$	25.1 ± 3.8	25.3 ± 4.3	0.8%ß	$p > 0.05$	$p > 0.05$	−0.743
Soares et al. [46]	BMI (kg/m^2)	33.1 ± 1.0	31.4 ± 0.8	−5.1%ß*	*$p < 0.05$	33.3 ± 1.2	31.4 ± 1.1	−5.7%ß	*$p < 0.05$	$p > 0.05$	< 0.001
Soares et al. [43]	BMI (kg/m^2)	30.7 ± 5.0	29.4 ± 4.8	−4.2%ß*	*$p < 0.001$	32.5 ± 4.1	34.1 ± 4.7	4.9%Ý*	*$p < 0.001$	$p = 0.05$ favoring TSG	−1.101
Vasconcellos et al. [44]	BMI (kg/m^2)	31.1 ± 5.2	30.4 ± 4.2	−2.3%ß*	$p = 0.024$	32.2 ± 4.9	33.5 ± 5.8	4.0%Ý*	*$p = 0.001$	$p < 0.001$ favoring TSG	−0.884
Vasconcellos et al. [45]	BMI (kg/m^2)	30.5 ± 2.1	30.4 ± 4.2	−0.3%ß	$p > 0.05$	30.8 ± 3.1	32.5 ± 5.8	5.5%Ý	$p > 0.05$	$p > 0.05$	−0.784
Cvetkovic et al. [25]	Body fat mass (%)	36.25 ± 6.70	33.47 ± 6.99	−7.6%ß	$p > 0.05$	29.94 ± 8.41	29.60 ± 7.68	−1.1%ß	$p > 0.05$	$p > 0.05$	0.527
Hornstrup et al. [48]#	Gynoid fat mass (kg)	5.9 ± 1.8	5.8 ± 1.8	−1.7%ß	ND	6.6 ± 1.7	6.7 ± 1.7	1.5%Ý	ND	$p > 0.05$	−0.529
Mohr et al. [49]	Total fat mass (kg)	36.6 ± 2.0	35.7 ± ND	−2.7%ß*	*$p < 0.05$	33.0 ± 1.6	33.2 ± ND	0.6%Ý	$p > 0.05$	$p < 0.05$ favoring TSG	

TABLE 6. Continue

Study	Variable	TSG pre	TSG post	%dif (post-pre)	Within-TSG (p-value)	CG pre	CG post	%dif (post-pre)	Within-CG (p-value)	Between groups (p-value)	ES between groups (post)
Moller et al. [47]$	Fat mass (kg)	36.8 ± 14.5	35.9 ± ND	−2.4%ß*	*p < 0.05	39.1 ± 16.2	37.5 ± ND	−4.1%ß*	*p < 0.05	p > 0.05	
Seabra et al. [42]	Body fat (%)	34.3 ± 5.6	32.1 ± 5.7	−6.4%ß*	*p < 0.05	34.4 ± 7.6	37.5 ± 10.5	9.0%Ý*	*p < 0.05	p < 0.05 favoring TSG	−0.639
Soares et al. [46]	Body fat (%)	34.3 ± 1.7	31.8 ± 2.1	−7.3%ß*	*p < 0.05	36.2 ± 2.0	34.3 ± 1.9	−5.3%ß	*p < 0.05	p > 0.05	−1.072
Soares et al. [43]	Body fat (%)	41.4 ± 5.8	39.2 ± 5.5	−5.3%ß*	*p = 0.001	42.1 ± 5.5	41.9 ± 5.2	−0.5%ß	p > 0.05	p > 0.05	−0.427
Vasconcellos et al. [44]	Fat (%)	41.1 ± 6.1	38.9 ± 6.1	−5.3%ß*	*p < 0.001	42.0 ± 5.4	41.7 ± 5.1	−0.7%ß	p > 0.05	p = 0.024 favoring TSG	−0.483
Vasconcellos et al. [45]	Fat (%)	42.3 ± 7.2	38.9 ± 6.1	−8.0%ß	p > 0.05	40.9 ± 7.2	41.7 ± 5.1	1.9%Ý	p > 0.05	p > 0.05	−0.483
Seabra et al. [42]	Waist circumference (cm)	83.6 ± 9.4	79.4 ± 9.5	−5.0%ß*	*p < 0.05	85.7 ± 11.7	85.5 ± 12.3	−0.2%ß	p > 0.05	p < 0.05 favoring TSG	−0.554
Soares et al. [46]	Waist circumference (cm)	109.0 ± 3.1	104.0 ± 2.6	−4.6%ß*	*p < 0.05	106.5 ± 2.3	101.2 ± 2.0	−5.0%ß	*p < 0.05	p > 0.05	1.182
Soares et al. [43]	Waist circumference (cm)	97.9 ± 9.8	91.4 ± 9.9	−6.7%ß*	p = 0.003	106.6 ± 13.2	106.0 ± 13.6	−0.6%ß	p > 0.05	p = 0.02 favoring TSG	−1.116
Vasconcellos et al. [44]	Waist circumference (cm)	98.7 ± 10	90.5 ± 8.9	−8.4%ß*	p = 0.004	103.5 ± 14.5	101.9 ± 17.0	−1.5%ß	p > 0.05	p > 0.05	−1.147
Vasconcellos et al. [45]	Waist circumference (cm)	99.2 ± 9.6	87.5 ± 10.9	−11.8%ß	p > 0.05	101.5 ± 12.3	107.9 ± 17.0	6.3%Ý	p > 0.05	p > 0.05	−1.327
Cvetkovic et al. [25]	Lean body mass (%)	63.76 ± 6.72	66.50 ± 6.99	4.3%Ý	p > 0.05	69.96 ± 8.40	70.33 ± 7.67	0.5%Ý	p > 0.05	p > 0.05	−0.522
Cvetkovic et al. [25]	Muscle mass (%)	34.51 ± 3.70	36.03 ± 3.79	4.4%Ý	p > 0.05	38.42 ± 4.94	38.85 ± 4.58	1.1%Ý	p > 0.05	p > 0.05	−0.672
Mohr et al. [49]	Lean body mass (kg)	42.7 ± 1.4	43.3 ± ND	1.4%Ý	p > 0.05	43.7 ± 1.2	43.9 ± ND	0.5%Ý	p > 0.05	p > 0.05	N/A
Moller et al. [47]$	Lean body mass (kg)	58.5 ± 10.0	58.3 ± ND	−0.3%ß	p > 0.05	61.7 ± 12.4	61.3 ± ND	−0.6%ß	p > 0.05	p > 0.05	N/A
Seabra et al. [42]	Lean mass (%)	17.9 ± 4.7	19.4 ± 4.6	8.4%Ý	p > 0.05	18.4 ± 5.3	19.4 ± 5.1	5.4%Ý*	*p < 0.05	p > 0.05	< 0.001
Soares et al. [46]	Lean mass (kg)	59.6 ± 2.4	59.7 ± 2.3	0.2%Ý	p > 0.05	54.4 ± 3.0	53.3 ± 2.6	−2.0%ß	p > 0.05	p > 0.05	2.612
Vasconcellos et al. [44]	Fat free mass (kg)	43.2 ± 8.2	45.0 ± 8.0	4.2%Ý	p > 0.05	48.3 ± 7.5	49.9 ± 8.9	3.3%Ý	p > 0.05	p > 0.05	−0.578

TSG: team sports group; CG: control group; #unexperienced group; $: the control group was active and was enrolled at fitness classes; ND: not described; N/A: not applicable; ES: calculation of Cohen's d for the post-intervention comparison between TSG and control groups.

TABLE 7. Results of individual studies on blood pressure

Study	Variable	TSG pre	TSG post	%dif (post-pre)	Within-TSG (p-value)	CG pre	CG post	%dif (post-pre)	Within-CG (p-value)	Between groups (p-value)	ES between groups (post)
Cvetkovic et al. [25]	SBP (mm/Hg)	121.00 ± 11.74	117.50 ± 11.12	-2.9%ß	p > 0.05	123.93 ± 15.34	124.85 ± 11.58	0.7%Ý	p > 0.05	p > 0.05	-0.576
Hansen et al. [41]	SBP (mm/Hg)	114 ± 7	112 ± 9	-1.8%ß	p > 0.05	112 ± 6	122 ± 10	8.9%Ý*	*p = 0.02	p < 0.05 favoring TSG	-0.696
Hornstrup et al. [48]#	SBP (mm/Hg)	107 ± 14	110 ± 14	2.8%Ý	p > 0.05	112 ± 13	116 ± 14	3.6%Ý	p > 0.05	p > 0.05	--0.429
Mohr et al. [49]	SBP (mm/Hg)	139 ± 2	127.4 ± 3.4	-8.3%ß*	*p < 0.05	134 ± 4	133.6 ± 2.9	-0.3%ß	p > 0.05	p < 0.05 favoring TSG	-0.492
Moller et al. [47]$	SBP (mm/Hg)	129 ± 15	126.2 ± ND	−2.2%ß	p > 0.05	133 ± 13	135.8 ± ND	2.1%Ý	p > 0.05	p < 0.05 favoring TSG	N/A
Seabra et al. [42]	SBP (mm/Hg)	111.0 ± 12.4	111.4 ± 10.6	0.4Ý	p > 0.05	109.1 ± 15.3	110.5 ± 8.9	1.3%Ý	p > 0.05	p > 0.05	0.056
Vasconcellos et al. [44]	SBP (mm/Hg)	128 ± 10	123 ± 13	−3.9%ß*	*p = 0.006	128 ± 9	129 ± 6	0.8%Ý	p > 0.05	p = 0.025 favoring TSG	-0.526
Vasconcellos et al. [45]	SBP (mm/Hg)	135 ± 4	128 ± 3	−5.2ß	p > 0.05	137 ± 6	137 ± 3	0.0%Þ	p > 0.05	p > 0.05	-0.690
Cvetkovic et al. [25]	DBP (mm/Hg)	70.00 ± 10.80	64.00 ± 3.94	−8.6%ß	p > 0.05	62.68 ± 9.29	64.57 ± 8.42	3.0%Ý	p > 0.05	p > 0.05	-0.148
Hansen et al. [41]	DBP (mm/Hg)	62 ± 8	63 ± 13	1.6%Ý	p > 0.05	67 ± 6	64 ± 7	-4.5%ß	p > 0.05	p > 0.05	-0.092
Hornstrup et al. [48]#	DBP (mm/Hg)	72 ± 9	70 ± 8	−2.8%ß	p > 0.05	79 ± 10	79 ± 11	1.3%Ý	p > 0.05	p > 0.05	-1.093
Mohr et al. [49]	DBP (mm/Hg)	86 ± 2	79.9 ± 2.5	−7.3%ß*	*p < 0.05	82 ± 3	82.5 ± 2.1	0.6%Ý	p > 0.05	p < 0.05 favoring TSG	-0.715
Moller et al. [47]$	DBP (mm/Hg)	78 ± 8	75.4 ± ND	−3.3%ß	p > 0.05	79 ± 8	79.2 ± ND	0.3%Ý	p > 0.05	p > 0.05	N/A
Seabra et al. [42]	DBP (mm/Hg)	57.6 ± 8.6	53.7 ± 7.5	−6.8%	p > 0.05	54.9 ± 10.3	56.7 ± 6.2	3.3%Ý	p > 0.05	p > 0.05	-0.483
Vasconcellos et al. [44]	DBP (mm/Hg)	81 ± 5	79 ± 14	−2.5%ß	p > 0.05	79 ± 5	79 ± 4	-1.3%ß	p > 0.05	p > 0.05	< 0.001
Vasconcellos et al. [45]	DBP (mm/Hg)	87 ± 2	84 ± 3	−3.4%ß	p > 0.05	89 ± 4	88 ± 4	1.1%ß	p > 0.05	p > 0.05	-0.557

TSG: team sports group; CG: control group; #unexperienced group; $: the control group was active and was enrolled at fitness classes; ND: not described; N/A: not applicable; ES: calculation of Cohen's d for the post-intervention comparison between TSG and control groups.

TABLE 8. Results of individual studies on health biomarkers

Study	Variable	TSG pre	TSG post	%dif (post-pre)	Within-TSG (p-value)	CG pre	CG post	%dif (post-pre)	Within-CG (p-value)	Between groups (p-value)	ES between groups (post)
Hornstrup et al. [48]#	Total cholesterol (mmol/L)	5.3 ± 0.8	5.6 ± 0.9	5.7%Ý	ND	4.9 ± 0.7	5.2 ± 0.7	6.1%Ý	ND	$p > 0.05$	0.590
Mohr et al. [49]	Total cholesterol (mmol/L)	5.8 ± 0.1	ND	N/A	ND	5.3 ± 0.2	5.3 ± 0.2	0.0%Þ	ND	$p < 0.05$ favoring TSG	N/A
Seabra et al. [42]	Total cholesterol (mg/dl)	171.6 ± 42.7	159.6 ± 32.1	−7.0%ß*	*$p < 0.05$	166.4 ± 21.3	173.1 ± 25.3	4.0%Ý	$p > 0.05$	$p < 0.05$ favoring TSG	−0.420
Soares et al. [46]	Cholesterol (mg/dl)	179.6 ± 9.0	163.3 ± 9.5	−9.1%ß*	*$p < 0.05$	181.7 ± 13.3	203 ± 14.6	11.8%Ý	$p > 0.05$	$p < 0.05$ favoring TSG	−1.150
Vasconcellos et al. [44]	Total cholesterol	166.4 ± 21.6	150.2 ± 25.2	−9.7%ß*	*$p = 0.008$	168.7 ± 32.7	181.4 ± 30.2	7.5%Ý*	*$p = 0.021$	$p = 0.001$ favoring TSG	−0.708
Hornstrup et al. [48]#	Triglycerid (mmol/L)	1.0 ± 0.3	1.0 ± 0.3	0.0%Þ	ND	1.0 ± 0.5	1.1 ± 0.7	10.0%Ý	ND	$p > 0.05$	−0.095
Mohr et al. [49]	Triglycerid (mmol/L)	1.3 ± 0.1	ND	N/A	ND	1.0 ± 0.1	1.0 ± 0.1	0.0%Þ	ND	$p < 0.05$ favoring TSG	N/A
Seabra et al. [42]	Triglycerides (mg/dl)	70.9 ± 31.8	54.9 ± 15.9	−22.4%ß*	*$p < 0.05$	61.8 ± 26.5	74.0 ± 44.6	19.8%Ý	$p > 0.05$	$p > 0.05$	−0.573
Soares et al. [46]	Triglycerides (mg/dl)	140 ± 10.1	117.1 ± 13.9	−16.4%ß*	*$p < 0.05$	150.3 ± 23.0	164.6 ± 20.8	9.6%Ý	$p > 0.05$	$p > 0.05$	−0.783
Vasconcellos et al. [44]	Triglycerides (mg/dl)	118.4 ± 38.8	97.9 ± 19.6	−17.4%ß*	*$p = 0.018$	120.3 ± 72.6	145.4 ± 91.4	20.9%Ý*	*$p = 0.008$	$p = 0.001$ favoring TSG	−0.695
Vasconcellos et al. [45]	Triglycerides (mg/dl)	173.0 ± 22.1	138.3 ± 19.3	−20.1%ß*	*$p = 0.02$	189.1 ± 31.7	185.4 ± 21.4	−1.9%ß	$p > 0.05$	$p = 0.05$ favoring TSG	−-0.839
Seabra et al. [42]	Glucose (mg/dl)	80.6 ± 5.5	83.4 ± 8.1	3.5%Ý	$p > 0.05$	82.6 ± 7.0	82.5 ± 5.3	−0.1%ß	$p > 0.05$	$p > 0.05$	0.011
Soares et al. [46]	Glucose plasma (mg/dl)	167 ± 3.0	135 ± 7.5	−19.2%ß*	*$p < 0.05$	172 ± 9.9	141 ± 4.3	−17.8%ß*	*$p < 0.05$	$p > 0.05$	−0.155
Vasconcellos et al. [44]	Fasting glucose (mg/dl)	92.9 ± 6.4	91.9 ± 6.4	−1.1%ß	$p > 0.05$	87.6 ± 8.9	94.3 ± 8.3	7.7%Ý*	$p = 0.007$	$p = 0.029$ favoring TSG	−0.235

TSG: team sports group; CG: control group; #unexperienced group; ND: not described; N/A: not applicable; ES: calculation of Cohen's d for the post-intervention comparison between TSG and control groups.

TABLE 9. Results of individual studies on physical fitness

Study	Variable	TSG pre	TSG post	%dif (post-pre)	Within-TSG (p-value)	CG pre	CG post	%dif (post-pre)	Within-CG (p-value)	Between groups (p-value)	ES between groups (post)
Cvetkovic et al. [25]	YYIRT (m)	476.0 ± 182.4	856.0 ± 456.0	79.0%Ý*	*p = 0.025	722.8 ± 576.0	857.2 ± 542.0	18.6%Ý	p > 0.05	p < 0.005 favoring TSG	−0.004
Hornstrup et al. [48]#	YYIET (m)	650 ± 342	890 ± 454	36.9%Ý*	*p < 0.01	474.7 ± 237.4	479.1 ± 219.8	0.9%Ý	ND	p < 0.005 favoring TSG	1.307
Mohr et al. [49]	YYIET (m)	420 ± 45	454 ± 81	8.1%Ý*	*p < 0.05	458 ± 43	453 ± 42	−1.1%ß	p > 0.05	p < 0.005 favoring TSG	0.008
Hornstrup et al. [48]#	$\dot{V}O_{2max}$ (ml/kg/min)	29.4 ± 5.8	31.3 ± 5.0	6.5%Ý*	*p < 0.01	29.1 ± 5.0	28.5 ± 4.7	−2.1%ß	ND	p < 0.005 favoring TSG	0.144
Moller et al. [47]$	$\dot{V}O_{2max}$ (ml/kg/min)	21.7 ± 5.4	22.2 ± ND	2.3%Ý	p > 0.05	22.4 ± 5.9	23.5 ± ND	4.9%Ý	p > 0.05	p > 0.05	N/A
Seabra et al. [42]	$\dot{V}O_{2max}$ (ml/kg/min)	44.7 ± 8.5	50.4 ± 5.6	12.7%Ý*	*p < 0.05	48.6 ± 11.5	50.7 ± 13.9	4.3%Ý	p > 0.05	p > 0.05	−0.053
Soares et al. [46]	$\dot{V}O_{2max}$ (ml/kg/min)	24.6 ± 3.5	30.4 ± 5.7	23.6%Ý*	*p < 0.001	23.3 ± 3.4	24.9 ± 4.1	6.9%Ý	p > 0.05	p = 0.013 favoring TSG	1.042
Vasconcellos et al. [44]	$\dot{V}O_{peak}$ (ml/kg/min)	25.2 ± 3.2	33.1 ± 9.2	31.0%Ý*	*p < 0.001	22.9 ± 3.1	24.0 ± 3.9	4.8%Ý	p > 0.05	p = 0.013 favoring TSG	1.334
Cvetkovic et al. [25]	CMJ arm swing (cm)	17.57 ± 4.24	20.56 ± 3.62	17.0%Ý	p > 0.05	21.42 ± 6.72	24.86 ± 5.68	15.9%Ý	p > 0.05	p > 0.05	−0.728
Cvetkovic et al. [25]	Agility T-test (s)	8.58 ± 1.05	7.67 ± 0.63	−10.6%ß*	*p = 0.031	8.06 ± 0.57	7.66 ± 0.49	−5.0%ß	p > 0.05	p < 0.005 favoring TSG	0.002
Cvetkovic et al. [25]	Sit and reach (cm)	5.00 ± 3.73	8.93 ± 6.27	78.6%Ý	p > 0.05	10.33 ± 6.97	12.51 ± 7.18	21.1%Ý	p > 0.05	p > 0.05	−0.698
Moller et al. [47]$	STS (stand/30 s)	ND	+1.5	N/AÝ	p > 0.05	ND	+3.5	N/A Ý*	*p < 0.05	p < 0.005 favoring CG$	N/A
Moller et al. [47]$	Balance (s)	ND	+3.6	N/A Ý*	*p < 0.05	ND	+4.5	N/A Ý*	*p < 0.05	p > 0.05	N/A
Moller et al. [47]$	6MWT (m)	ND	+27.2	N/A Ý*	*p < 0.05	ND	+54.4	N/A Ý*	*p < 0.05	p > 0.05	N/A

TSG: team sports group; CG: control group; YYIRT: Yo-Yo intermittent recovery test; YYIET: Yo-Yo Intermittent endurance test; $\dot{V}O_{2max}$: maximal oxygen uptake; #unexperienced group; STS: sit-to-stand. 6MWT: 6-minute walking test; $: the control group was active and was enrolled at fitness classes; #unexperienced group; N/A: not applicable; ES: calculation of Cohen's d for the post-intervention comparison between TSG and control groups.

several patterns emerge in regards body composition and anthropometrics. Looking at body mass index (BMI), Cvetkovic et al. [25], Soares et al. [43] and Vasconcellos et al. [44] show a significant decrease in BMI favoring TSG. Hansen et al. [41], Hornstrup et al. [48], and Seabra et al. [42] display no significant changes within TSG or CG or between groups. Soares et al. [46] demonstrate a decrease in BMI within TSG, although not significant from CG.

Examining body fat metrics, several studies reveal a consistent pattern favoring TSG. Mohr et al. [49], Seabra et al. [42] and Vasconcellos et al. [44] report a decrease in body fat percentage favoring TSG. Cvetkovic et al. [25], Hornstrup et al. [48] and Vasconcellos et al. [45] reports no within-group or between group significant differences. Moller et al. [11, Soares et al. [46] and Soares et al. [43] show a significant improvement in TSG although not significantly different from CG. In terms of lean body mass and muscle mass, none of the studies presents significant differences in within-group analysis or between-groups analysis.

Waist circumference, another key measure, sees consistent favorable changes in TSG. Seabra et al. [42], and Soares et al. [43] report a significant decrease in waist circumference favoring TSG in regards between group differences. Soares et al. [46] and Vasconcellos et al. [44] presents significant improvements on TSG, although not significantly different from CG.

Looking at the results from various studies comparing the impact of TSG to CG on blood pressure, several trends emerge (Table 7). In terms of systolic blood pressure (SBP), the within-group differences in TSG varied across studies, with some showing a significant decrease as the cases of Mohr et al. [49] and Vasconcellos et al. [44], while others did not. Between-group comparisons indicated a significant favoring of TSG in terms of SBP in some studies as Hansen et al. [41], Mohr et al. [49], Moller et al. [47] and Vasconcellos et al. [44], highlighting the potential positive impact of team sports on SBP.

For diastolic blood pressure (DBP), within-group differences in TSG also varied, with one study showing a significant decrease Mohr et al. [49], while others did not. The between-group comparisons indicated a significant favoring of TSG in terms of DBP in one study Mohr et al. [49], suggesting that the majority of the studies does not confirm a significant and positive impact of team sports on DBP.

In terms of total cholesterol levels, within-group differences in TSG showed mixed results (Table 8), with some studies indicating a significant decrease as Seabra et al. [42], Soares et al. [46] and Vasconcellos et al. [44], while others did not as Hornstrup et al. [48] and Mohr et al. [49]. Between-group comparisons indicated a significant favoring of TSG in terms of total cholesterol in most of studies as Mohr et al. [49], Seabra et al. [42], Soares et al. [46] and Vasconcellos et al. [44], suggesting a potential positive impact of team sports on cholesterol levels.

For triglyceride levels, within-group differences in TSG showed a significant decrease across studies as Mohr et al. [49], Vasconcellos et al. [44] and Vasconcellos et al. [45]. Between-group comparisons indicated a significant favoring of TSG in terms of triglyceride levels in Mohr et al. [49], Vasconcellos et al. [44] and Vasconcellos et al. [45], highlighting a potential positive impact of team sports on triglyceride levels.

In terms of glucose levels, within-group differences in TSG varied, with one study showing a significant decrease as Vasconcellos et al. [44] and others not as Seabra et al. [42] and Soares et al. [46]. Between-group comparisons indicated a significant favoring of TSG in terms of fasting glucose levels Vasconcellos et al. [44].

In terms of aerobic fitness (Table 9), the Yo-Yo Intermittent Endurance Test (YYIET) and the Yo-Yo Intermittent Recovery test (YYIRT) showed within-group improvements in TSG as demonstrated in Hornstrup et al. [6], Cvetkovic et al. [25] and Mohr et al. [49], with significant increases in distance covered and being consistently favored to TSG, indicating a significant positive impact on aerobic fitness in comparison to CG.

Similar trends were observed for $\dot{V}O_{2max}$, where TSG demonstrated within-group improvements across studies as Hornstrup et al. [48], Seabra et al. [42], Soares et al. [46] and Vasconcellos et al. [44]. Between-group comparisons favored TSG in most studies as Hornstrup et al. [48], Soares et al. [46] and Vasconcellos et al. [44], emphasizing the positive influence of team sports on aerobic performance.

DISCUSSION

In the analysis of team sports recreational interventions on overweight and obese populations, distinct patterns emerge across various metabolic health indicators, body composition and physical fitness. Body composition and anthropometric measures, such as BMI and body fat percentage, consistently show favorable outcomes (small-to-moderate effect sizes) in team sports groups (TSG) compared to control groups (CG). On the cardiovascular health, TSG demonstrate a positive impact on SBP, indicating significant improvements and differences with CG. However, the influence on DBP appears less consistent. TSG showcase a potential positive influence (small-to-moderate effect sizes) on lipid profiles, with total cholesterol and triglyceride levels favoring TSG in most studies, although the positive effects on glucose seems to be less consistent. Aerobic fitness, assessed through the field-based tests and $\dot{V}O_{2max}$, consistently improves within TSG, underscoring the beneficial impact of team sports on overall fitness. These findings collectively emphasize the potential of team sports interventions in addressing various metabolic health, body composition and physical fitness parameters among overweight and obese populations.

The impact of recreational team sports interventions on anthropometry and body composition

The evidence presented in the analysis of recreational team sports interventions for overweight and obese populations suggests a multifaceted positive impact on various anthropometric and body composition parameters. The consistent decrease in BMI and body fat

percentage within TSG, as observed in studies by Cvetkovic et al. [25], Soares et al. [14] or Seabra et al. [12] underscores the effectiveness of team sports in addressing weight-related concerns. Although the results were not completely unanimous across the studies as the cases of Hornstrup et al. [48] or Soares et al. [46], it is possible to disclose a trend for TSG being favorable for enhancing critical body composition parameters.

It is important to note that the fight against fat mass and the enhancement of body mass composition cannot rely solely on physical efforts. For example, combining team sports with other strategies such as nutritional plans and education, as well as considering activity and lifestyle, is crucial. This is evident in studies that combined a dietary plan with TSG, compared to running-based high-intensity interval training or a control group employing only a dietary plan [46]. The results show enhancements in BMI and fat mass within the combined dietary plan and TSG group, although not significantly different from the control group [46].

The physiological benefits of TSG that commonly use small-sided games may lie in the high-intensity intermittent nature of the activities, promoting substantial caloric expenditure. Studies, including those by Toh et al [50], demonstrate that the metabolic demands of SSGs in invasion sports as soccer, basketball or handball contribute to increased involvement and energy expenditure. Furthermore, SSGs induce an elevated post-exercise lowered blood glucose concentration [51], as well as postprandial lipemia [52], leading to a more favorable adaptation in health parameters and ultimately body composition. Improved insulin sensitivity, a key factor in managing body weight, is also observed in small-sided games [53]. Additionally, the social and team-based aspects of SSGs, contribute to enhanced adherence, fostering a positive behavioral environment that promotes long-term engagement and, subsequently, significant improvements in fat mass and BMI among overweight and obese populations [54].

The impact of recreational team sports interventions on metabolic health parameters

The comparison of TSG against CG across various studies provides valuable insights into the potential impact on metabolic health markers. Focusing on blood pressure, when examining SBP within the TSG, there were variations across studies, with some showing a significant decrease, such as the cases of Mohr et al. [49] and Vasconcellos et al. [44]. Between-group comparisons supported a significant favoring of TSG in terms of SBP in several studies as Hansen et al. [41], Mohr et al. [49], Moller et al. [47] and Vasconcellos et al. [44] suggesting a potential positive impact of team sports on SBP. SSG involves dynamic and intermittent physical activities, including rapid accelerations, decelerations, and changes in direction [55]. These characteristics contribute to increased cardiovascular demands and enhanced aerobic fitness [56]. Regular participation in SSG has been shown to improve endothelial function, reduce arterial stiffness, and enhance vasodilatory capacity [41]. The cumulative effect of these physiological adaptations likely leads to a reduction in systemic vascular resistance, ultimately contributing to the observed improvement in SBP. In contrast, the impact of TSG on DBP exhibited more variability, with only one study, Mohr et al. [49], indicating a significant decrease. The majority of between-group comparisons did not confirm a significant and positive impact of team sports on DBP, highlighting a need for further investigation in this regard.

Moving on to lipid profiles, the assessment of total cholesterol levels within the TSG showed mixed results, with some studies reporting a significant decrease as Seabra et al. [42], Soares et al. [46] and Vasconcellos et al. [44]. Moreover, between-group comparisons consistently favored TSG in terms of total cholesterol, suggesting a potential positive impact on this marker. Regular participation in TSG has been associated with increased high-density lipoprotein cholesterol, and decreased low-density lipoprotein cholesterol as demonstrated in Soares et al. [13].

Triglyceride levels within the TSG demonstrated a significant decrease across studies as Mohr et al. [49], Vasconcellos et al. [44] and Vasconcellos et al. [45]. The between-group comparisons further supported a significant favoring of TSG, underscoring a potential positive impact of team sports on triglyceride levels. The use of small-sided games with a more metabolic demands and high-intensity efforts may justify the stimulation of lipid oxidation, reducing triglyceride synthesis and storage [57].

Regarding glucose levels, within-group differences in TSG varied, with only one study Vasconcellos et al. [44] showing a significant decrease. While small-sided games used by TSG promotes cardiovascular fitness and contributes to weight management, its specific impact on glucose regulation may be influenced by individual metabolic differences, adherence levels, and the duration of the intervention. It is possible that the intermittent and varied nature of small-sided games may not provide a sustained stimulus for optimizing glucose metabolism compared to more continuous and structured exercise regimens [58].

The impact of recreational team sports interventions on physical fitness

The analysis of studies comparing TSG against CG in terms of aerobic fitness, as measured by the field-based tests, reveals consistent and positive trends. Within-group improvements in TSG were evident in studies conducted by Hornstrup et al. [48], Mohr et al. [49] and Cvetkovic et al. [25], with significant increases in the distance covered. This pattern, consistently favoring TSG, indicates a substantial positive impact on aerobic fitness when compared to CG. Similar trends were observed for $\dot{V}O_{2max}$ across various studies, including those by Hornstrup et al. [48], Seabra et al. [42], Soares et al. [46], and Vasconcellos et al. [44]. These findings collectively suggest that engagement in team sports leads to notable enhancements in aerobic fitness parameters compared to control groups, emphasizing the potential of team sports as an

effective intervention for improving cardiovascular endurance. The dynamic and intermittent nature of small-sided games involving high metabolic demands can explain the improvement. The varied high intensity and duration of small-sided games stimulate adaptations in muscle mitochondria, increasing their efficiency in utilizing oxygen for energy production [59].

Moreover, the dynamic and high-intensity nature of TSG by using small-sided games necessitates increased oxygen delivery to active muscles, leading to heightened cardiac output. This heightened demand manifests as an elevated heart rate, a response indicative of the heart's intensified effort to meet metabolic requirements [55]. With consistent exposure to such stimuli, the cardiovascular system undergoes adaptations, including improvements in stroke volume and cardiac output efficiency [60]. These adaptations contribute to heightened aerobic fitness by augmenting the heart's ability to efficiently supply oxygenated blood to exercising muscles. The intricate interplay between intensified exercise, cardiovascular adaptations, and improved aerobic capacity underscores the scientific rationale behind the observed enhancement in aerobic fitness resulting from regular engagement in intense activities like small-sided games in TSG.

Study limitations, future research and practical implications

While the findings of this analysis highlight the positive impact of recreational team sports interventions on various metabolic health indicators, body composition, and physical fitness in overweight and obese populations, certain limitations must be acknowledged. Firstly, the heterogeneity in study designs, intervention durations, and participant characteristics across the included studies may contribute to variations in the observed outcomes. Additionally, the reliance on self-reported dietary and lifestyle information in some studies introduces the potential for measurement bias and limits the precision of associations between team sports interventions and metabolic health improvements. Furthermore, the generalizability of the results may be influenced by the specific team sports included in the interventions and the unique characteristics of the study populations. These limitations underscore the need for future research to employ standardized methodologies and larger, more diverse samples to enhance the generalizability and robustness of the findings.

Future research endeavors should address the identified limitations by adopting more rigorous study designs, including randomized controlled trials with well-defined protocols for team sports interventions. Long-term follow-up assessments are crucial to elucidate the sustainability of the observed improvements in metabolic health markers and physical fitness. Moreover, investigating the optimal frequency, intensity, duration, and types of team sports activities for achieving specific health outcomes will provide valuable insights for designing targeted interventions. Additionally, exploring the potential moderating effects of individual characteristics, such as age, sex, and baseline fitness levels, will contribute to a nuanced understanding of the differential responses to team sports interventions.

The positive impact of recreational team sports interventions on metabolic health, body composition, and physical fitness observed in this analysis holds promising implications for practical applications in addressing overweight and obesity. Health practitioners, fitness professionals, and policymakers can consider incorporating team sports activities, especially those involving small-sided games, into lifestyle interventions for weight management and overall health improvement. In general, soccer training groups commonly incorporate three to four sessions per week, lasting 60 to 90 minutes each, using small-sided games formats from 4v4 to 8v8. Sessions typically include warm-ups, technical drills, small-sided games, and cool-downs.

The social and enjoyable nature of team sports may enhance adherence, making them an attractive and sustainable option for individuals with overweight and obesity. Moreover, combining team sports with tailored nutritional plans and educational components may amplify the synergistic effects on metabolic health. Implementing community-based team sports programs, particularly those that target specific health outcomes, can serve as a feasible and engaging strategy to combat the rising prevalence of overweight and obesity, promoting a holistic approach to health and well-being.

CONCLUSIONS

In conclusion, the systematic review of team sports recreational interventions for overweight and obese populations reveals consistent and favorable outcomes across various metabolic health indicators, body composition, and physical fitness parameters. Team sports groups consistently exhibit positive effects on body composition, including a notable decrease in BMI and body fat percentage. The cardiovascular benefits of TSG are evident in the significant improvements in systolic blood pressure, although the impact on diastolic blood pressure appears less consistent. TSG also demonstrate potential positive influences on lipid profiles, with total cholesterol and triglyceride levels favoring TSG in most studies. Additionally, aerobic fitness consistently improves within TSG, emphasizing the overall positive impact of team sports on fitness. However, variations in glucose outcomes suggest a need for further investigation. Future investigations should focus on optimizing team sports interventions and exploring individual moderating factors. The practical implications highlight the potential for health practitioners and policymakers to integrate team sports, particularly those involving small-sided games, into lifestyle interventions for effective weight management and overall health improvement. In the future, it is expected that governments and health systems will integrate recreational team sports under the guidance of sports technical staff in community-based structured programs. This approach is seen as a key strategy to prevent non-communicable diseases and offer advantages to overweight and obese populations. It is an integral component of a multidisciplinary response to the challenges presented by changing lifestyles.

Declarations

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Conflicts of interest

The authors declare that they have no conflicts of interest relevant to the content of this review.

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REFERENCES

1. Chooi YC, Ding C, Magkos F. The epidemiology of obesity. Metabolism. 2019; 92:6–10.
2. Haththotuwa RN, Wijeyaratne CN, Senarath U. Worldwide epidemic of obesity. In: Mahmood TA, Arulkumaran S, Chervenak, FA, editors. Obesity and Obstetrics. 2nd ed. Elsevier; 2020, p. 3–8.
3. The GBD 2015 Obesity Collaborators. Health Effects of Overweight and Obesity in 195 Countries over 25 Years. N Engl J Med. 2017; 377:13–27.
4. Vasconcellos F, Seabra A, Katzmarzyk PT, Kraemer-Aguiar LG, Bouskela E, Farinatti P. Physical Activity in Overweight and Obese Adolescents: Systematic Review of the Effects on Physical Fitness Components and Cardiovascular Risk Factors. Sports Med. 2014; 44:1139–52.
5. Stevens GA, Singh GM, Lu Y, Danaei G, Lin JK, Finucane MM, et al. National, regional, and global trends in adult overweight and obesity prevalences. Popul Health Metr. 2012; 10:22.
6. Morgen CS, Sørensen TIA. Global trends in the prevalence of overweight and obesity. Nat Rev Endocrinol. 2014; 10:513–4.
7. Nuttall FQ. Body Mass Index. Nutr Today 2015; 50:117–28.
8. Bray G. Pathophysiology of obesity. Am J Clin Nutr. 1992; 55:488S–494S.
9. Dixon JB. The effect of obesity on health outcomes. Mol Cell Endocrinol. 2010; 316:104–8.
10. Ouerghi N, Fradj MK Ben, Bezrati I, Khammassi M, Feki M, Kaabachi N, et al. Effects of high-intensity interval training on body composition, aerobic and anaerobic performance and plasma lipids in overweight/obese and normal-weight young men. Biol Sport. 2017; 34:385–92.
11. Jakicic JM, Rogers RJ, Davis KK, Collins KA. Role of Physical Activity and Exercise in Treating Patients with Overweight and Obesity. Clin Chem. 2018; 64:99–107.
12. Garber CE. The Health Benefits of Exercise in Overweight and Obese Patients. Curr Sports Med Rep. 2019; 18:287–91.
13. Westerterp KR. Physical activity as determinant of daily energy expenditure. Physiol Behav. 2008; 93:1039–43.
14. Ismail I, Keating SE, Baker MK, Johnson NA. A systematic review and meta-analysis of the effect of aerobic vs. resistance exercise training on visceral fat. Obesity Reviews. 2012; 13:68–91.
15. Roberts CK, Hevener AL, Barnard RJ. Metabolic Syndrome and Insulin Resistance: Underlying Causes and Modification by Exercise Training. Compr Physiol. 2013; 3:1–58.
16. Burgess E, Hassmén P, Pumpa KL. Determinants of adherence to lifestyle intervention in adults with obesity: a systematic review. Clin Obes. 2017; 7:123–35.
17. Venditti EM, Wylie-Rosett J, Delahanty LM, Mele L, Hoskin MA, Edelstein SL. Short and long-term lifestyle coaching approaches used to address diverse participant barriers to weight loss and physical activity adherence. Int J Behav Nutr Phys Act. 2014; 11:16.
18. Clark J. The impact of duration on effectiveness of exercise, the implication for periodization of training and goal setting for individuals who are overfat, a meta-analysis. Biol Sport. 2016; 33:309–33.
19. Dombrowski SU, Knittle K, Avenell A, Araujo-Soares V, Sniehotta FF. Long term maintenance of weight loss with non-surgical interventions in obese adults: systematic review and meta-analyses of randomised controlled trials. BMJ. 2014; 348:g2646–g2646.
20. Batacan RB, Duncan MJ, Dalbo VJ, Tucker PS, Fenning AS. Effects of high-intensity interval training on cardiometabolic health: a systematic review and meta-analysis of intervention studies. Br J Sports Med. 2017; 51:494–503.
21. Vasconcellos F, Seabra A, Cunha F, Montenegro R, Penha J, Bouskela E, et al. Health markers in obese adolescents improved by a 12-week recreational soccer program: a randomised controlled trial. J Sports Sci. 2016; 34:564–75.
22. Maillard F, Pereira B, Boisseau N. Effect of High-Intensity Interval Training on Total, Abdominal and Visceral Fat Mass: A Meta-Analysis. Sports Med. 2018; 48:269–88.
23. Mohammed MHH, Al-Qahtani MHH, Takken T. Effects of 12 weeks of recreational football (soccer) with caloric control on glycemia and cardiovascular health of adolescent boys with type 1 diabetes. Pediatr Diabetes. 2021; 22:625–37.
24. de Sousa MV, Fukui R, Krustrup P, Dagogo-Jack S, da Silva MER. Combination of recreational soccer and caloric restricted diet reduces markers of protein catabolism and cardiovascular risk in patients with type 2 diabetes. J Nutr Health Aging. 2017; 21:180–6.
25. 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.
26. Calcaterra V, Larizza D, Codrons E, De Silvestri A, Brambilla P, Abela S, et al. Improved metabolic and cardiorespiratory fitness during a recreational training program in obese children. J Pediatr Endocrinol Metab. 2013; 26:271–276.
27. Aslan A, Salci Y, Guvenc A. The Effects of Weekly Recreational Soccer Intervention on the Physical Fitness Level of Sedentary Young Men. Montenegrin J Sports Sci Med. 2019; 8:51–9.
28. Castagna C, de Sousa M, Krustrup P, Kirkendall DT. Recreational team sports: The motivational medicine. J Sport Health Sci. 2018; 7:129–31.
29. Krustrup P, Nielsen JJ, Krustrup BR, Christensen JF, Pedersen H, Randers MB, et al. Recreational soccer is an effective health-promoting activity for untrained men. Br J Sports Med. 2009; 43:825–31.
30. Bellissimo MP, Galaviz KI, Paskert MC, Lobelo F. Cardiometabolic Risk Reduction Through Recreational Group Sport Interventions in Adults: A Systematic Review and Meta-analysis. Mayo Clin Proc. 2018; 93:1375–96.

31. Fogelholm M. Physical activity, fitness and fatness: relations to mortality, morbidity and disease risk factors. A systematic review. Obes Rev. 2010; 11:202–21.
32. Olander EK, Fletcher H, Williams S, Atkinson L, Turner A, French DP. What are the most effective techniques in changing obese individuals' physical activity self-efficacy and behaviour: a systematic review and meta-analysis. Int J Behav Nutr Phys Act. 2013; 10:29.
33. Sarmento H, Manuel Clemente F, Marques A, Milanovic Z, David Harper L, Figueiredo A. Recreational football is medicine against non-communicable diseases: A systematic review. Scand J Med Sci Sports. 2020; 30:618–37.
34. Milanović Z, Pantelić S, Čović N, Sporiš G, Mohr M, Krustrup P. Broad-spectrum physical fitness benefits of recreational football: a systematic review and meta-analysis. Br J Sports Med. 2019; 53:926–39.
35. Milanović Z, Čović N, Helge EW, Krustrup P, Mohr M. Recreational Football and Bone Health: A Systematic Review and Meta-analysis. Sports Med. 2022; 52:3021–3037.
36. Barbosa A, Brito J, Figueiredo P, Seabra A, Mendes R. Football can tackle type 2 diabetes: a systematic review of the health effects of recreational football practice in individuals with prediabetes and type 2 diabetes. Res Sports Med. 2021; 29:303–321.
37. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021; 372:n71.
38. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med. 2009; 6:e1000097. https://doi.org/10.1371/journal.pmed.1000097.
39. Rico-González M, Pino-Ortega J, Clemente FM, Arcos AL, Los Arcos A. Guidelines for performing systematic reviews in sports science. Biol Sport. 2022; 39:463–71.
40. Cohen J. Statistical Power Analysis for the Behavioral Sciences. vol. 2nd. 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates; 1988.
41. Hansen PR, Andersen LJ, Rebelo AN, Brito J, Hornstrup T, Schmidt JF, et al. Cardiovascular effects of 3 months of football training in overweight children examined by comprehensive echocardiography: a pilot study. J Sports Sci. 2013; 31:1432–40.
42. Seabra A, Katzmarzyk P, Carvalho MJ, Seabra A, Coelho ESM, Abreu S, et al. Effects of 6-month soccer and traditional physical activity programmes on body composition, cardiometabolic risk factors, inflammatory, oxidative stress markers and cardiorespiratory fitness in obese boys. J Sports Sci. 2016; 34:1822–9.
43. Soares IF, Cunha FA, Vasconcellos F. Effects of a 12-Week Recreational Soccer Program on Resting Metabolic Rate Among Adolescents with Obesity. J Sci Sport Exerc. 2023; 5:218–25.
44. Vasconcellos F, Seabra A, Cunha F, Montenegro R, Penha J, Bouskela E, et al. Health markers in obese adolescents improved by a 12-week recreational soccer program: a randomised controlled trial. J Sports Sci. 2016; 34:564–75.
45. Vasconcellos F, Cunha FA, Gonet DT, Farinatti PT V. Does Recreational Soccer Change Metabolic Syndrome Status in Obese Adolescents? A Pilot Study. Res Q Exerc Sport. 2021; 92:91–9.
46. da Silva Soares DB, Shinjo SK, Santos AS, de Cassia Rosa de Jesus J, Schenk S, de Castro GS, et al. Skeletal muscle gene expression in older adults with type 2 diabetes mellitus undergoing calorie-restricted diet and recreational sports training – a randomized clinical trial. Exp Gerontol. 2022; 164:111831.
47. Møller TK, Nielsen T-T, Andersen R, Lundager I, Hansen HF, Ottesen L, et al. Health Effects of 12 Weeks of Team-Sport Training and Fitness Training in a Community Health Centre for Sedentary Men with Lifestyle Diseases. Biomed Res Int. 2018; 2018:1–9.
48. 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; 30:281–94.
49. Mohr M, Lindenskov A, Holm PM, Nielsen HP, Mortensen J, Weihe P, et al. Football training improves cardiovascular health profile in sedentary, premenopausal hypertensive women. Scand J Med Sci Sports. 2014; 24:36–42.
50. Toh SH, Guelfi KJ, Wong P, Fournier P a. Energy expenditure and enjoyment of small-sided soccer games in overweight boys. Hum Mov Sci. 2011; 30:636–47.
51. Mendham AE, Duffield R, Marino F, Coutts AJ. Differences in the acute inflammatory and glucose regulatory responses between small-sided games and cycling in sedentary, middle-aged men. J Sci Med Sport. 2015; 18:714–9.
52. Smallcombe JW, Barrett LA, Morris JG, Sherar LB, Tolfrey K. Small-Sided Soccer in School Reduces Postprandial Lipemia in Adolescent Boys. Med Sci Sports Exerc. 2018; 50:2351–9.
53. Mendham AE, Duffield R, Coutts AJ, Marino F, Boyko A, Bishop DJ. Rugby-specific small-sided games training is an effective alternative to stationary cycling at reducing clinical risk factors associated with the development of type 2 diabetes: a randomized, controlled trial. PLoS One. 2015; 10:e0127548.
54. García-Sánchez E, Rubio-Arias JÁ, Ávila-Gandía V, López-Román FJ, Menarguez-Puche JF. Effects of Two Community-Based Exercise Programs on Adherence, Cardiometabolic Markers, and Body Composition in Older People with Cardiovascular Risk Factors: A Prospective Observational Cohort Study. J Pers Med. 2020; 10:176.
55. Zouhal H, Hammami A, Tijani JM, Jayavel A, de Sousa M, Krustrup P, et al. Effects of Small-Sided Soccer Games on Physical Fitness, Physiological Responses, and Health Indices in Untrained Individuals and Clinical Populations: A Systematic Review. Sports Med. 2020; 50:987–1007.
56. Milanović Z, Pantelić S, Čović N, Sporiš G, Krustrup P. Is Recreational Soccer Effective for Improving $\dot{V}O_{2max}$ A Systematic Review and Meta-Analysis. Sports Med. 2015; 45:1339–53.
57. Astorino TA, Schubert MM. Changes in fat oxidation in response to various regimes of high intensity interval training (HIIT). Eur J Appl Physiol. 2018; 118:51–63.
58. Mendham AE, Duffield R, Coutts AJ, Marino FE, Boyko A, McAinch AJ, et al. Similar mitochondrial signaling responses to a single bout of continuous or small-sided-games-based exercise in sedentary men. J Appl Physiol. 2016; 121:1326–34.
59. Fransson D, Nielsen TS, Olsson K, Christensson T, Bradley PS, Fatouros IG, et al. Skeletal muscle and performance adaptations to high-intensity training in elite male soccer players: speed endurance runs versus small-sided game training. Eur J Appl Physiol. 2018; 118:111–21.
60. Knobloch K. Non-invasive determination of stroke volume and cardiac output after high intensity playing exercise in elite female soccer players. Int J Cardiol. 2009; 132:267–9.
61. Gallagher D, Heymsfield SB, Heo M, Jebb SA, Murgatroyd PR, Sakamoto Y. Healthy percentage body fat ranges: an approach for developing guidelines based on body mass index. Am J Clin Nutr. 2000; 72:694–701.
62. de Onis M. Development of a WHO growth reference for school-aged children and adolescents. Bull World Health Organ. 2007; 85:660–7.

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SUPPLEMENTARY FILE 1. Full-text screening.

STUDY	POPULATION	INTERVENTION	COMPARATOR	OUTCOME	DESIGN	DECISION
Calcaterra, V., Larizza, D., Codrons, E., De Silvestri, A., Brambilla, P., Abela, S., … Vandoni, M. (2013). Improved metabolic and cardiorespiratory fitness during a recreational training program in obese children. Journal of Pediatric Endocrinology and Metabolism, 26(3–4), 271–276. doi:10.1515/jpem-2012-0157	Y	Y	N	Y	N	Excluded
Gray, C. M., Hunt, K., Mutrie, N., Anderson, A. S., Leishman, J., Dalgarno, L., & Wyke, S. (2013). Football Fans in Training: The development and optimization of an intervention delivered through professional sports clubs to help men lose weight, become more active and adopt healthier eating habits. BMC Public Health, 13(1). doi:10.1186/1471-2458-13-232	Y	N	N	N	N	Excluded
Gray, C. M., Hunt, K., Mutrie, N., Anderson, A. S., Treweek, S., & Wyke, S. (2013). Weight management for overweight and obese men delivered through professional football clubs: A pilot randomized trial. INTERNATIONAL JOURNAL OF BEHAVIORAL NUTRITION AND PHYSICAL ACTIVITY, 10. doi:10.1186/1479-5868-10-121	Y	N	Y	Y	Y	Excluded
Bendiksen, M., Williams, C. A., Hornstrup, T., Clausen, H., Kloppenborg, J., Shumikhin, D., … Krustrup, P. (2014). Heart rate response and fitness effects of various types of physical education for 8- to 9-year-old schoolchildren. EUROPEAN JOURNAL OF SPORT SCIENCE, 14(8), 861–869. doi:10.1080/17461391.2014.884168	N	Y	Y	Y	Y	Excluded
Mohr, M., Lindenskov, A., Holm, P. M., Nielsen, H. P., Mortensen, J., Weihe, P., & Krustrup, P. (2014). Football training improves cardiovascular health profile in sedentary, premenopausal hypertensive women. Scandinavian Journal of Medicine and Science in Sports, 24(SUPPL.1), 36–42. doi:10.1111/sms.12278	Y	Y	Y	Y	Y	INCLUDED
Rutherford, Z., Gough, B., Seymour-Smith, S., Matthews, C. R., Wilcox, J., Parnell, D., & Pringle, A. (2014). 'Motivate': the effect of a Football in the Community delivered weight loss programme on over 35-year old men and women's cardiovascular risk factors. Soccer and Society, 15(6), 951–969. doi:10.1080/14660970.2014.920628	Y	N	N	N	N	Excluded
Milanovic, Z., Pantelic, S., Kostic, R., Trajkovic, N., & Sporis, G. (2015). Soccer vs. running training effects in young adult men: which programme is more effective in improvement of body composition? Randomized controlled trial. BIOLOGY OF SPORT, 32(4), 301–305. doi:10.5604/20831862.1163693	N	Y	Y	Y	Y	Excluded
Wyke, S., Hunt, K., Gray, C. M., Fenwick, E., Bunn, C., Donnan, P. T., … Treweek, S. (2015). Football Fans in Training (FFIT): a randomised controlled trial of a gender-sensitised weight loss and healthy living programme for men – end of study report. Southampton (UK): NIHR Journals Library.	Y	N	Y	Y	Y	Excluded
Eichner, J. E., Folorunso, O. A., & Moore, W. E. (2016). A physical activity intervention and changes in body mass index at a middle school with a large American Indian Population, Oklahoma, 2004–2009. Preventing Chronic Disease, 13(12). doi:10.5888/pcd13.150495	N	N	N	N	N	Excluded

SUPPLEMENTARY FILE 1. Continue

STUDY	POPULATION	INTERVENTION	COMPARATOR	OUTCOME	DESIGN	DECISION
Gill, D. P., Blunt, W., De Cruz, A., Riggin, B., Hunt, K., Zou, G., … Petrella, R. J. (2016). Hockey Fans in Training (Hockey FIT) pilot study protocol: A gender-sensitized weight loss and healthy lifestyle program for overweight and obese male hockey fans. BMC Public Health, 16(1). doi:10.1186/s12889-016-3730-5	Y	N	N	N	N	Excluded
Seabra, A., Katzmarzyk, P., Carvalho, M. J., Coelho-E-Silva, M., Abreu, S., Vale, S., … Malina, R. M. (2016). Effects of 6-month soccer and traditional physical activity programmes on body composition, cardiometabolic risk factors, inflammatory, oxidative stress markers and cardiorespiratory fitness in obese boys. JOURNAL OF SPORTS SCIENCES, 34(19), 1822–1829. doi:10.1080/02640414.2016.1140219	Y	Y	Y	Y	Y	INCLUDED
Vasconcellos, F., Seabra, A., Cunha, F., Montenegro, R., Penha, J., Bouskela, E., … Farinatti, P. (2016). Health markers in obese adolescents improved by a 12-week recreational soccer program: a randomised controlled trial. JOURNAL OF SPORTS SCIENCES, 34(6), 564–575. doi:10.1080/02640414.2015.1064150	Y	Y	Y	Y	Y	INCLUDED
Azman, N., Mohamed, N. G., Aziz, A. R., Farah, N., & Muhamed, A. M. C. (2018). The effectiveness of futsal as a game-simulated exercise for promoting weight loss and metabolic health in overweight/obese men. Malaysian Journal of Public Health Medicine, 2018(Specialissue1), 174–182. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85044829530&partner ID=40&md5=ae948d8cee94c8b09417f178696bf689	Y	Y	N	Y	N	Excluded
Cvetković, N., Stojanović, E., Stojiljković, N., Nikolić, D., Scanlan, A. T., & Milanović, Z. (2018). 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, 28 Suppl 1, 18–32. doi:10.1111/sms.13241	Y	Y	Y	Y	Y	INCLUDED
Gray, C. M., Wyke, S., Zhang, R. Q., Anderson, A. S., Barry, S., Boyer, N., … Hunt, K. (2018). Long-term weight loss trajectories following participation in a randomised controlled trial of a weight management programme for men delivered through professional football clubs: a longitudinal cohort study and economic evaluation. INTERNATIONAL JOURNAL OF BEHAVIORAL NUTRITION AND PHYSICAL ACTIVITY, 15. doi:10.1186/s12966-018-0683-3	Y	N	Y	Y	N	Excluded
Jaafar, Z., Kee, J., Abdul Hadi, H., & Ahmad Tajuddin, N. A. (2018). Anthropometrical and fitness level changes following a 12-week walking football program for obese primary school children aged 8–11. Medicina dello Sport, 71(3), 451–460. doi:10.23736/s0025-7826.18.03285-4	Y	Y	N	Y	N	Excluded
Møller, T. K., Nielsen, T. T., Andersen, R., Lundager, I., Hansen, H. F., Ottesen, L., … Randers, M. B. (2018). Health Effects of 12 Weeks of Team-Sport Training and Fitness Training in a Community Health Centre for Sedentary Men with Lifestyle Diseases. BioMed Research International, 2018. doi:10.1155/2018/1571807	Y	Y	Y	Y	Y	INCLUDED

SUPPLEMENTARY FILE 1. Continue

STUDY	POPULATION	INTERVENTION	COMPARATOR	OUTCOME	DESIGN	DECISION
Frediani, J. K., Bienvenida, A. F., Li, J., Higgins, M. K., & Lobelo, F. (2020). Physical fitness and activity changes after a 24-week soccer-based adaptation of the U.S diabetes prevention program intervention in Hispanic men. Progress in Cardiovascular Diseases, 63(6), 775–785. doi:10.1016/j.pcad.2020.06.012	Y	Y	N	Y	N	Excluded
Hornstrup, T., Póvoas, S., Helge, J. W., Melcher, P. S., Fristrup, B., Andersen, J. L., … Krustrup, P. (2020). Cardiovascular and metabolic health effects of team handball training in overweight women: Impact of prior experience. SCANDINAVIAN JOURNAL OF MEDICINE & SCIENCE IN SPORTS, 30(2), 281–294. doi:10.1111/sms.13563	Y	Y	Y	Y	Y	INCLUDED
Mielke, G. I., Bailey, T. G., Burton, N. W., & Brown, W. J. (2020). Participation in sports/recreational activities and incidence of hypertension, diabetes, and obesity in adults. Scandinavian Journal of Medicine and Science in Sports, 30(12), 2390–2398. doi:10.1111/sms.13795	Y	N	N	Y	N	Excluded
Broglio, L. P., Gonelli, P. R. G., Costa, C. O., Sajorato, T. C., Massarutto, V., & Cesar, M. C. (2021). Volleyball as an exercise program for overweight and obese female adolescents. Revista Brasileira de Medicina do Esporte, 27(6), 545–548. doi:10.1590/1517-869220212706169680	N	Y	N	Y	N	Excluded
Frediani, J. K., Li, J., Bienvenida, A., Higgins, M. K., & Lobelo, F. (2021). Metabolic Changes After a 24-Week Soccer-Based Adaptation of the Diabetes Prevention Program in Hispanic Males: A One-Arm Pilot Clinical Trial. Frontiers in Sports and Active Living, 3. doi:10.3389/fspor.2021.757815	Y	Y	N	Y	N	Excluded
Vasconcellos, F., Cunha, F. A., Gonet, D. T., & Farinatti, P. T. V. (2021). Does Recreational Soccer Change Metabolic Syndrome Status in Obese Adolescents? A Pilot Study. Research Quarterly for Exercise and Sport, 92(1), 91–99. doi:10.1080/02701367.2019.1711007	Y	Y	Y	Y	Y	INCLUDED
Colpitts, B. H., Keshavarz, M., Blake, M., Sénéchal, M., Gallibois, M., Olthuis, J., … Bouchard, D. R. (2022). Health benefits associated with the Hockey Fans in Training® program for overweight men who are university hockey fans. SCIENCE & SPORTS, 37(1). doi:10.1016/j.scispo.2020.12.009	Y	Y	N	Y	N	Excluded
da Silva Soares, D. B., Shinjo, S. K., Santos, A. S., de Cassia Rosa de Jesus, J., Schenk, S., de Castro, G. S., … de Sousa, M. V. (2022). Skeletal muscle gene expression in older adults with type 2 diabetes mellitus undergoing calorie-restricted diet and recreational sports training – a randomized clinical trial. EXPERIMENTAL GERONTOLOGY, 164. doi:10.1016/j.exger.2022.111831	Y	Y	Y	Y	Y	INCLUDED

SUPPLEMENTARY FILE 1. Continue

STUDY	POPULATION	INTERVENTION	COMPARATOR	OUTCOME	DESIGN	DECISION
Maddison, R., Hargreaves, E. A., Jiang, Y., Calder, A. J., Wyke, S., Gray, C. M., … Marsh, S. (2023). Rugby Fans in Training New Zealand (RUFIT NZ): a randomized controlled trial to assess the effectiveness of a healthy lifestyle program for overweight men delivered through professional rugby clubs. INTERNATIONAL JOURNAL OF BEHAVIORAL NUTRITION AND PHYSICAL ACTIVITY, 20(1). doi:10.1186/s12966-022-01395-w	Y	N	Y	Y	Y	Excluded
Pinho, C. D. F., Farinha, J. B., Lisboa, S. D. C., Bagatini, N. C., Leites, G. T., Voser, R. D. C., … Cunha, G. S. (2023). EFFECTS OF A SMALL-SIDED SOCCER PROGRAM ON HEALTH PARAMETERS IN OBESE CHILDREN. Revista Brasileira de Medicina do Esporte, 29. doi:10.1590/1517-8692202329012021_0398	Y	Y	N	Y	N	Excluded
Soares, I. F., Cunha, F. A., & Vasconcellos, F. (2023). Effects of a 12-Week Recreational Soccer Program on Resting Metabolic Rate Among Adolescents with Obesity. Journal of Science in Sport and Exercise, 5(3), 218–225. doi:10.1007/s42978-022-00181-1	Y	Y	Y	Y	Y	INCLUDED

EXTRA						
Hansen, P. R., Andersen, L. J., Rebelo, A. N., Brito, J., Hornstrup, T., Schmidt, J. F., … & Krustrup, P. (2013). Cardiovascular effects of 3 months of football training in overweight children examined by comprehensive echocardiography: a pilot study. Journal of sports sciences, 31(13), 1432–1440.	Y	Y	Y	Y	Y	Included

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Analysing substitutions in recent World Cups and European Championships in male and female elite football – influence of new substitution rules

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ABSTRACT: Substitutions play a key role in modern football and can substantially affect the physical and overall performance of a team, and the recent substitution rule changes are worth investigating. This study explored the characteristics of substitutions, including different substitution rules, game results, sex, competition stages, tournaments and penalty shoot-outs success rates. We analysed data from a total of 3,738 substitutions from the last 10 years (2013–2023) of European Championships and World Cups, both men's and women's games. Non-parametric tests and chi-square tests were used for statistical analysis with the significance level set at $p < 0.05$. With the 5-substitution rule, 48% more substitutions occurred compared to the 3-substitution rule (4.26 ± 1.07 vs. 2.87 ± 0.43, $p < 0.05$) with a slight increase in the average substitution time (70.6 ± 14.3 vs. 69.2 ± 14.6 min, $p < 0.05$), and 10% more substitutions in the men's game compared to the women's game ($p < 0.05$). The timing of the first substitution was slightly different in the knock-out stage compared to group stage (59.8 ± 14.7 vs. 57.2 ± 13.3 min, $p < 0.05$), and the timing for the winning team and drawing team was later than for the losing team ($p < 0.05$). A total of 13.2% goals were scored by substitutes, with no significant difference between the 5-substitution rule (15.9%) vs the 3-substition rule (12.5%) ($p > 0.05$). Interestingly, substitute players had a lower success rate in penalty shoot-out compared to starters (61 vs. 74%, $p < 0.05$). Additionally, substitute player goal scorers entered the pitch later ($p < 0.05$) in male games compared to female games and in knock-out stage games compared to group games. This study highlights the importance of substitution rules and timing in modern elite football matches. The timing of the first substitution, introduction of substitutes in knock-out stages, and a lower success rate of substitute players in penalty shoot-outs are crucial factors to consider. Coaches can use this information to make strategic substitution decisions to improve team performance.

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Key words:
Elite soccer
International tournaments
Performance analysis
Goal scoring
Penalty shoot-out

INTRODUCTION

One of the most prevalent tactical adjustments made by football coaches during matches is substitutions which can be used for formation changes, rotation, or changes in style of play to achieve the coach's intentions [1–3]. Additionally, starting players who are in poor condition but tactically important can be replaced by substitutes to maintain the physical performance of the team [4]. Therefore, the quality of the substitutes is often considered as a sign of the strength of a team [5, 6]. In 2020, Fédération Internationale de Football Association (FIFA) adopted the 5-substitution rule to ensure the fitness and health status of elite football players during and after the COVID-19 pandemic, and this rule has since been continued, possibly impacting the timing and number of substitutions in international men's and women's football. In light of this rule change and the increase in intensity of elite football matches [7, 8], Nassis and colleagues predict that substitutes will become even more important in football in the future and that practitioners will need to consider this more [9, 10]. In this situation, it is essential to study the characteristics of substitutions in modern football.

Using time-motion analysis, Bradley et al. [11] and Carling et al. [12] found that substitutes ran more at high intensity, both in terms of accumulated high-speed running as well as high-intensity running in peak intensity periods. Specifically in terms of high-speed running in 5-min periods, Hill et al. [13] found that the most intense 5 minutes of high-intensity running was when substitutes came on and Marcin et al. [14] found that the difference in sprinting distance between starters and substitutes was greatest at the very end of the game between 90–95 minutes. In addition, the running performance of substitutes is also affected by their position and stage of the season [15]. Despite the fact that the substitutes come on to the pitch with a greater running intensity, their overall game load is considerably lower than that of the starters due to the lower playing time [16, 17]. More recently, studies have shown that teams under the new substitution rule have an overall increase in running performance while the team load and RPE decrease [18–21], which is especially important during congested fixtures [22], indicating the importance of using multiple substitutions. In fact, the data from the 2022 World Cup shows that there was no reduction in high-intensity running by teams in the second half [23], in contrast to the results from previous World Cups [24].

When examining the tactical characteristics of substitutions, studies from La Liga [25] and Premier League [11] found that substitutions occurred mostly in the second half and regarding positional differences, most often for midfielders. Additionally, results from the aforementioned studies show that substitution time in La Liga is earlier than in the Premier League, and that the defensive players are replaced later in the game than the attacking players [25]. Specifically, the substitute player had an average playing time of 23–25 minutes in a French Ligue 1 teams [12], which means substitutions on average occur around 70 min, slightly earlier than in in the Premier League [11]. In addition, researchers found that losing teams used substitutions earlier in the game due to the need for tactical changes [25, 26], and had a better chance of changing the scoreline by using three substitutions before the 58^{th}, 73^{rd} and 79^{th} minute, respectively [26]. Furthermore, late substitutions are sometimes used to make players available for penalty shoot-outs, and one study gave advice on prioritising substitute players for penalty shoot-outs [27].

Male and female football players have different physical capacity and physical match performance [28, 29]. With a lower physical capacity, especially anaerobic capacity, female athletes may experience fatigue earlier in the match compared to male players [30, 31]. Thus, coaches may adopt a different substitution strategy for female than male players. To the best of our knowledge, it has not yet been studied whether there is a difference between timing, number, or importance of substitutions in men's and women's elite football, and overall, the information about the impact of the 5-substitution rule is scarce. Nonetheless, recent data from domestic league football suggest men's football has more high-intensity running under the 5-sub rule [19, 32], whereas this was not the case in a study on women's football under the 5-sub rule [20]. However, compared to league matches, international tournament matches are more physically demanding for players due to the congested schedule [33]. In this case, a reasonable squad rotation and substitution is important for the overall performance of the team, especially for the most exploited players [34]. Therefore, a separate study of substitutions during tournaments is warranted.

Among the many football tournaments, the FIFA World Cup and the UEFA European Championship are the two highest-level tournaments. Thus, the aims of this study were to examine the substitution and goal scoring characteristics of the World Cups and Euros for male and female elite football players over the last 10 years in relation to different rules, gender, stages, tournaments, ordinary playing time and penalty shoot-outs.

MATERIALS AND METHODS

Sample

We analysed a total of 549 matches and 3,738 substitutions in the Women's World Cup in 2015, 2019, 2023, the World Cup in 2014, 2018 and 2022, the Women's UEFA Euro in 2013, 2017 and 2022 as well as the UEFA Euro 2016 and 2020. The men's and women's 5-substitutition rule matches accounted for 39.1% and 37.3% of the total number of analysed matches, respectively. All match data were taken from the official websites of FIFA (www.fifa.com) and UEFA (www.uefa.com) and transferred to the Excel format. As all data are anonymous and available online and no participants needed for the study, no ethical documentation was required.

Procedure

Substitute data for different match results (win, draw and lose), phases (group and knock-out stage), sex (men and women) and rules are counted separately and analysed for comparison. Average substitution time was determined as the total sum of substitution times for all substitutes divided by the number of substitutes, and the first substitution time is based on the time the first substitute athlete come onto the pitch. When comparing average substitution time and the average number of playing minutes for the substitute players, extra time data were excluded to avoid data confusion [35, 36]. However, substitution goals in extra time were included in the goal characteristic analysis and the result after ordinary playing time was used as the match result. Substitution goals were furthermore categorised as goals with or without an impact on the outcome of the match based on whether the result of the game changed after removing the substitute goal. With relation to matches with extra time, statistics are merely done in relation to the participation of substitutes in penalty shoot-outs.

Statistical analysis

Data were processed using SPSS 26.0 (IBM, Chicago, USA) software. Normality was evaluated using Kolmogorov-Smirnov tests. Data are expressed as mean and standard deviation. Differences in time and numbers between different results, gender, phases, rules, match

impact and tournaments were analysed using the Mann-Whitney U test and Kruskal–Wallis test with Dunn's post hoc tests as data was not normally distributed. Chi-square tests were used to analysis differences in the ratios of goals with regards to different substitutes and starters as well as men and women. The significance level was set at $p < 0.05$.

RESULTS

Table 1 presents the analysis of variance for mean substitution time, first substitution time and number of substitutions. The results show that 48% more substitutions are made with the 5 vs. 3-substitution rule (4.3 ± 1.1 vs. 2.9 ± 0.4, $z = -22.228$, $p < 0.05$) and that the average substitution appeared 1.4 min later with the 5 vs. 3-substitution rule (70.6 ± 14.3 vs. 69.2 ± 14.6 min, $z = -3.067$, $p < 0.05$). No significant difference was found between gender, stages and tournaments ($z = -1.116$ to -1.534, $p > 0.05$). There was no significant difference in the time of first substitution by gender, rules and tournaments ($z = -0.339$ to -1.414, $p > 0.05$). However, a difference in the time of first substitution by stage was found (57.2 ± 13.3 vs. 59.8 ± 14.7 min, $z = -2.564$, $p < 0.05$), which shows a later time of first substitution in knock out stage. In addition, there are more substitution in men's football (3.5 ± 0.7 vs. 3.2 ± 0.5, $z = -4.953$, $p < 0.05$) compared to women and the 3-substitution rule, but there is no difference between different stages and tournaments in terms of the number of substitutions ($z = -0.027$ to -1.571, $p > 0.05$).

With regard to match outcome, there was a significant difference in the time of first substitution ($k = 33.773$, $p < 0.05$, figure 1), with winning and draw teams made their first substitution later compared to losing teams (59.3 ± 13.9, 60.2 ± 14.1 vs. 55.3 ± 13.1 min, $p < 0.05$). For the number of substitutes, no difference between match outcomes were observed ($k = 1.083$, $p > 0.05$).

Figure 2 shows the general goal distribution during the last 10 years' WC and EC. The percentage of goals scored by substitutes in the last 10 years of the EC and World Cup is 13.4%, with no significant differences found in the percentage of substitute goals scored by male and female footballers (14.8 vs. 11.7%, $\chi^2 = 3.021$, $p > 0.05$), 5 and 3-substitute rules (14.7 vs. 12.5%, $\chi^2 = 1.388$, $p > 0.05$), different stages (13.5 vs. 13.0%, $\chi^2 = 0.055$, $p > 0.05$) and tournaments (13.2 vs. 13.6%, $\chi^2 = 0.049$, $p > 0.05$, table 2). Interestingly, the success rate of substitute players in penalty shoot-outs was observed to be significantly lower compared to the starters (61.4 vs. 73.9%, $\chi^2 = 5.019$, $p < 0.05$).

The chi-square analysis shows no significant differences ($\chi^2 = 0.519$–3.468, $p > 0.05$) between male and female athletes in terms of goal contributions by substitutes in different stage, rules and match impact. However, the p value and percentages indicate a trend towards more substitutes' goals for men's football during knock-out stage (31.0 vs. 19.0%), with a trend towards a larger impact on results (54.0 vs. 41.3%, Table 3) compared to women's football ($p < 0.10$).

TABLE 1. Comparison of substitution time and number of substitutions between different gender, rules and stages.

		Mean substitution time (min)	Z	p	First substitution (min)	Z	p	No. of substitutes (n)	Z	p
Gender	Men	70.0 ± 14.3	-1.116	0.264	58.0 ± 13.3	-0.761	0.447	3.54 ± 0.98	-4.953	0.000*
	Women	69.5 ± 14.6			57.8 ± 14.2			3.24 ± 1.00		
Rules	3-Substitution	69.2 ± 14.6	-3.067	0.002*	58.0 ± 13.9	-0.339	0.735	2.87 ± 0.43	-22.228	0.000*
	5-Substitution	70.6 ± 14.3			57.8 ± 13.5			4.26 ± 1.07		
Stages	Group	69.7 ± 14.4	-1.461	0.144	57.2 ± 13.3	-2.564	0.010*	3.39 ± 0.94	-0.027	0.978
	Knock out	70.3 ± 14.5			59.8 ± 14.7			3.44 ± 1.16		
Tournaments	World Cup	69.5 ± 14.6	-1.534	0.125	57.6 ± 13.8	-1.434	0.152	3.36 ± 0.95	-1.571	0.116
	Euro	70.4 ± 14.1			58.5 ± 13.7			3.49 ± 1.10		

* denotes significant difference between groups

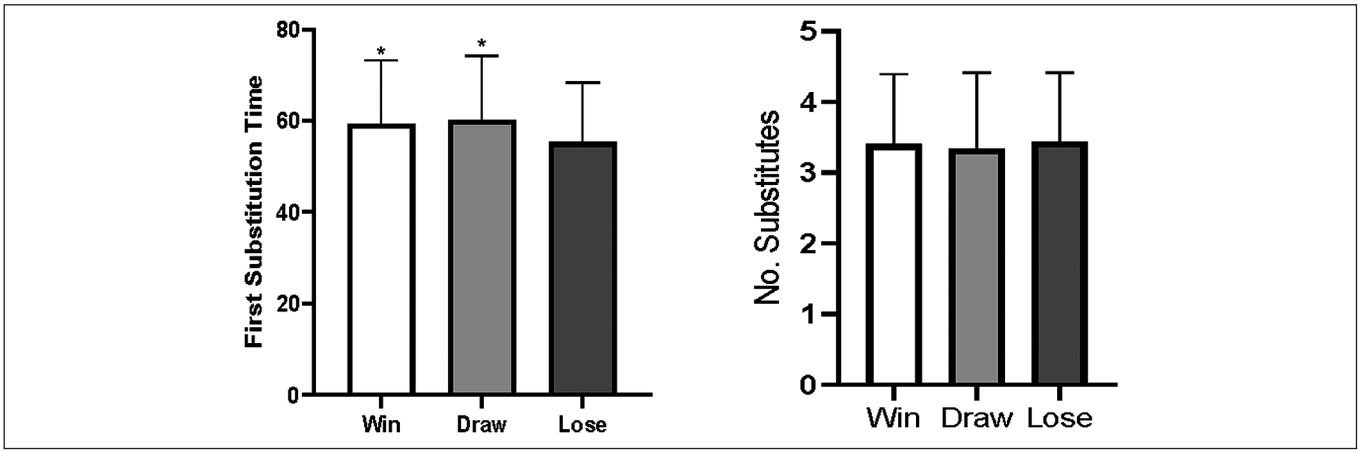


FIG. 1. Substitutions characteristics in relation to the match outcome.

TABLE 2. Goal characteristics comparison of starters and substitutes

		Substitutes	Starters	χ^2	P
Gender	Men	113	649	3.021	0.082
	Women	79	596		
Rules	3-substitution	108	756	1.388	0.239
	5-substitution	84	489		
Stages	Group	142	910	0.055	0.814
	Knock out	50	334		
Tournaments	World Cup	128	840	0.049	0.825
	Euro	64	405		
Penalty shoot-outs	Success	70	130	5.019	0.025*
	Failed	44	46		

Data presented as number of goals (n), * denotes significant difference between groups

TABLE 3. Comparison of Substitutes Goal Characteristics for men's and women's football tournaments.

		Men	Women	χ^2	P
Rules	3-substitution	66	42	0.519	0.471
	5-substitution	47	37		
Stages	Group	78	64	3.468	0.063
	Knock out	35	15		
Impact on match results	Yes	61	33	3.039	0.081
	No	52	47		

Data presented as number of goals (n).

Substitutes who scored a goal came on the pitch later in the men's games than the women's games (66.3 ± 16.1 vs. 60.3 ± 13.5 min, $z = -2.404$, $p < 0.05$, figure 3), and during knockout stage compared to group stage (61.4 ± 16.1 vs. 71.9 ± 13.5 min, $z = -3.695$, $p < 0.05$), while there was no difference across rules, match results impact and tournament ($z = -0.780$ to -1.401, $p > 0.05$). The goal-scoring substitute players were substituted 18.1 ± 13.4 minutes prior to the goal scoring situation, with no differences between rules, gender, stages, result impacts and tournaments ($z = -0.017$ to -1.108, $p > 0.05$).

DISCUSSION

The present study analysed the characteristics of substitutions in top-level tournaments for male and female players under different substitution rules, and revealed a marked increase in the number of substitutions and substitution playing minutes with the introduction of the 5-substitution rule. Moreover, it was shown that more substitutions are performed in the men's compared to the women's game, that the fraction of goals scored by substitute players has reached ~15% and that substitute players scoring goals came on later in the knockout games and in the men's game. Interestingly, the scoring rate in penalty shoot-outs was observed to be much lower for substitute players compared to starters.

The average time of substitutions in our study is around 70 min, which is in line with previous studies of French Ligue 1 [12] and Premier League [11], but later than in La Liga [25], with 10% more substitutions in the men's game compared to the women's game. This is somewhat surprising as fatigue is just as predominant in women's elite football as in men's football [31], and some studies indicate that fatigue occurs earlier in the women's game [37]. On the other hand, it may be speculated that the female substitutes are less capable than starters, especially in lower ranked teams. This is supported by tendencies towards a higher percentage of goals scored

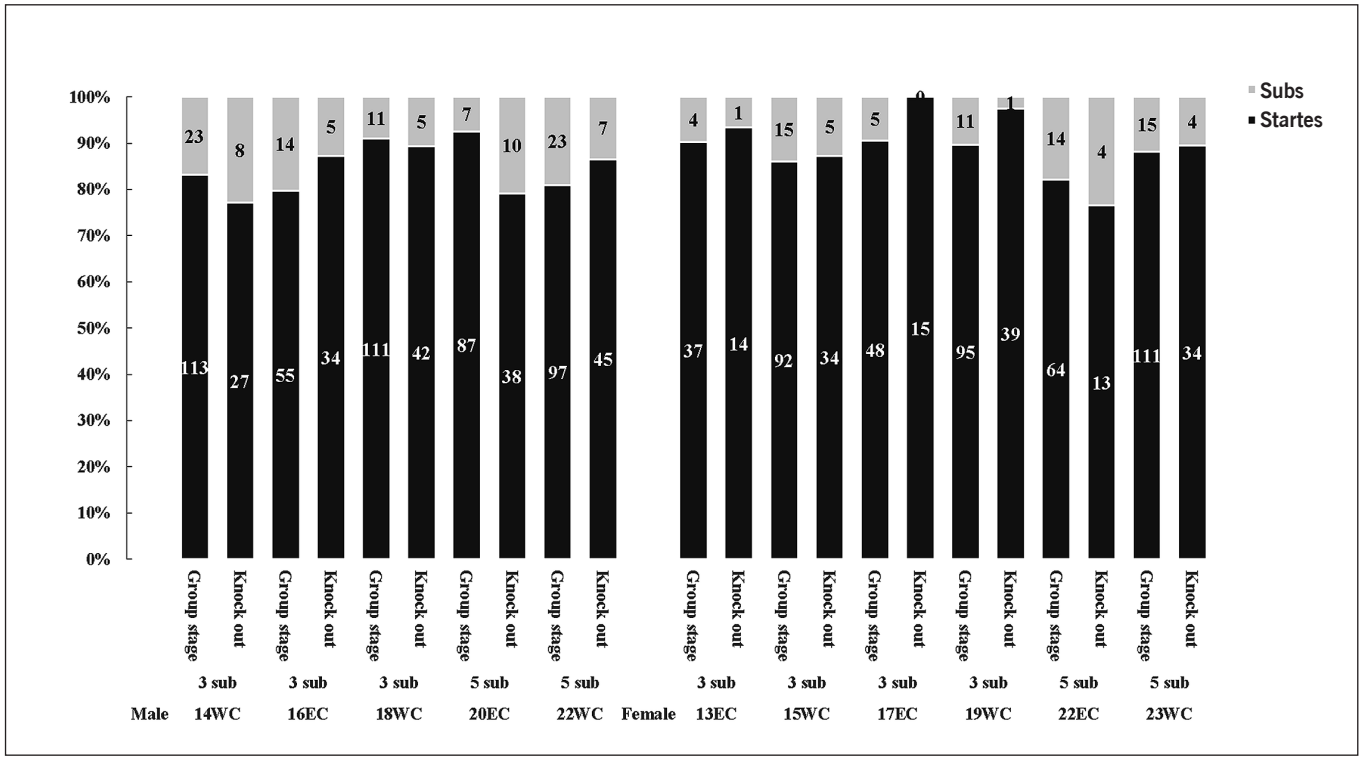


FIG. 2. Goal distribution between starters and substitute players during the 2013-2023 World Cups and European Championships in men's and women's football.

that affected the outcome of the game by men's substitutes than women's substitutes (54% vs 41%, NS, p = 0.081) as well as goals scored in the knock-out stage compared to the group stage (31 vs 19%, NS, p = 0.063). One clear exception from this finding was seen in the Women's Euro 2021 where the England team performed early substitutions in all games and scored 8 substitute goals in the tournament, including both goals in the final against Germany. Future studies are required to investigate the gender differences in greater depth.

No difference was observed between the 5 and 3-substitution rules in terms of time for the first substitution. However, the average substitution time was significantly later with the 5-substitution rule, as coaches used a larger percentage of the 5 substitutes in the final stages of the game. The first substitution may be more influenced by the team's performance, and a very early substitution may be seen as a substitution for a player in poor physical condition or as a tactical mistake by the coaching staff. However, the "cost" of a substitution is reduced with five substitutions making it easier for the coaching to consider early substitutions. In present study, it was shown that the first substitution was conducted later in the knock-out stage compared to the group stage. Previous studies from from World Cups have indicated that the group stage has different tactics compared to the knockout stage [36, 38]. Considering that many knock-out matches continue to the extra time and penalty shoot-out, the coaches would thus be more cautious using substitutions in ordinary playing time. Another finding in this study regarding the timing of the first substitution was that the losing team substituted earlier than the draw and winning team, which is consistent with previous studies [25, 26]. The score line has been found to be one of the most critical factors influencing substitutions [5, 39]. With the score trailing, the coaches were more likely to adjust their tactics in order to break the passive situation on the field and try to tie the score [39].

When examining the goals scored by substitutes, we found that substitutes scored 14% of all goals, of which around 50% directly influenced the outcome of the game. The substitute players accounted for around 9–10% of the playing time, meaning that substitute players had a higher goal per playing time score than the starters. Considering that substitutes can also impact the game in other ways such as through challenges, assists, defending and improved running performance [21], it is important for coaches to arrange substitutions thoughtfully. Contrary to our hypothesis, no significant differences were found in the percentage of goals scored by substitutes during matches with different substitution rules, albeit we observed some statistical tendencies. The reasons for this may be that only 36% of the tournaments in this study applied the 5-substitution rule; goals were affected in a number of ways and averaging less than 3 goals a game. Another more important reason is that teams have a limited number of strikers and coaches cannot have all their substitutions in the offensive line at the expense of the defence. In fact, most of the starting players were replaced by players from the same

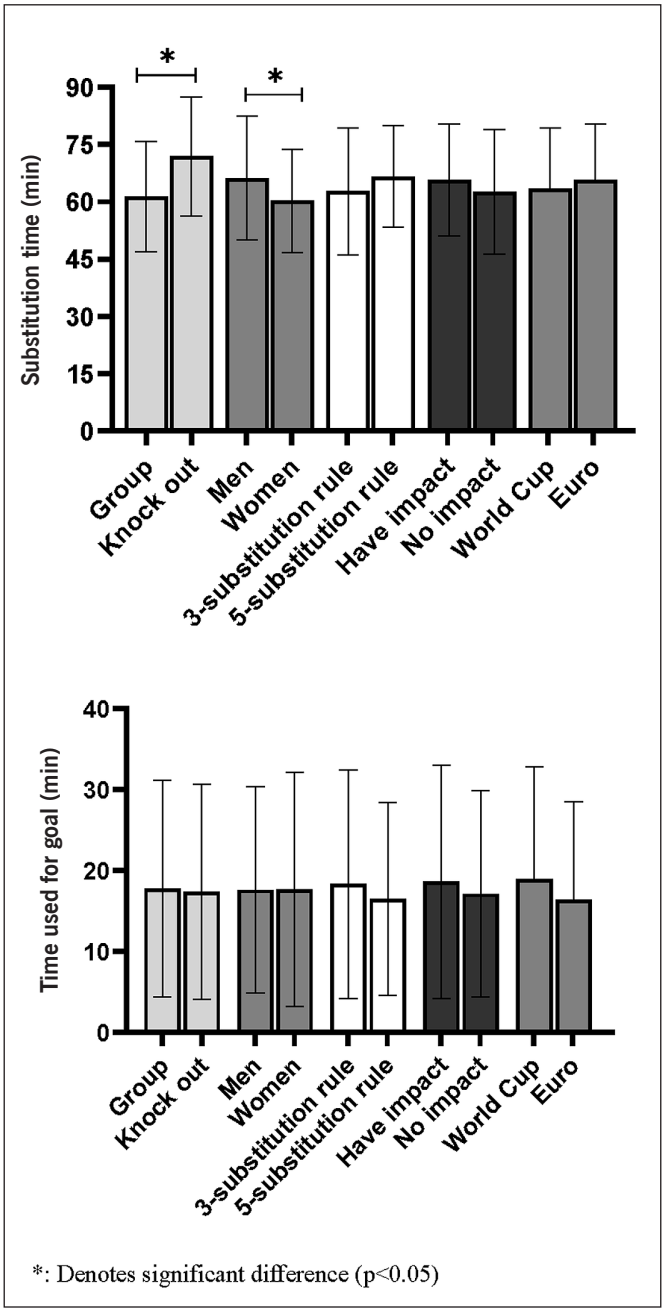


FIG. 3. Goal scoring characteristics for substitute players in relation to substitution time and time on the pitch during the 2013-2023 World Cups and European Championships in men's and women's football.

playing position [4, 39]. Furthermore, the aforementioned data suggests that the average substitution happens later in the matches with the 5-substitution rule, and the later the substitution, the more likely it is to happen for a defensive players [25], which could mean that defensive substitutes account for a higher fraction of the substitutions under the 5-substitutition rule. This means that the 5-subsitution rule may lead to a higher overall running performance [19, 32], but this change is related to the number as well as the type of substitutions being made [20]. In addition, coaches may use substitutions to reduce the load of team [18, 21], which is extremely important to maintain the physical condition of the whole team in the World Cup with a congested schedule.

Interestingly, we found that substitutes score less often than the starting players in penalty shoot-outs (61.4 vs. 73.9%), with an almost identical difference for male players (61.4 vs. 73.8%) and female players (61.3 vs. 73.9%). We also observed more penalties taken by substitute players in the penalty shoot-outs in the men's tournaments compared to the women's tournaments (43.7 vs 31.0%), leading to an overall scoring percentage of 68.4% in the men's tournaments and 70.0% in the women's tournaments. Considering that the number of substitute players taking penalties have more than doubled over the last two decades coming from 2 to 3 to 3+1 to 5+1 substitutions in the international tournaments, this may have a decisive role in the distribution of medals, as seen in the Euro 2022 men's final, where England's two last-minute substitute players both missed their penalties. Penalty shoot-outs are extremely mentally demanding for players [40, 41], and without good mental preparation, it appear to be difficult to achieve success in penalty shoot-outs [41]. In fact, substitutes are usually under more pressure and anxiety than the starting athletes [42, 43]. If a player is substituted into the game, the fear of failure may be even more pronounced [42], although it may be considered an advantage that the substitute players are less fatigued. Another reason may also be that, on average, substitutes may be less experienced than starters [16, 44]. Furthermore, there is a greater psychological burden on players who are substituted exclusively for taking part in the penalty shoot-outs. More research is required to elucidate possible explanations for the lower penalty success rate of substitute players. Nonetheless, coaches need to be careful in their selection of players for the penalty shoot-out and be aware that the substitute players appear to have a higher miss rate in penalty shoot-outs in international tournaments.

Finally, we found that substitute goal scorers came on later in the knockout stage than in the group stage and among male compared to female players. The main reason why substitute goal scorers come on later in the knockout stages may be that coaches want more fresh players in the extra time to improve the chances of success in the decisive part of a the long and fatiguing games, which may also explain the statistical tendencies of the higher level of substitute goals being scored in the knockout phase. Aside from this, no difference was found between different gender, rules, stages and impact on matches in terms of time taken to score. However, we found that the highest frequency of substitute goals was 2 minutes after they come onto the pitch. More goals scored during this period may be because the defenders had not yet clarified their defensive responsibilities in relation to the new players coming in, and that the substitute players have their peak 5-min high-intensity running period in the first five minutes after substitution [13].

One limitation of this study is that the 5-substition rule is new and that relatively limited data are available under the new substitution rule, and that coaches have adapted gradually to the new

substitution possibilities. In the future, more match data under the 5-substitution rule will be available, which will enable us to explore the full impact of the 5-substitution rule on the impact on the modern elite football game and find the interaction effect of multiple two variables in relation to the substitution characteristics. Moreover, it should be emphasized that this study solely investigated international tournaments and that specific research on the role of substitute players in the domestic leagues should be studied separately.

CONCLUSIONS

Taken together, we observed a huge increase in the number of substitutions and substitution playing minutes with the introduction of the 5-substitution rule, and that that the fraction of goals scored by substitute players have reached ~15%. It was also seen that substitute players scoring goals came on later in the knockout games compared to the group stage, and that more substitutions are currently performed in the men's compared to the women's game. Another interesting new finding of the present study was that the scoring rate in penalty shoot-outs was much lower for substitute players compared to starters, both in international men's and women's tournaments. Thus, the present study provides coaches with valuable information on the characteristics of substitutions in modern international men's and women's elite football tournaments, which may enable them to make better decisions about when to make substitutions and on selecting the right players to use in penalty shoot-outs, potentially leading to better game outcomes.

Author Contributions

Concept and design: Xiaobin Wei and Peter Krustrup; Data collection and analysis: Xiaobin Wei and Jiajun Liu; Drafting of the article: Xiaobin Wei; Critical revision of the article for important intellectual content: Peter Krustrup, Morten B Randers, Paweł Chmura and Yang Shu; Study Supervision: Peter Krustrup. All the authors approved the final article.

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Conflict of interest disclosure

The authors report there are no competing interests to declare.

REFERENCES

1. Siegle MM Lames. Game interruptions in elite soccer. J Sports Sci. 2012; 30(7):619–24. doi: 10.1080 /02640414.2012.667877.
2. Reilly T, B DrustN Clarke. Muscle fatigue during football match-play. Sports Med. 2008; 38(5):357–67. doi: 10.2165 /00007256-200838050-00001.
3. Lorenzo-Martínez M, R Rein, M Garnica-Caparrós, et al. The Effect of Substitutions on Team Tactical Behavior in Professional Soccer. Res Q Exerc Sport. 2022; 93(2):301–09. doi: 10.1080 /02701367.2020.1828563.
4. Varela-Quintana C, J del Corral CuervoJ Prieto-Rodriguez. The effect of an additional substitution in association football. Evidence from the Italian Serie A. Revista De Psicologia Del Deporte. 2016; 25:101–05.
5. Hills S P, M J Barwood, J N Radcliffe, et al. Profiling the Responses of Soccer Substitutes: A Review of Current Literature. Sports Med. 2018; 48(10):2255–69.
6. Gomez M-A, C Lago-PeñasL A Owen. The influence of substitutions on elite soccer teams' performance. Int J Perform Anal Sport. 2016; 16(2):553–68.
7. Barnes C, D T Archer, B Hogg, et al. The evolution of physical and technical performance parameters in the English Premier League. Int J Sports Med. 2014; 35(13):1095–100. doi: 10.1055 /s-0034-1375695.
8. Ekstrand J, H Bengtsson, M Waldén, et al. Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: the UEFA Elite Club Injury Study from 2001/02 to 2021/22. Br J Sports Med. 2022; 57(5):292–8. doi: 10.1136/bjsports-2021-105407.
9. Nassis G P, A Massey, P Jacobsen, 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):962–64. doi: 10.1111/sms.13681.
10. Nassis G P, J Brito, R Tomás, et al. Elite women's football: Evolution and challenges for the years ahead. Scand J Med Sci Sports. 2022; 32 Suppl 1:7–11. doi: 10.1111/sms.14094.
11. Bradley P S, C Lago-PeñasE Rey. Evaluation of the match performances of substitution players in elite soccer. Int J Sports Physiol Perform. 2014; 9(3):415–24.
12. Carling C, V Espié, F Le Gall, et al. Work-rate of substitutes in elite soccer: a preliminary study. J Sci Med Sport. 2010; 13(2):253–5. doi: 10.1016/j. jsams.2009.02.012.
13. Hills S P, S Barrett, R G Feltbower, et al. A match-day analysis of the movement profiles of substitutes from a professional soccer club before and after pitch-entry. PLoS One. 2019; 14(1):e0211563. doi: 10.1371/journal.pone.0211563.
14. Janusiak M, A Filipa Silva, R Silva, et al. Testing variations between starters and substitute players in terms of total distance, high-speed running, and sprinting distance: a descriptive study on professional male soccer players. Biol Sport. 2023; 41(2):95–103. doi: 10.5114/biolsport.2024.131817.
15. Padrón-Cabo A, E Rey, B Vidal, et al. Work-rate Analysis of Substitute Players in Professional Soccer: Analysis of Seasonal Variations. J Hum Kinet. 2018; 65:165–74. doi: 10.2478/ hukin-2018-0025.
16. Sydney M G, M Wollin, D Chapman, et al. Substitute running outputs in elite youth male soccer players: less peak but greater relative running outputs. Biol Sport. 2023; 40(1):241–48. doi: 10.5114/biolsport.2023.112969.
17. Gualtieri A, E Rampinini, R Sassi, et al. Workload Monitoring in Top-level Soccer Players During Congested Fixture Periods. Int J Sports Med. 2020; 41(10):677–81. doi: 10.1055/a-1171-1865.
18. Meyer JS Klatt. Additional substitutions in elite European football. Int J Sports Sci Coach. 2023. 10.1177/17479541231164090.
19. López-Valenciano A, V Moreno-Perez, R L Campo, et al. The Five-substitution Option Enhances Teams' Running Performance at High Speed in Football. Int J Sports Med. 2023; 44(5):344–51. doi: 10.1055/a-1982-9808.
20. Kobal R, R Aquino, L Carvalho, et al. Does the Number of Substitutions Used during the Matches Affect the Recovery Status and the Physical and Technical Performance of Elite Women's Soccer? Int J Environ Res Public Health. 2022; 19(18). doi: 10.3390/ ijerph191811541.
21. Meyer JS Klatt. Impact of one additional substitution on player load and coaching tactics in elite football. Applied Sci. 2021; 11(16):7676.

22. Tønnessen E, E Hem, S Leirstein, et al. Maximal aerobic power characteristics of male professional soccer players, 1989–2012. Int J Sports Physiol Perform. 2013; 8(3):323–9. doi: 10.1123 /ijspp.8.3.323.
23. Bradley P. 'Setting the Benchmark' Part 2: Contextualising the Physical Demands of Teams in the FIFA World Cup Qatar 2022. Biol Sport. 2024;41(1):271-278. doi:10.5114/biolsport.2024.131091.
24. Peñas C L, A Dellal, A L Owen, et al. The influence of the extra-time period on physical performance in elite soccer. Int J Perform Anal Sport. 2015; 15(3):830–39. doi: 10.1080 /24748668.2015.11868834.
25. Del Corral J, C P BarrosJ Prieto-Rodriguez. The determinants of soccer player substitutions: A survival analysis of the Spanish soccer league. J Sports Econ. 2008; 9(2):160–72.
26. Myers B R. A proposed decision rule for the timing of soccer substitutions. J Quant Anal Sports. 2012; 8(1).
27. McGarry TI M Franks. On winning the penalty shoot-out in soccer. J Sports Sci. 2000; 18(6):401–9. doi: 10.1080 /02640410050074331.
28. Sonesson S, M Hägglund, J Kvist, et al. Neuromuscular control and hop performance in youth and adult male and female football players. Phys Ther Sport. 2022; 55:189–95. doi: 10.1016 /j.ptsp.2022.04.004.
29. Pappalardo L, A Rossi, M Natilli, et al. Explaining the difference between men's and women's football. PLoS One. 2021; 16(8):e0255407. doi: 10.1371/journal .pone.0255407.
30. Krustrup P, M Mohr, H Ellingsgaard, et al. Physical demands during an elite female soccer game: importance of training status. Med Sci Sports Exerc. 2005; 37(7):1242.
31. Krustrup P, M Zebis, J M Jensen, et al. Game-induced fatigue patterns in elite female soccer. J Strength Cond Res. 2010; 24(2):437–41. doi: 10.1519 /JSC.0b013e3181c09b79.
32. Ayabe M, S Sunami, H Kumahara, et al. Effects of substitute allowance on match activity characteristics in Japanese professional football across 2019, 2020, and 2021 seasons. J Sports Sci. 2022; 40(23):2654–60. doi: 10.1080/0264 0414.2023.2182878.
33. Modric T, T Sattler, R Morgans, et al. Physical Performance in Highest-Level Soccer: Comparison between FIFA World Cup and UEFA Champions League Matches. Sport Mont. 2023; 21(2):3–7.
34. Kołodziejczyk M, P Chmura, M Konefał, et al. The Effect of Squad Rotation on Physical Activity at the 2018 World Cup in Russia. Analysis the Most Exploited Players of the 4 Best Teams. Front Psychol. 2021; 12:726207. doi: 10 .3389/fpsyg.2021.726207.
35. Liu H, L Wang, G Huang, et al. Activity profiles of full-match and substitution players in the 2018 FIFA World Cup. Eur J Sport Sci. 2020; 20(5):599–605. doi: 10.1080/17461391.2019 .1659420.
36. Liu H, M Á Gomez, C Lago-Peñas, et al. Match statistics related to winning in the group stage of 2014 Brazil FIFA World Cup. J Sports Sci. 2015; 33(12):1205–13. doi: 10.1080/0264 0414.2015.1022578 .
37. Goulart K N O, C C Coimbra, H O Campos, et al. Fatigue and Recovery Time Course After Female Soccer Matches: A Systematic Review And Meta-analysis. Sports Med Open. 2022; 8(1):72. doi: 10.1186/s40798-022 -00466-3.
38. Alves D L, R Osiecki, D P Palumbo, et al. What variables can differentiate winning and losing teams in the group and final stages of the 2018 FIFA World Cup? Int J Perform Anal Sport. 2019; 19(2):248–57. doi: 10.1080/247486 68.2019.1593096.
39. Wittkugel J, D MemmertF Wunderlich. Substitutions in football – what coaches think and what coaches do. J Sports Sci. 2022; 40(15):1668–77. doi: 10.1080 /02640414.2022.2099177.
40. Jordet G, E Hartman, C Visscher, et al. Kicks from the penalty mark in soccer: the roles of stress, skill, and fatigue for kick outcomes. J Sports Sci. 2007; 25(2):121–9. doi: 10.1080/02640410600624020.
41. Wood G, G JordetM R Wilson. On winning the "lottery": psychological preparation for football penalty shoot-outs. J Sports Sci. 2015; 33(17):1758–65. doi: 10.1080 /02640414.2015.1012103.
42. Woods BJ Thatcher. A qualitative exploration of substitutes' experiences in soccer. Sport Psychol. 2009; 23(4):451–69.
43. Gilbourne DD Richardson. Tales from the field: Personal reflections on the provision of psychological support in professional soccer. Psychol Sport Exerc. 2006; 7(3):325–37.
44. Hills S P, J N Radcliffe, M J Barwood, et al. Practitioner perceptions regarding the practices of soccer substitutes. PLoS One. 2020; 15(2):e0228790. doi: 10.1371/journal.pone.0228790.

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Match running performance is influenced by possession and team formation in an English Premier League team

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ABSTRACT: The aim of this study was to examine the possession (very low, low, high, and very high), team formation (3-5-2 and 4-3-3) and position (centre-backs, full-backs, centre midfielders, attacking midfielders, and centre forwards) on match load across two consecutive seasons in elite soccer. Twenty-seven English Premier League outfield players were recruited. Data was monitored through an 18 Hz Global Positioning System and a 25 Hz semi-automated camera tracking system, respectively, and all variables were analysed per minute. Main effects for formation on total distance (TD) ($p = 0.006$; $\eta^2 = 0.010$), high-speed running (HSR) ($p = 0.009$; $\eta^2 = 0.009$), number of high metabolic load (HML) efforts ($p = 0.004$; $\eta^2 = 0.011$) were observed. In addition, there were significant interaction effects with formation × possession on TD ($p < 0.001$; $\eta^2 = 0.043$), HSR ($p = 0.006$; $\eta^2 = 0.018$), sprinting ($p < 0.001$; $\eta^2 = 0.030$), HML efforts ($p < 0.001$; $\eta^2 = 0.035$), accelerations ($p < 0.001$; $\eta^2 = 0.025$). From the position-specific analysis, only the running performance of centre-backs was affected by formation or positional factors. These results indicate that formation and possession can have a significant impact on TD, HSR, and HML distance. Furthermore, players performed more high-intensity efforts in 3-5-2 than 4-3-3 formation. These findings suggest that coaches can evaluate running performance in the context of formation and possession and tailor tactical strategies to optimise physical performance.

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INTRODUCTION

Soccer is a team sport known for its significant physical, technical, and tactical demands. It involves frequent intermittent bouts of high-intensity actions such as accelerations, decelerations, changes of direction, sprinting, and jumping, that are interspersed with phases of prolonged low-intensity aerobic activity, such as standing, walking and jogging [1]. Recent studies have highlighted the increasing intensity of soccer match-play over time, and assuming a similar future trend, match speed is expected to increase by ~7% by 2030 [2, 3]. Furthermore, high-intensity actions such as sprints, accelerations and decelerations are associated with the crucial moments of match-play, such as goal scoring, assisting, and defensive scenarios [4–6].

Since soccer involves the interaction of physical, technical and tactical activities among players, the adoption of differing technical/tactical strategies will result in distinct physical demands [7]. Recently, time spent in ball possession has provided a good indication of playing style. Wang et al. [8] examined the relationship between ball possession strategies, match-running performance and team success. The study found that ball possession percentage alone is not a good indicator of successful match outcome. Instead, possession affects passing (frequency and success rate), organizational aspects and running distance during ball possession. Furthermore, different ball possession strategies and durations were observed across different leagues, with the English Premier League (EPL) teams favouring a more direct playing style, while La Liga teams employed a passing through-the-pitch attack.

Additionally, during the 2018 FIFA World Cup, the majority of teams that qualified for the knockout stage adopted a higher possession-based playing style [9]. Specifically, while no significant difference in total distance (TD) was observed, teams with greater possession percentages covered more sprinting (above 25 km/h) and high-speed running (HSR) distance (between 20–25 km/h) than teams with direct-play characteristics. More recent studies have shown that teams who have finished higher in the final ranking position in La Liga and the German Bundesliga exhibited lower TD and HSR distance without ball possession, while displaying higher running outputs with ball possession [7, 10]. These results contrast with those provided by Lorenzo-Martinez et al. [11], who reported that, independent of playing position, players in very high possession teams covered significantly less distance across all speed zones.

The integration of physical and tactical demands has gained some relevance over the last few years, where an increased interest in contextualising the physical performance of soccer players concerning tactical activities [12, 13] has been observed. This novel approach has demonstrated the existence of different physical-tactical match profiles depending on playing position, both in and out of possession. It was also suggested that the adoption of generalist positions is less sensitive to estimating player's actual physical and tactical match demands. Furthermore, it is widely accepted that the physical demands of soccer are multifactorial, and these demands may vary depending on the tactical formation, opponent standard and other contextual factors [13–18].

In this sense, tactical formation is another variable analysed recently [19]. These authors compared the three best Spanish soccer teams examining running measures with and without possession. Specifically, the first team applied a 4-4-2 formation with a compact defense and direct attack strategy, the second team applied a 4-3-3 formation with an indirect style of play and the third team applied a 4-3-3 formation with intricate attacks and effective counterattacks. These authors also analysed playing position in the different formations. The main findings reported minimal differences between the three teams. However, when considering the various positions, it was clear that team formation and the differing tactical demands have a significant influence on running performance [19]. It is also unclear whether these factors are significant in other leagues, including the EPL and thus warrant further examination.

Therefore, the aim of this study was to examine the effect of possession, team formation and playing position on physical match performance variables in an EPL soccer team across two consecutive seasons. Based on previous research [19], the study hypothesis was that possession and team formation would affect positional match running demands.

MATERIALS AND METHODS

Study design

This investigation utilised a two-year longitudinal study design to examine a male professional team. The team competed in the EPL during the study period that consisted of 38 official matches, 19 home and 19 away in each season. The 3-5-2 formation was utilised on 44 occasions across both study seasons, while the 4-3-3 was employed in 32 matches.

A non-probabilistic sampling protocol was employed to recruit the participants. The emphasis of the study was on monitoring player match load and the effect of possession and team formation during competitive matches. During the observation period of seasons 2021/22 and 2022/23, consistent player monitoring approaches were implemented without any interference from the researchers [20].

Participants

Twenty-seven professional outfield first-team soccer players (age 23.2 ± 5.9 years, weight 75.2 ± 8.1 kg, height 1.83 ± 0.06 m) from an EPL club were involved in the study. Data from the complete 2021/22 and 2022/23 seasons were included in the analysis. The research inclusion criteria have been previously applied [13] and were: (i) named in the first-team squad at the start of both seasons, (ii) played in at least 80% of matches, and (iii) only completed official team training during the study period. Additionally, the exclusion criteria for the study have also been previously employed [13] and included: (i) long-term injured player data, (ii) joining the team late in either of the study seasons, (iii) lack of full, complete match data, (iv) an in-sufficient number of satellite connection signals, and (v) goalkeepers, due to the different variations in the physical demands with outfield players [21].

Players were classified into one of five positions due to varying match demands. These were: centre-backs (CB; n = 7), full-backs (FB; n = 4), centre midfielders (CM; n = 9), attacking midfielders (AM; n = 5), and centre forwards (CF; n = 2). All data collected resulted from normal analytical procedures regarding player monitoring over the competitive season [13], nevertheless, written informed consent was obtained from all participants. The study was conducted according to the requirements of the Declaration of Helsinki and was approved by the local Ethics Committee of University of Central Lancashire and the club from which the participants volunteered [22]. To ensure confidentiality, all data were anonymised prior to analysis.

Procedure

In each season, only data from home and away EPL matches 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 [23, 24]. For each season, players were considered when the playing time inclusion criterion was met in eight (10.5%) or more league matches across the two-season examined period. Only players with match data from both examined seasons were included in the sample. The participants performed in a median of 32% (range = 9 to 88%) of league matches across both seasons. A total of 714 individual match data points were examined across both seasons, with a median of 24 matches per player (range = 7 to 67). No data from international camps (training or matches) was included. Although,

some players (n = 14) participated in 93 national team matches over both seasons (range = 2 to 8 in season 2021/22 and range = 1 to 8 in season 2022/23), this data was not utilised in the current analysis to avoid any bias when interpreting the present study results due to varying team formation and possession characteristics of the respective national teams.

Data collection

Physical match data were consistently monitored across the study seasons using an 18 Hz Global Positioning System (GPS) (Apex Pod, version 4.03, 50 g, 88 × 33 mm; Statsports; Northern Ireland, UK) that has been previously validated for tracking distance covered and peak velocity during simulated team sports and linear sprinting [25]. All data collection procedures and unit error and reliability have previously been reported [25–28]. The distance biases for the Apex 18 Hz during a 400 m trial (1.17 ± 0.73%), 128.5 m circuit (2.11 ± 1.06%), and 20 m trial (1.15 ± 1.23%) have previously been reported [25], where these units reported a small error of around 1–2% compared to criterion distances and good levels of accuracy (bias < 5%) in sport specific metrics [25].

Following every match, running data were extracted using proprietary software (Apex, version 4.3.8, Statsports Software; Northern Ireland, UK) as software-derived data is a more simple and efficient way for practitioners to obtain data in an applied environment, with no differences reported between processing methods (software-derived to raw processed) [29]. The minimum effort duration (dwell time) to quantify HSR (0.5 s) and sprint distance (1 s) have previously been suggested [29]. Additionally, to display a higher level of precision and less error, the GPS internal processing utilised the Doppler shift method to calculate both distance and velocity [30].

Physical variables analysed were selected based on previous publications [31–33] and in practical settings are commonly utilised by elite soccer coaches. The absolute TD covered (m); HSR distance (m; distance covered > 5.5 m/s); sprint distance (m; distance covered > 7 m/s); high metabolic load distance (HMLD) (m; the total amount of HSR, coupled with the total distance of accelerations (> 3 m/s^2) and decelerations (< -3 m/s^2). This variable refers to the distance covered with a power consumption above 25.5 W/kg. This value corresponds to running at a constant velocity of 5.5 m/s or 19.8 km/h on grass); the number of accelerations (> 3 m/s^2 with minimum duration of 0.5 s); the number of decelerations (< -3 m/s^2 with minimum duration of 0.5 s) [34] were examined. Distances covered per minute (m/min) in the following categories: TD; HSR distance (> 5.5 m/s); sprint distance (> 7 m/s); HML efforts (n/min); the number of accelerations (> 3 m/s^2; n/min) and decelerations (< -3 m/s^2; n/min) were also observed. The mean average and peak average of each given metric per minute during match-play were obtained and analysed across all study seasons.

For each match, the effect of tactical variables were recorded utilising the Second Spectrum system (Second Spectrum, California, USA). Competitive match data was recorded using a semi-automated camera tracking system (Second Spectrum, California, USA) with a sampling frequency of 25 Hz, which has previously been installed to standardise match data collection in the EPL. The installation process, reliability and validity of Second Spectrum have previously been validated to verify the capture process and accuracy of data as reported by the FIFA Electronic Performance Tracking Systems [35]. The tactical variables examined included: possession (duration the home team had the ball divided by ball in play time) and team formation.

All examined metrics were expressed in meters, m/min and number of efforts (HML efforts only). Before calculating these values, when the individual match playing time was less than 90-minutes, distances were extrapolated to 90-minutes utilising the meters per minute calculation. All variables obtained were calculated or pre-determined in the Second Spectrum System Software. These variables have been previously utilised by soccer practitioners to longitudinally track player external load [36].

Statistical Analysis

Data Sorting

Preliminary *k*-means cluster analyses were performed to identify a cut-off value of ball possession percentage and classify matches in which the study team had very low (VL) possession, low (L) possession, high (H) possession, and very high (VH) possession. The results identified cluster 1 (VL) with 35.2% of ball possession (range of 27.5–39.3%) cluster 2 (L) with 43.3% of ball possession (range of 39.4–47.1%), cluster 3 (H) with 50.9% of ball possession (range of 47.2–55.4%), and cluster 4 (VH) with 59.9% of ball possession (range of 55.5–65.7%).

Data Analysis

Descriptive data (mean ± SD) were determined for all GPS variables of interest for the different formations (3-5-2 and 4-3-3), and possession classification (VL, L, H, VH). Homogeneity of variance was assessed via Levene's statistic and, where violated, Welch's adjustment was used to correct the F-ratio. Two-way (2 × 4) analysis of variance (ANOVA's) were conducted to identify differences in physical running outputs with the different formations and possession classifications. These were conducted for all positions combined and for each specific position (centre-back, full-back, centre midfield, attacking midfield, and centre forward). Post-hoc analysis was used to identify the formation and possession classification that were significantly different to one another using either Bonferroni or Games-Howell post-hoc analyses, where equal variances were and were not assumed, respectively.

Effect size (η^2) values and Cohen's *d* values (*d*) were also reported for significant results. η^2 values in the range 0–0.009 are considered insignificant effect sizes, 0.01–0.0588 as small effect sizes, 0.0589–0.1379 as medium effect sizes, and values greater than 0.1379 as large effect sizes. Cohens *d* effect size magnitudes were

interpreted using the following classifications: trivial < 0.19; small 0.2–0.59; 0.6–1.19 moderate; 1.2–1.9 large; 2.0–3.9 very large; > 4.0 extremely large [37]. All significance values were accepted at $p < 0.05$ and all statistical procedures were conducted using JASP (version 0.18) for Macintosh.

RESULTS

Team

Descriptive statistics (mean ± standard deviation) for distances covered at different intensities for the various possession classifications and formations are presented in Figure 1. For distance covered per minute, there was a main effect for formation ($p = 0.006$; $\eta 2 = 0.010$), where players covered significantly more distance in a 3-5-2 formation compared to a 4-3-3 formation ($p = 0.006$; $d = 0.243$). There was also a significant interaction effect with formation × possession ($p < 0.001$; $\eta 2 = 0.043$), as players covered significantly less total distance per minute in a 3-5-2 formation when having very low possession and a 4-3-3 formation with high possession, compared to 3-5-2 formation with low, high, and very high possession ($p = 0.001$–0.014; $d = 0.528$–0.893). Players also covered a lower total distance per minute in a 4-3-3 formation with high possession compared to a 4-3-3 formation with very low possession ($p = 0.028$; $d = 0.620$).

For HSR distance per minute, there was a significant interaction effect with formation × possession ($p = 0.006$; $\eta 2 = 0.018$), as players covered less HSR distance per minute in a 3-5-2 formation when having very low possession compared to a 3-5-2 formation with low possession ($p = 0.039$; $d = 0.361$). There was a significant main effect for formation for HMLD per minute ($p = 0.009$; $\eta 2 = 0.009$). Where players covered significantly more HMLD per minute in a 3-5-2 formation compared to a 4-3-3-formation ($p = 0.009$; $d = 0.232$).

There was also a significant interaction effect with formation × possession ($p < 0.001$; $\eta 2 = 0.030$), where players covered less HMLD in a 3-5-2 formation with very low possession and 4-3-3 formation with high possession compared to a 3-5-2 formation with low, high,

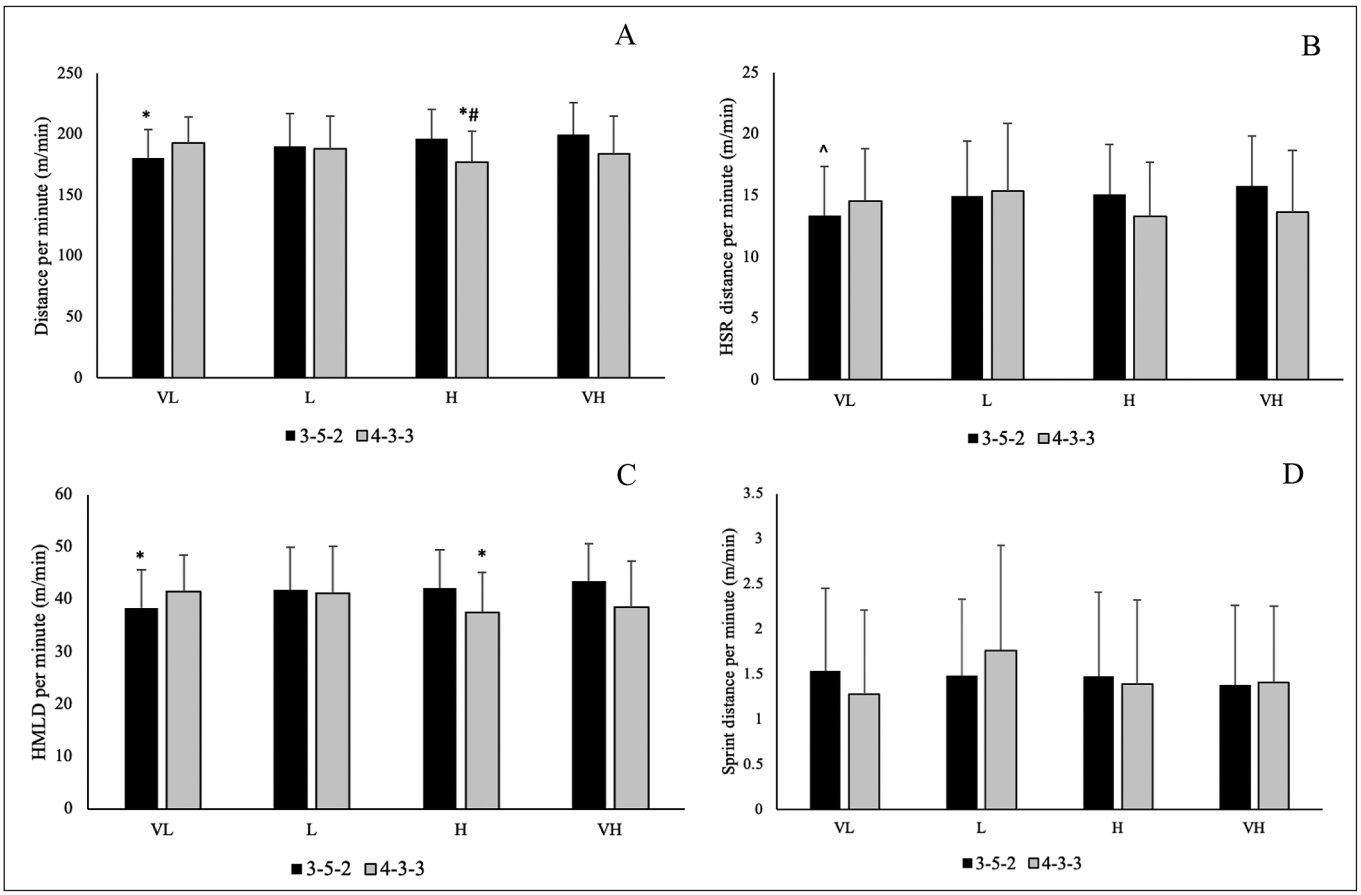


FIG. 1 A–D. Descriptive statistics for match running demands relative to effective ball time across each possession classification and between formations (mean ± SD). A: Total distance per minute; B: High-Speed running (HSR) distance per minute; C: High Metabolic Load distance (HMLD) per minute; D: Sprint distance per minute.

* significantly less than 3-5-2 L, 3-5-2 H, 3-5-2 VH; # significantly less than 4-3-3 VL; ^ significantly less than 3-5-2 L

Note: VL: Very low possession percentage; L: Low possession percentage; H: High possession percentage; VH: Very high possession percentage

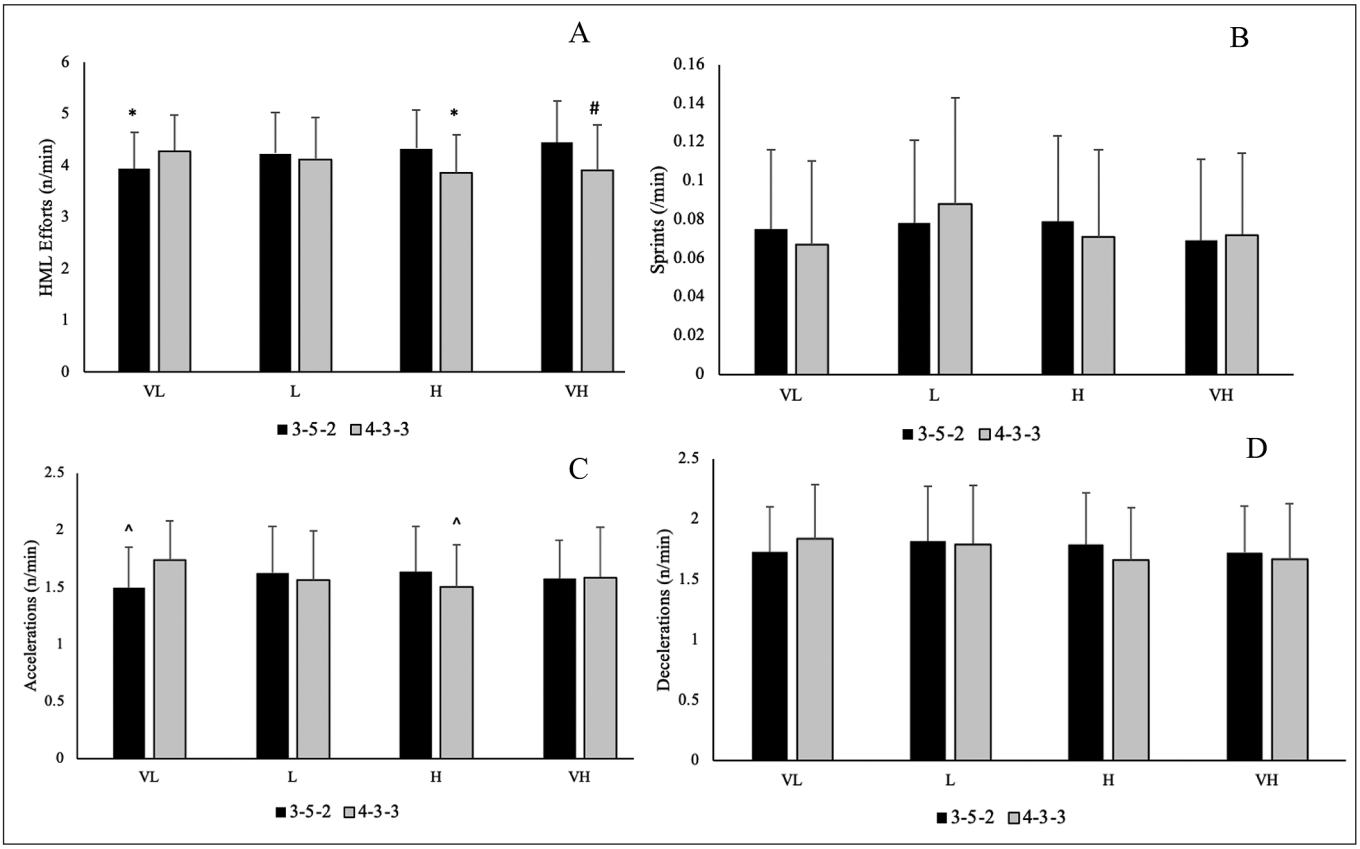


FIG. 2 A–D. Descriptive statistics for match running demands relative to effective ball time across each possession classification and between formations (mean ± SD). A: Number of High Metabolic Load (HML) efforts per minute; B: Number of sprints per minute; C: Number of accelerations per minute; D: Number of decelerations per minute

* significantly less than 3-5-2 L, 3-5-2 H, 3-5-2 VH; # significantly less than 3-5-2 VH; ^ significantly less than 4-3-3 VL

Note: VL: Very low possession percentage; L: Low possession percentage; H: High possession percentage; VH: Very high possession percentage

and very high possession (p = 0.001–0.027; *d* = 0.442–0.762). There were no main or interaction effects for sprint distance per minute.

Descriptive statistics (mean ± standard deviation) for the number of high intensity efforts for the various possession classifications and formations are presented in Figure 2. For the number of HML efforts per minute, there was a main effect for formation (p = 0.004; $\eta 2$ = 0.011), where players performed more HML efforts in a 3-5-2 formation compared to a 4-3-3 formation (p = 0.004; *d* = 0.255). There was also a significant interaction effect for formation × possession (p < 0.001; $\eta 2$ = 0.035), as players completed significantly less HML efforts per minute in a 3-5-2 formation when having very low possession and a 4-3-3 formation with high possession, compared to 3-5-2 formation with low, high, and very high possession (p = 0.002–0.013; *d* = 0.396–0.764). Players also performed less HML efforts per minute in a 4-3-3 formation with very high possession compared to a 3-5-2 formation with very high possession (p = 0.032; *d* = 0.706).

For number of accelerations per minute, there was a significant interaction effect with formation × possession (p < 0.001; $\eta 2$ = 0.025), as players covered less accelerations per minute in a 3-5-2 formation when having very low possession and in a 4-3-3 formation with high possession compared to a 4-3-3 formation with very low possession (p = 0.018–0.040; *d* = 0.601–0.622). There were no main effect of possession or formation, as well no interaction effects for number of sprints or decelerations per minute.

Position Specific

Table 1 shows the descriptive statistics (mean ± standard deviation) for distances covered at different intensities for each position in terms of possession classification and formation. For centre-backs, there was a main effect for distance covered per minute for formation (p = 0.027; $\eta 2$ = 0.023), where this position covered more distance per minute in a 3-5-2 formation than a 4-3-3 formation (p = 0.027; *d* = 0.390). There was also a significant interaction effect for formation and possession (p = 0.001; $\eta 2$ = 0.077), as centre-backs

covered less distance per minute a 4-3-3 formation with high possession compared to in a 3-5-2 formation with low, high, and very high possession (p = 0.008–0.029; *d* = 0.855–1.263).

In terms of HSR distance per minute, there was a main effect for formation (p < 0.001; $\eta 2$ = 0.079), as centre-backs covered more HSR distance per minute in a 3-5-2 formation compared with a 4-3-3 formation (p < 0.001; *d* = 0.729). There was also a significant interaction effect for formation and possession (p = 0.019; $\eta 2$ = 0.047), as centre-backs covered less HSR distance per minute in a 3-5-2 formation with very low possession and a 4-3-3 formation with high possession compared to a 3-5-2 formation with high, and very high possession (p = 0.002–0.016; *d* = 1.019–1.407).

There was a main effect for formation (p < 0.001; $\eta 2$ = 0.061) and HMLD per minute, as centre-backs covered more HMLD per minute in 3-5-2 formations than a 4-3-3 formation (p < 0.001; *d* = 0.647). There was also a significant interaction effect for

TABLE 1. Match running distances for each position depending on formation and possession

	Formation	Possession	Centre Backs	Full Backs	Centre Midfield	Attacking Midfield	Centre Forward
Total Distance (m/min)	3-5-2	VL	178.12 ± 16.53	188.80 ± 17.82	181.01 ± 31.18	172.51 ± 25.24	179.27 ± 15.29
		L	188.64 ± 16.02	195.66 ± 20.81	192.72 ± 35.08	185.11 ± 34.84	189.18 ± 13.22
		H	192.44 ± 23.49	194.76 ± 27.62	208.17 ± 26.03	191.32 ± 22.94	191.81 ± 11.93
		VH	196.33 ± 19.12	188.79 ± 34.27	212.91 ± 27.28	195.12 ± 29.89	191.91 ± 16.70
	4-3-3	VL	192.32 ± 16.08	200.17 ± 18.31	200.50 ± 25.14	173.27 ± 24.32	196.21 ± 3.13
		L	180.78 ± 17.80	190.29 ± 25.09	204.01 ± 29.82	180.24 ± 28.56	184.28 ± 21.02
		H	172.52 ± 19.21[a]	172.45 ± 26.01[c]	189.89 ± 28.48	169.78 ± 26.67	175.43 ± 10.89
		VH	180.42 ± 29.08	182.83 ± 23.24	188.67 ± 35.12	182.01 ± 40.45	184.14 ± 15.43
High-Speed Running Distance (m/min)	3-5-2	VL	10.02 ± 3.02[b]	16.11 ± 3.89	14.24 ± 2.92	15.67 ± 3.59	12.18 ± 1.90
		L	11.70 ± 2.91	17.75 ± 3.96	15.52 ± 3.88	17.80 ± 5.36	14.05 ± 1.91
		H	13.13 ± 3.72	17.76 ± 5.27	15.15 ± 3.35	17.63 ± 3.74	13.97 ± 2.53
		VH	13.89 ± 3.04	17.14 ± 4.32	16.13 ± 3.90	17.60 ± 5.48	14.68 ± 3.78
	4-3-3	VL	10.08 ± 2.31	14.77 ± 2.30	16.37 ± 3.33	17.89 ± 5.22	13.95 ± 2.69
		L	10.54 ± 2.67	18.25 ± 5.58	15.56 ± 4.90	19.06 ± 5.10	14.14 ± 2.69
		H	9.60 ± 3.29[b]	14.41 ± 3.90[c]	13.27 ± 3.52	17.42 ± 3.82	12.08 ± 1.76
		VH	9.63 ± 2.66	15.78 ± 3.36	13.68 ± 3.85	18.43 ± 6.35	10.78 ± 2.74
HMLD (m/min)	3-5-2	VL	33.18 ± 5.57[a]	42.26 ± 5.23	41.82 ± 6.86	39.44 ± 7.12	33.11 ± 3.32
		L	36.86 ± 5.04	44.98 ± 5.86	45.56 ± 7.52	44.43 ± 11.1	35.45 ± 2.77
		H	38.94 ± 6.45	44.45 ± 8.03	47.09 ± 6.37	43.32 ± 6.70	35.94 ± 2.95
		VH	40.38 ± 5.45	43.35 ± 7.90	47.89 ± 4.24	43.26 ± 10.05	39.05 ± 7.88
	4-3-3	VL	35.87 ± 3.19	42.84 ± 3.65	46.31 ± 5.54	42.56 ± 10.86	37.26 ± 4.36
		L	34.31 ± 4.76	43.15 ± 9.33	46.79 ± 7.83	43.36 ± 8.97	35.48 ± 6.16
		H	32.21 ± 5.11[a]	37.84 ± 6.01	41.44 ± 7.03	40.97 ± 8.07	32.04 ± 3.25
		VH	33.04 ± 6.42	41.76 ± 5.80	40.22 ± 7.69	42.46 ± 12.87	32.18 ± 4.59
Sprint Distance (m/min)	3-5-2	VL	1.46 ± 0.91	1.85 ± 0.98	1.33 ± 0.80	1.64 ± 0.87	1.66 ± 1.15
		L	1.40 ± 0.90	1.64 ± 1.07	1.27 ± 0.65	1.68 ± 0.72	1.81 ± 0.91
		H	1.63 ± 1.12	1.22 ± 0.64	1.28 ± 0.72	1.74 ± 1.04	1.29 ± 0.88
		VH	1.43 ± 0.49	2.14 ± 1.46	0.99 ± 0.54	1.67 ± 1.14	1.01 ± 0.57
	4-3-3	VL	0.66 ± 0.54	1.63 ± 0.95	1.50 ± 1.09	1.37 ± 0.78	1.38 ± 1.15
		L	1.25 ± 0.75	2.09 ± 1.00	1.72 ± 1.16	2.28 ± 1.49	1.42 ± 1.08
		H	1.20 ± 0.94	1.40 ± 0.97	1.35 ± 0.95	1.65 ± 0.96	1.45 ± 0.69
		VH	1.18 ± 0.96	1.66 ± 0.69	1.30 ± 0.88	1.84 ± 0.67	1.10 ± 0.91

VL: Very Low Possession; L: Low Possession; H: High Possession; VH: Very High Possession. HMLD: High Metabolic Load Distance; a: Less than 3-5-2 L, H, VH for Centre backs (p < 0.05); b: Less than 3-5-2 H, VH for Centre backs (p < 0.05); c: Less than 3-5-2 L for Full backs (p < 0.05)

formation and possession ($p < 0.001$; $\eta 2 = 0.078$), as centre-backs covered less HMLD per minute in a 3-5-2 formation with very low possession and a 4-3-3 formation with high possession compared to 3-5-2 formations with low, high, and very high possession ($p = 0.001–0.032$; $d = 0.684–1.519$). There were no main or interaction effects for sprint distance per minute for centre-backs.

Full-backs completed less TD per minute and HSR distance per minute in 4-3-3 formations with high possession compared to 3-5-2 formations with low possession ($p = 0.029$ and 0.009; $d = 1.035$ and 1.145, respectively). There were no main or interaction effects for HMLD or sprint distance per minute for full-backs.

There were also no main or interaction effects for TD per minute, HSR distance per minute, HMLD per minute or sprint distance per minute for centre midfielders, attacking midfielders and centre forwards.

Table 2 shows the descriptive statistics (mean ± standard deviation) for number of efforts at various intensities per minute for each position in terms of possession classification and formation. For centre-backs, there was a main effect for HML efforts per minute for

TABLE 2. Number of high intensity efforts for each position depending on formation and possession

	Formation	Possession	Centre Backs	Full Backs	Centre Midfield	Attacking Midfield	Centre Forward
HML Efforts (n/min)	3-5-2	VL	3.58 ± 0.60	4.16 ± 0.44	4.32 ± 0.76	3.86 ± 0.68	3.38 ± 0.40
		L	3.93 ± 0.50	4.43 ± 0.56[a]	4.64 ± 0.82	4.32 ± 1.06	3.47 ± 0.30
		H	4.15 ± 0.64[ab]	4.37 ± 0.67	4.95 ± 0.72	4.23 ± 0.68	3.62 ± 0.31
		VH	4.19 ± 0.55	4.33 ± 0.66	5.08 ± 0.67	4.19 ± 1.02	3.84 ± 0.60
	4-3-3	VL	3.93 ± 0.40	4.55 ± 0.39	4.75 ± 0.64	4.01 ± 1.05	3.95 ± 0.26
		L	3.68 ± 0.48	4.30 ± 0.75	4.78 ± 0.79	3.98 ± 0.80	3.46 ± 0.66
		H	3.55 ± 0.49	3.84 ± 0.54	4.37 ± 0.71	3.89 ± 0.82	3.16 ± 0.31
		VH	3.61 ± 0.78	4.21 ± 0.61	4.16 ± 0.86	3.94 ± 1.16	3.27 ± 0.52
Number of Sprints (n/min)	3-5-2	VL	0.07 ± 0.04	0.09 ± 0.04	0.06 ± 0.03	0.09 ± 0.04	0.08 ± 0.04
		L	0.07 ± 0.04	0.09 ± 0.05	0.06 ± 0.03	0.10 ± 0.05	0.09 ± 0.05
		H	0.08 ± 0.04	0.06 ± 0.03	0.07 ± 0.03	0.10 ± 0.05	0.09 ± 0.06
		VH	0.07 ± 0.02	0.09 ± 0.06	0.05 ± 0.03	0.08 ± 0.07	0.06 ± 0.02
	4-3-3	VL	0.05 ± 0.04	0.09 ± 0.04	0.07 ± 0.05	0.07 ± 0.04	0.07 ± 0.04
		L	0.06 ± 0.03	0.10 ± 0.04	0.09 ± 0.05	0.12 ± 0.07	0.08 ± 0.05
		H	0.06 ± 0.03	0.08 ± 0.05	0.06 ± 0.04	0.09 ± 0.05	0.07 ± 0.04
		VH	0.05 ± 0.04	0.08 ± 0.04	0.07 ± 0.03	0.10 ± 0.04	0.08 ± 0.06
Number of Accelerations (n/min)	3-5-2	VL	1.35 ± 0.25	1.72 ± 0.26	1.38 ± 0.37	1.67 ± 0.47	1.64 ± 0.17
		L	1.58 ± 0.31[ab]	1.70 ± 0.29	1.49 ± 0.34	1.81 ± 0.70	1.73 ± 0.28
		H	1.56 ± 0.32	1.92 ± 0.33	1.45 ± 0.30	1.78 ± 0.59	1.74 ± 0.15
		VH	1.50 ± 0.12	1.68 ± 0.32	1.56 ± 0.27	1.53 ± 0.68	1.72 ± 0.19
	4-3-3	VL	1.66 ± 0.25[a]	1.87 ± 0.20	1.61 ± 0.36	1.78 ± 0.53	1.90 ± 0.23
		L	1.35 ± 0.32	1.78 ± 0.44	1.49 ± 0.40	1.68 ± 0.51	1.70 ± 0.31
		H	1.32 ± 0.25	1.55 ± 0.26	1.38 ± 0.31	1.77 ± 0.46	1.68 ± 0.25
		VH	1.37 ± 0.27	1.85 ± 0.39	1.35 ± 0.29	1.98 ± 0.57	1.68 ± 0.33
Number of Decelerations (n/min)	3-5-2	VL	1.49 ± 0.22	2.08 ± 0.25	1.78 ± 0.38	1.72 ± 0.45	1.56 ± 0.17
		L	1.57 ± 0.30[a]	2.15 ± 0.36[a]	1.86 ± 0.39	1.91 ± 0.70	1.69 ± 0.23
		H	1.59 ± 0.28	2.21 ± 0.40	1.87 ± 0.34	1.77 ± 0.64	1.78 ± 0.26
		VH	1.49 ± 0.16	2.05 ± 0.26	1.78 ± 0.20	1.67 ± 0.75	1.76 ± 0.27
	4-3-3	VL	1.52 ± 0.32	2.20 ± 0.27	1.87 ± 0.26	1.91 ± 0.75	1.70 ± 0.30
		L	1.44 ± 0.28	2.03 ± 0.41	1.94 ± 0.50	1.89 ± 0.56	1.69 ± 0.37
		H	1.35 ± 0.29	1.81 ± 0.39	1.72 ± 0.43	1.85 ± 0.51	1.59 ± 0.23
		VH	1.35 ± 0.32	2.03 ± 0.47	1.57 ± 0.28	1.93 ± 0.62	1.62 ± 0.31

VL: Very Low Possession; L: Low Possession; H: High Possession; VH: Very High Possession; HML: High Metabolic Load. a: More than 4-3-3 H ($p < 0.05$); b: More than 3-5-2 VL ($p < 0.05$).

formation ($p = 0.006$; $\eta 2 = 0.035$), where this position performed more HML efforts per minute in 3-5-2 formations than 4-3-3 formations ($p = 0.006$; $d = 0.482$). There was also a significant interaction effect for formation and possession ($p = 0.002$; $\eta 2 = 0.071$), as centre-backs performed more HML efforts per minute 3-5-2 formations with high possession compared with 4-3-3 formations with high possession and a 3-5-2 formation with very low possession ($p = 0.007$ and 0.004; $d = 1.068$ and 1.019, respectively).

Considering the number of sprints per minute, there was a main effect for formation ($p = 0.004$; $\eta 2 = 0.044$), as centre-backs performed more sprints per minute in a 3-5-2 formation than a 4-3-3 formation ($p = 0.004$; $d = 0.513$).

In terms of number of accelerations per minute, there was a significant interaction effect for formation and possession ($p < 0.001$; $\eta 2 = 0.103$), as centre-backs performed more accelerations per minute in a 3-5-2 formation with low possession and a 4-3-3 formation with very low possession compared to a 4-3-3 formation with high possession ($p = 0.002$ and 0.045; $d = 0.947$ and 1.212). Centre-backs also completed more accelerations per minute in 3-5-2 formations with low possession compared to 3-5-2 formations with very low possession ($p = 0.002$; $d = 0.840$).

There was a main effect for formation ($p = 0.011$; $\eta 2 = 0.032$) and the number of decelerations per minute, as centre-backs covered more decelerations per minute in 3-5-2 formations than 4-3-3 formations ($p = 0.011$; $d = 0.447$). Centre-backs also completed more decelerations per minute in a 3-5-2 formation with low possession compared to a 4-3-3 formation with high possession ($p = 0.019$; $d = 0.813$).

Full-backs completed more HML efforts and decelerations per minute in a 3-5-2 formation with low possession compared to a 4-3-3 formation with high possession ($p = 0.020$ and 0.041; $d = 1.072$ and 1.003, respectively).

There were no main or interaction effects for HML efforts per minute, sprints per minute, accelerations per minute or decelerations per minute for centre midfielders, attacking midfielders and centre forwards.

DISCUSSION

The aim of this study was to examine the effect of possession, team formation and playing position on physical match performance variables across two consecutive seasons of elite soccer match-play. The main observations from this study were that a significant main effect for formation on TD covered per minute was observed. Specifically, players covered significantly greater TD in a 3-5-2 formation compared to a 4-3-3 formation. Furthermore, there was a significant interaction effect between formation and possession on TD covered per minute. Particularly, players covered significantly lower TD per minute in a 3-5-2 formation when having very low possession and in a 4-3-3 formation with high possession, compared to a 3-5-2 formation with low, high, and very high possession. Additionally, players covered a lower TD per minute in a 4-3-3 formation with high possession compared to a 4-3-3 formation with very low possession. These findings suggests that the interaction between possession and formation can influence the distance covered by players, with different formations being more or less effective depending on the possession status of the team.

Team

For HSR distance per minute, there was a significant interaction effect between formation and possession. Specifically, players covered less HSR distance per minute in a 3-5-2 formation when having very low possession compared to a 3-5-2 formation with low possession. This highlights that possession interacts with team formation and affects the quantity of HSR performed by the team. Potentially, this may partly be explained by the in-possession tactical strategy adopted by the study team when choosing a 3-5-2 formation. The 3-5-2 formation can arguably be classified as a defensive formation and is often implemented against higher quality opponents and thus may reflect the very low possession observed in the current study. While also explaining less HSR distance per minute as this metric is often witnessed while undertaking attacking phases of play which were less evident in the study team during matches of low and very low possession. A recent study [19] that examined three elite soccer teams found that one of the analysed teams (Team 1) that had a more defensive style (4-4-2 formation) expended more time in defending actions and initiating more direct attacks. The same study [19] analysed two other teams that employed 4-4-3 formations in which one team employed an indirect style of play (Team 2) while the third team employed intricate attacks and effective counter-attacks (Team 3). While Team 2 employed complex attacks using short, explosive movements and a higher number of passes between thus decreasing the distances covered, Team 3 showed a greater number of counter-attacks and therefore covered greater distances at higher speeds. As an example, distance covered at > 14 km/h was higher in Team 1 compared with Team 2. Despite the different formation of Team 2 when compared with Team 1 of the previous study [19], the 3-5-2 formation seemed to have a similar defensive approach that may help explain the results, leading to the relevance of the tactical strategy adopted.

There were no main or interaction effects observed for sprint distance per minute. This may imply that neither the formation nor possession had a significant impact on sprint distance covered by players during match-play. Nonetheless, a different scenario occurred where a 4-3-3 formation team produced a greater number of counter-attacks that led to higher sprint distances, while another team employing the same 4-3-3 formation performed more complex attacks, with shorter movements and a higher number of passes that decreased sprint distances [17, 19, 33].

Furthermore, there was a significant interaction effect between formation and possession for the number of HML efforts per minute. This interaction effect revealed that in a 3-5-2 formation, the number of HML efforts per minute decreased significantly when possession was

very low compared to a 3-5-2 formation with low, high, and very high possession. Similarly, in a 4-3-3 formation, the number of HML efforts per minute decreased significantly when the possession was high compared to a 3-5-2 formation with low, high, and very high possession. Additionally, players performed fewer HML efforts per minute in a 4-3-3 formation with very high possession compared to a 3-5-2 formation with very high possession. This may partly be explained by a defensive tactical strategy that does not promote a 'high-press' and maintains a compact defensive shape and thus reduces HML efforts even with very low possession. Although, lower HML efforts per minute in a 4-3-3 formation with high possession may also suggest a 'building' approach when in possession compared to a more direct strategy that would require running in behind. For instance, a previous study compared the effects of high and low percentage ball possession of EPL teams (no formation analysis) on physical and technical profiles during elite soccer match-play and concluded that ball possession percentage does not influence TD. Although, ball possession does influence HSR efforts with and without the ball and some technical elements of performance [10, 14, 38].

A further identical study with data from FIFA World Cup reported that ball possession does not influence the activity patterns of international matches although high possession teams spend more time in offensive areas of the pitch (again no formation was considered for analysis) [39]. Moreover, other research [40] showed that HSR with ball possession in offensive, traditional formations (4-3-3 and 4-4-2) were ~30 to 40% higher than defensive formations (4-5-1). The same study reported that around 20% more HSR distance was covered without possession in defensive versus offensive, traditional formations [40], which again reinforces the importance of considering the tactical strategy.

In terms of the number of accelerations per minute, there was a significant interaction effect between formation and possession. Specifically, in a 4-3-3 formation, players performed fewer accelerations per minute with high possession compared to a 4-3-3 formation with very low possession. Therefore, it may be speculated that when selecting a 4-3-3 formation, that is often considered an attacking formation, and attempting to maintain high possession, this tactical combination lowers explosive acceleration actions performed by all positions, as these are frequently associated with defensive 'pressing' actions. This potentially suggests that the combination of formation and possession can have an impact on the number of accelerations performed by players regardless of playing position.

Position Specific

When analysing physical match performance and playing position based on possession and formation, centre-backs revealed a main effect for TD covered per minute in relation to formation. Specifically, centre-backs covered more TD per minute in a 3-5-2 formation than a 4-3-3 formation. Centre-backs also covered less TD per minute a 4-3-3 formation with high possession compared to a 3-5-2 formation with low, high, and very high possession. Regarding HSR distance per minute, centre-backs showed a main effect for formation, indicating that this position covered more HSR distance per minute in a 3-5-2 formation compared to a 4-3-3 formation. The practical significance of this effect was moderately small. Although, when considering the previous study that analysed three elite Spanish teams with differing formations and playing strategies, contrasting results emerge as centre-backs were reported to cover higher distances in teams with 4-4-2 formations and a defensive style, however that was not evident [19].

Similarly, a significant interaction effect was observed between formation and possession for HSR distance per minute for centre-backs. In this case, centre-backs covered less HSR distance per minute in a 3-5-2 formation with very low possession and a 4-3-3 formation with high possession compared to a 3-5-2 formation with high and very high possession. These effect sizes were moderately large, indicating a considerable practical significance that sustains the relevance of contextualising match physical demands by also analysing ball possession [39].

Moreover, a significant interaction effect between formation and possession was found for HMLD per minute in centre-backs. Specifically, centre-backs covered less HMLD per minute in a 3-5-2 formation with very low possession and a 4-3-3 formation with high possession compared to 3-5-2 formations with low, high, and very high possession. These effect sizes suggested moderately large practical significance. A study conducted with Chinese Premier League players also reported that centre-backs covered more high-intensity (5.5–7 m/s) and sprint (> 7 m/s) distance in the high possession teams, although no formation analysis was considered [40], which also leads to the importance of ball possession. Full-backs covered less TD per minute and HSR distance per minute in 4-3-3 formations with high possession compared to 3-5-2 formations with low possession. These differences were statistically significant and demonstrated moderately large effect sizes.

In terms of accelerations per minute, there was a significant interaction effect between formation and possession for centre-backs. Centre-backs performed more accelerations per minute in a 3-5-2 formation with low possession and a 4-3-3 formation with very low possession compared to 4-3-3 formations with high possession. Additionally, centre-backs completed more accelerations per minute in 3-5-2 formations with low possession compared to 3-5-2 formations with very low possession. This indicates that time in possession, in combination with formation, has a significant effect on the number of acceleration efforts made by centre-backs as this defensive position will potentially be required to produce more out of possession 'pressing' actions or perform more 1 v 1 moments. The effect size here also suggests a large influence on physical performance for this position.

For the number of decelerations per minute, there was a significant main effect for formation. Centre-backs covered more decelerations per minute in 3-5-2 formations compared to 4-3-3 formations. This suggests that the tactical setup also influences the frequency of

decelerations for centre-backs. The effect size indicates a small to moderate influence of formation on decelerations for centre-backs. Additionally, centre-backs completed more decelerations per minute in a 3-5-2 formation with low possession compared to a 4-3-3 formation with high possession. Furthermore, full-backs exhibited higher numbers of HML efforts and decelerations per minute in a 3-5-2 formation with low possession compared to a 4-3-3 formation with high possession. This not only indicates that the tactical setup affects these explosive, out-of-possession performance metrics for full-backs but also suggests that possession plays a significant role in the physical demands for this position.

Furthermore, the 3-5-2 formation may gain an advantage where the wing-back role acting as an external defender will have longer runners to cover due to the multi-faceted role this position plays, including the role of wide midfielders. According to previous research, there may be three justifications: 1) when the team with higher possession attacks, three lines of players move together deep into the opponents' half which produces greater distances for centre-backs and wing-backs to cover [40]; 2) when the team with higher possession defends, wing-backs and centre-backs will need to sprint to mark opponent players or chase the ball until the ball is intercepted, resulting in fast counter-attacks [40]; and 3) teams with low ball possession have to choose a counter-attack strategy when facing high quality opponents as low possession teams have fewer chances of achieving penetrative passes, thus have to exploit any weaknesses in the opponents' defence and effectively take advantage of an imbalanced defensive line [41, 42]. However, no main or interaction effects were observed for HMLD or sprint distance per minute for full-backs. Lastly, no main or interaction effects were found for any of the distance measures (distance per minute, HSR distance per minute, HMLD per minute, and sprint distance per minute) for centre midfielders, attacking midfielders, and centre forwards.

In summary, the results highlight the importance of both formation and possession in relation to the distances covered at different intensities, specifically for centre-backs and full-backs. These findings suggest that tactical and strategic factors, such as formation and possession, influence the physical demands placed on players in different positions.

Practical implications, limitations, and future research directions

Overall, these team findings highlight the importance of considering both the formation and possession when analysing the intensity of match efforts. Specifically, the present results suggest that different team formation and possession may lead to variations in the number of high-intensity efforts and accelerations performed. These findings may have practical implications for coaches and players in terms of optimising tactical game strategies (formation, in-possession, out-of-possession and transitional approaches) and player performance based on formation and possession.

Several limitations should be noted when interpretating the findings of this study. The current data are reflective of the methods and practices of a single elite soccer club, the positional match running performance and variations resulting from possession classifications and team formation. Also, this study did not examine the outcome of effective playing time on locomotor performance [43]. In addition, other contextual factors such as opponent level [44], match location [20], match outcome [45] and match half were not considered. For example, when playing against top-level teams, players covered greater distance of high-speed running and sprinting [46]. In the same line, other study showed that more decelerations were performed against top-level than middle- and bottom-level opponents [44]. Regarding match location, a recent study showed that more acceleration and decelerations were performed when playing against home than away matches [20]. Considering the outcomes, previous research showed that winning increased external load than a draw or loss [45]. Moreover, fatigue is another variable that take a role in all results and considered the inclusion criteria adopted for this study, it is possible that some players could be fresher than others through the season or within the match (e.g. first half and second half) which could influence the results. For that reason, the inclusion of some physiological (heart rate), psychophysiological (rating of perceived exertion), or a wellness (through a questionnaire, e.g., Hooper Index) variable is warranted in future research. Finally, the context of the game is also other variables that can influence results. For instance, the matches of the season can decide if the team is regulated to a lower division or if it can participate in a European competition in the next season. Thus, future research should also include such variable in the analysis.

Consequently, the results should only be generalised to similar cohorts, level of competition, and tactical approaches. Thus, future studies should be conducted to compare current findings utilising larger sample sizes with various team formations and possession time.

CONCLUSIONS

In conclusion, the findings of this study provide insights into the influence of formation and possession on the physical performance of soccer players. The results indicate that the choice of formation and possession can have a significant impact on TD covered, HSR distance, and HMLD per minute of elite soccer teams. These findings suggest that coaches and teams can tailor tactical strategies and formations based on possession classifications to optimise player match-play performance.

Furthermore, the study revealed that the number of high intensity efforts per minute was influenced by formation, with players performing more high intensity efforts in a 3-5-2 formation compared to a 4-3-3 formation. Additionally, the interaction between formation and possession affected the number of high intensity efforts performed, indicating that different formations and possession classifications can influence the physical demands placed on players.

In addition, the results highlight the importance of both formation and possession in relation to the distances covered at different intensities, specifically for centre-backs and full-backs in the two

formations analysed. These findings suggest that both formation and possession, influence the physical demands placed on players in different positions.

Conflict of interest

The authors declare no conflict of interest.

REFERENCES

1. Caldbeck P, Dos'Santos T. A classification of specific movement skills and patterns during sprinting in English Premier League soccer. PLoS One. 2022; 17(11):e0277326.
2. Lago-Peñas C, Lorenzo-Martinez M, López-Del Campo R, Resta R, Rey E. Evolution of physical and technical parameters in the Spanish 2012–2019. Sci Med Football. 2023; 7(1):41–46.
3. Nassis GP, Massey A, Jacobsen P, Brito J, Randers MB, Castagna C, Mohr M, Krustrup P. 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):962–964.
4. Martínez-Hernández D, Quinn M, Jones P. Linear advancing actions followed by deceleration and turn are the most common movements preceding goals in male professional soccer. Sci Med Football. 2023; 7(1):25–33.
5. Rhodes D, Valassakis S, Bortnik L, Eaves R, Harper D, Alexander J. The Effect of High-Intensity Accelerations and Decelerations on Match Outcome of an Elite English League Two Football Team. Int J Environ Res Public Health. 2021; 18(18):9913. https://doi.org/10.3390/ijerph18189913.
6. Schulze E, Julian R, Meyer T. Exploring Factors Related to Goal Scoring Opportunities in Professional Football. Sci Med Football. 2022; 6(2):181–188.
7. Souza DB, Campo RL-D, 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. https://doi.org/10.1080/24748668.2020.1762279.
8. Wang SH, Qin Y, Jia Y, Igor KE. A systematic review about the performance indicators related to ball possession. PLoS One. 2022; 17(3):e0265540.
9. Yi Q, Liu H, Nassis GP, Gómez M-Á. Evolutionary Trends of Players' Technical Characteristics in the UEFA Champions League. Front Psychol. 2020; 11:1032.
10. Andrzejewski M, Oliva-Lozano JM, Chmura P, Chmura J, Czarniecki S, Kowalczuk E, Rokita A, Muyor JM, Konefał M. Analysis of team success based on match technical and running performance in a professional soccer league. BMC Sports Sci Med Rehabil. 2022; 14(1):1–7.
11. Lorenzo-Martinez M, Kalén A, Rey E, López-Del Campo R, Resta R, Lago-Peñas C. Do elite soccer players cover less distance when their team spent more time in possession of the ball? Sci Med Football. 2021; 5(4):310–316.
12. Ju W, Doran D, Hawkins R, Evans M, Laws A, Bradley PS. Contextualised high-intensity running profiles of elite football players with reference to general and specialised tactical roles. Biol Sport. 2023; 40(1):291–301. doi: 10.5114/biolsport.2023.116003.
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; 40(4):1197–1205. DOI: https://doi.org/10.5114/biolsport.2023.126667
14. Arjol-Serrano JL, Lampre M, Díez A, Castillo D, Sanz-López F, Lozano D. The Influence of Playing Formation on Physical Demands and Technical-Tactical Actions According to Playing Positions in an Elite Soccer Team. Int J Environ Res Public Health. 2021; 18(8):4148.
15. Díez A, Lozano D, Arjol-Serrano JL, Mainer-Pardos E, Castillo D, Torrontegui-Duarte M, Nobari H, Jaén-Carrillo D, Lampre M. 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):157.
16. Gollan S, Bellenger C, Norton K. Contextual Factors Impact Styles of Play in the English Premier League. J Sports Sci Med. 2020; 19(1):78–83.
17. Modric T, Versic S, Sekulic D. Position Specific Running Performances in Professional Football (Soccer): Influence of Different Tactical Formations. Sports. 2020; 8(12):161.
18. Ponce-Bordon JC, Diaz-Garcia J, Lopez-Gajardo MA, Lobo-Trivino D, Lopez Del Campo R, Resta R, Garcia-Calvo T. The influence of time winning and time losing on position-specific match physical demands in the top one Spanish soccer league. Sensors. 2021; 21(20):6843. doi.org/10.3390/s21206843.
19. 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; 82:135–144. https://doi.org/10.2478/hukin-2022-0040.
20. 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.
21. 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; 15:101–110.
22. Winter EM, Maughan RJ. Requirements of ethics approval. J Sports Sci. 2009; 27:85.
23. Morgans R, Bezuglov E, Orme P, Burns K, Rhodes D, Babraj J, Di Michele R, Oliveira R. The Physical Demands of Match-Play in Academy and Senior Soccer Players from the Scottish Premiership. Sports. 2022; 10:150. https://doi.org/10.3390/sports10100150.
24. Stevens TGA, de Ruiter CJ, Twisk JR, Savelsbergh GJP, Beek PJ. Quantification of in-season training load relative to match load in professional Dutch Eredivisie football players. Sci Med Football. 2017; 1(2):117–125. doi: 10.1080/24733938.2017.1282163.
25. Beato M, Coratella G, Stiff A, Iacono AD. The Validity and Between-Unit Variability of GNSS Units (STATSports Apex 10 and 18 Hz) for Measuring Distance and Peak Speed in Team Sports. Front Physiol. 2018; 9:1288.
26. Crang ZL, Duthie G, Cole MH, Weakley J, Hewitt A, Johnston RD. The inter-device reliability of global navigation satellite systems during team sport movement across multiple days. J Sci Med Sport. 2022 Apr; 25(4):340–344. doi: 10.1016/j.jsams.2021.11.044. Epub 2021 Nov 26. PMID: 34893434.
27. Beato M, Bartolini D, Ghia G, Zamparo P. Accuracy of a 10 Hz GPS unit in measuring shuttle velocity performed at different speeds and distances (5–20 M). J Hum Kinet. 2016; 54:15–22.
28. Malone JJ, Lovell R, Varley MC, Coutts AJ. Unpacking the Black Box: Applications and Considerations for Using GPS Devices in Sport. Int J Sports Physiol Perf. 2017; 12:1–26.
29. Heidi T, Andre RN, Delaney JA, Serpiello FR, Duthie GM. Inter-unit

reliability and effect of data processing methods of global positioning systems. Int J Sports Physiol Perform. 2018; 14(4):432–438.
30. Townshend AD, Worringham CJ, Stewart IB. Assessment of speed and position during human locomotion using nondifferential GPS. Med Sci Sports Exerc. 2008; 40(1):124–132.
31. Pollard BT, Turner AN, Eager R, et al. The ball in play demands of international rugby union. J Sci Med Sport. 2018; 21(10):1090–1094.
32. Wass J, Mernagh D, Pollard B, Stewart P, Fox W, Parmar N, Jones B, Kilduff L, Turner A. A comparison of match demands using ball-in-play vs. whole match data in elite male youth soccer players. Sci Med Football. 2020; 4(2):142–147.
33. 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. 2020; 38(2):195–205.
34. Maughan PC, Niall G, MacFarlane NG, Swinton PA. Quantification of training and match-play load across a season in professional youth football players. Int J Sports Sci Coaching. 2021; 16:5,1169–1177.
35. FIFA. Handbook of test methods for Electronic Performance Tracking Devices. http://quality.fifa.com/media/172234/2019-handbook-of-test-methods-epts.pdf (2019, accessed 28 Nov 2021).
36. 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; 30:2424–2432.
37. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009 Jan; 41(1):3–13. doi: 10.1249/MSS.0b013e31818cb278.
38. 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 Dec; 31(12):1261–1270. doi: 10.1080/02640414.2013.786185.
39. 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. doi: 10.1080/02640414.2015.1114660.
40. Liu T, Yang L, Chen H, García-de-Alcaraz A. Impact of Possession and Player Position on Physical and Technical-Tactical Performance Indicators in the Chinese Football Super League. Front Psychol. 2021; 12:722200. doi: 10.3389/fpsyg.2021.722200.
41. Bradley PS, Carling C, Archer D, Roberts J, Dodds A, Di Mascio M, Krustrup P. The effect of playing formation on high-intensity running and technical profiles in English FA Premier League soccer matches. J Sports Sci. 2011; 29:821–830.
42. Tenga A, Holme I, Ronglan LT, Bahr R. Effect of playing tactics on goal scoring in Norwegian professional soccer. J Sports Sci. 2010; 28:237–244. doi: 10.1080/02640410903502774.
43. Lago-Ballesteros J, Lago-Penas C, Rey E. The effect of playing tactics and situational variables on achieving score-box possessions in a professional soccer team. J Sports Sci. 2012; 30:1455–1461. doi: 10.1080/02640414.2012.712715.
44. Nobari H, Ramachandran A, Oliveira R. The influence of opponent level on professional soccer players' training and match performance assessed by using wearable sensor technology. Hum Mov. 2022; 24(1).
45. Reche-Soto P, Cardona-Nieto D, Diaz-Suarez A, Bastida-Castillo A, Gomez-Carmona C, Garcia-Rubio J, et al. Player load and metabolic power dynamics as load quantifiers in soccer. J Hum Kinet. 2019; 69:259–269. doi:10.2478/hukin-2018-0072.
46. Rampinini E, Coutts AJ, Castagna C, Sassi R, Impellizzeri F. Variation in top level soccer match performance. Int J Sports Med. 2007; 28(12):1018–1024. doi:10.1055/s-2007-965158.

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