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Effects of re-warm-up protocols on the physical performance of soccer players: A systematic review with meta-analysis

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ABSTRACT: This systematic review aimed to (1) identify and summarize studies that have examined the effects of re-warm-up (RWU) protocols on the physical performance of soccer players (vertical jump height and sprint time) and (2) establish a meta-comparison between performing a re-warm-up and not performing one regarding the outcomes of the aforementioned outcomes. A systematic review of EBSCO, PubMed, SciELO, SPORTDiscus, and Web of Science databases was performed on 12 January, 2021, according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. From the 892 studies initially identified, four studies were reviewed, and three of these were included in the present meta-analysis. Compared to a control condition, there was a moderate effect of RWU on vertical jump height (ES = 0.66; p = 0.001; I^2 = 0.0%). However, compared to a control condition, there was a trivial effect of RWU on linear sprint time (ES = 0.19; p = 0.440; I^2 = 38.4%). The nature of RWU enhances the performance of players with an emphasis on actions requiring vertical jumps. Therefore, the results provide essential information that soccer coaching staff can use to improve the performance of their teams. The limited number of studies available for the meta-analysis may have magnified the impact of heterogeneity on linear sprint time findings. More high-quality studies, with homogeneous study designs, may help to clarify the potential benefits of RWU for linear sprint time.

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INTRODUCTION

In soccer, re-warm-up (RWU) may increase players' readiness to perform actions at different intensity levels [1] at the start of the second half of a match, thereby enhancing their athletic performance [2]. Indeed, RWU strategies have demonstrated that soccer players' acute explosive performance improved during the first minutes of the second half of the match [3–5].

A review of the literature reveals that the physical performance of soccer players decreases during the second half of the match [6]. Common examples of this evidence can be found in studies showing poorer performances for different variables, such as the number of high-intensity actions and the total distance covered in the second half in comparison with the first half [7, 8]. Traditionally, these effects have been linked to changes in muscle and core temperatures [9] induced by passive half-time practice [10]. Nevertheless, improvements in physical performance in the second half have also been associated with RWU based on post-activation potentiation and supplementation with carbohydrate and caffeine [11]. Therefore, the direction of these physiological changes depends on the active behaviours performed during the 15 minutes of rest between halves [12].

Player's capability of keep high values of physical strength plays an important role in the performance of soccer players in terms of their maximal strength, jumping ability, and sprint performance [7, 13] and decrease over the course of a match. In this sense, it is widely known that efficient neuronal activation generates more applicated weight reflected in vertical jump height, and improves the change-of-direction and linear sprinting performance in elite soccer players [14]. On the one hand, the higher level of fatigue generated during the first half and the team's passive behaviour negatively impact players' sprint and jump performance at the beginning of the second half. On the other hand, the implementation of RWU is positively related to an improvement in the performance at the beginning of the second half [15].

Even though there is evidence supporting the influence of acute effects of RWU on the physical performance of soccer players, described in a systematic review [4–6], little is known about its effect on certain physical variables of the game, such as vertical jump height, and sprint time. In fact, the most recent systematic review in RWU (as far as we know), centred the analysis in a myriad of performance analyses without a quantitative synthesis in the form of a meta-analysis [5]. Therefore, the aim of this systematic review was twofold: (i) to identify and summarize studies that have examined the effects of RWU protocols on the physical performance of soccer players (vertical jump height and sprint time) and (ii) to establish a meta-comparison between performing and not performing an RWU protocol regarding vertical jump height and sprint time.

MATERIALS AND METHODS

Design and protocol

The systematic review strategy was conducted according to Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines [16]. The protocol was registered with the International Platform of Registered Systematic Review and Meta-Analysis Protocols with the number 202110055 and DOI: 10.37766/inplasy2021.1.0055.

Eligibility criteria

The inclusion and exclusion criteria can be found in Table 1 according to the PICOS approach [17].

Information sources and search

Five electronic databases (EBSCO, PubMed, SciELO, SPORTDiscus, and Web of Science) were explored for relevant publications prior to 29 January 2022. The Web of Science database search was performed restricting the search to the area of "sport sciences". Keywords and synonyms were entered in various combinations in the title, abstract or keywords: (soccer OR football) AND ("re-warm-up" OR "post-warm-up" OR "warm-up" OR "pre-activity" OR "post-activation potentiation" OR "stretch*") AND ("jump*" OR "sprint*" OR "change-of-direction" OR "agility").

The searches, the removal of duplicates, screening of titles and abstracts, and analysis of the full texts in an independent way were performed by two authors (FTGF and AIP). The inter-rater agreement

TABLE 1. Inclusion and exclusion criteria

	Inclusion criteria	Exclusion criteria
Population	Soccer players of any age or sex with no injury or illness, with normal vision, no partial/chronic injury or illness, and no history of neuropsychological impairment.	Population other than soccer players or members of the soccer player population with special conditions (e.g., injury, treatment, illness, diseases).
Intervention	RWU protocols (always performed after an initial warm-up) conducted under one of the two following possible conditions: (i) after the warm-up and before the match. (ii) between the halves of the match.	Warm-up protocols.
Comparator	Passive control conditions.	Intervention conditions other than passive conditions.
Outcome	Vertical jump height, and sprint time	Physiological or physical conditions not related to the included outcomes.
Study design	Counterbalanced cross-over design (randomized and non-randomized can be included since none of them reveal significant differences in control conditions).	Study designs that do not allow within-subjects comparisons for the two conditions (control and RWU).
Additional criteria	Only original and full-text studies written in English.	Studies written in any language other than English. Articles other than original research (e.g., reviews, letters to editors, trial registrations, proposals for protocols, editorials, book chapters, and conference abstracts).

was measured through Cohen's kappa [17], which was found to be good (kappa = 0.70). Any discrepancy in the selection process was solved by consensus with a third author (HS).

Data extraction

An ad-hoc Microsoft Excel sheet (Microsoft Corporation, Redmond, WA, USA) was used to assess inclusion requirements in accordance with the Cochrane Consumers and Communication Review Group's data extraction template [18]. The Excel sheet was used to assess inclusion requirements and subsequently tested for all selected studies. The process was independently conducted by two authors (HS and FTGF). Any disagreement regarding study eligibility was resolved in a discussion. Full text articles excluded, with reasons, were recorded. All the records were stored in the sheet.

Data items

The outcomes chosen for this systematic review and meta-analysis included vertical jump height (VJH) and sprint time (ST). The VJH (measured in cm) was usually assessed during a countermovement jump (CMJ) with or without arm swing. The linear ST (measured in seconds) at different distances was also collected, without including values of partial times. Additionally, the following data items were extracted: (i) type of study design, number of participants (n), age group (youth, adults or both), sex (men, women or both), competitive level, moment of the season; (ii) characteristics of the RWU protocol (duration and intensity); (iii) moment of the match (after warm-up and between halves); (iv) characteristics of the experimental approach to the problem, procedures and settings of each study.

Methodological assessment

The included studies were assessed according to their methodological quality with the Risk of Bias 2 (RoB 2) tool for RCTs [19]. We conducted a risk of bias assessment using the RoB-2 tool for RCTs [20] and the ROBINS-I for nonrandomized interventions [21]. These tools allow one to assess the risk of bias (i.e., "low risk," "some concerns," or "high risk") of several dimensions, which vary according to the study design (namely, bias arising from the randomization process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in measurement of the outcome, and bias in selection of the reported result). Altogether an overall level of risk of bias per study was computed. Risk of bias assessments were based on the published articles. Two of the authors (FTGF and AIP) independently screened and assessed the included articles. The inter-rater agreement was very good (Cohen's kappa = 0.99). Discrepancies were solved by consensus between the two authors.

Summary measures, synthesis of results, and publication bias

Although meta-analyses can be done with as few as two studies [22], considering the fact that reduced sample sizes are common in the sports science literature [23], meta-analysis was only conducted in the present case when three or more studies were available for the same outcome. Effect sizes (ES; Hedge's *g*) for each outcome (i.e., linear sprint; vertical jump) in the experimental and control groups were calculated using pre-intervention and post-intervention mean and standard deviation (SD) for each outcome. Data were standardized using post-intervention SD values. The random-effects model was used to account for differences between studies that might impact the intervention effect [24–25]. The ES values are presented with 95% confidence intervals (95% CIs). Calculated ES were interpreted using the following scale: < 0.2, trivial; 0.2–0.6, small; > 0.6–1.2, moderate; > 1.2–2.0, large; > 2.0_4.0, very large; > 4.0, extremely large [26]. In studies including more than one intervention group, the sample size in the active control group was proportionately divided to facilitate comparisons across multiple groups [27] The impact of heterogeneity in the findings was assessed using the I^2 statistic, with values of < 25%, 25–75%, and > 75% representing low, moderate, and high levels of heterogeneity, respectively. The risk of reporting bias was explored using Egger's test [28], with $p < 0.05$ implying bias. To adjust for risk of reporting bias, a sensitivity analysis was conducted using the trim and fill method [29], with L_0 as the default estimator for the number of missing studies [30]. All analyses were carried out using the Comprehensive Meta-Analysis software (Version 2.0; Biostat, Englewood, NJ, USA). Statistical significance was set at $p < 0.05$.

RESULTS

Study identification and selection

The search of databases identified a total of 1309 titles (PubMed = 267; Scopus = 352; SPORTDiscus = 327; Web of Science = 363). These studies were then exported to reference manager software (EndNote X9, Clarivate Analytics, Philadelphia, PA, USA). Duplicates (664 references) were subsequently removed either automatically or manually. The remaining 645 articles were screened for their relevance based on the information contained in titles and abstracts and considering the selection and exclusion criteria (see Table 1). This resulted in the removal of a further 619 studies. Following the screening procedure, 26 articles were selected for in depth reading and analysis. After reading full texts, four studies were selected (Figure 1).

Methodological quality

Table 2 shows the overall methodological quality assessment of the cross-sectional studies. Two out of three studies were classified as presenting high risk of bias studies, based on their overall RoB 2 quality scale [9, 31], and the other one was considered as having some concerns [32], while another study was classified as showing serious risk of bias in ROBINS-I [15]. Some issues were found regarding the quality of the information reported on the randomization process, the reporting of possible deviations from the intended interventions, the treatment of missing outcome data, and the selection of the reported result.

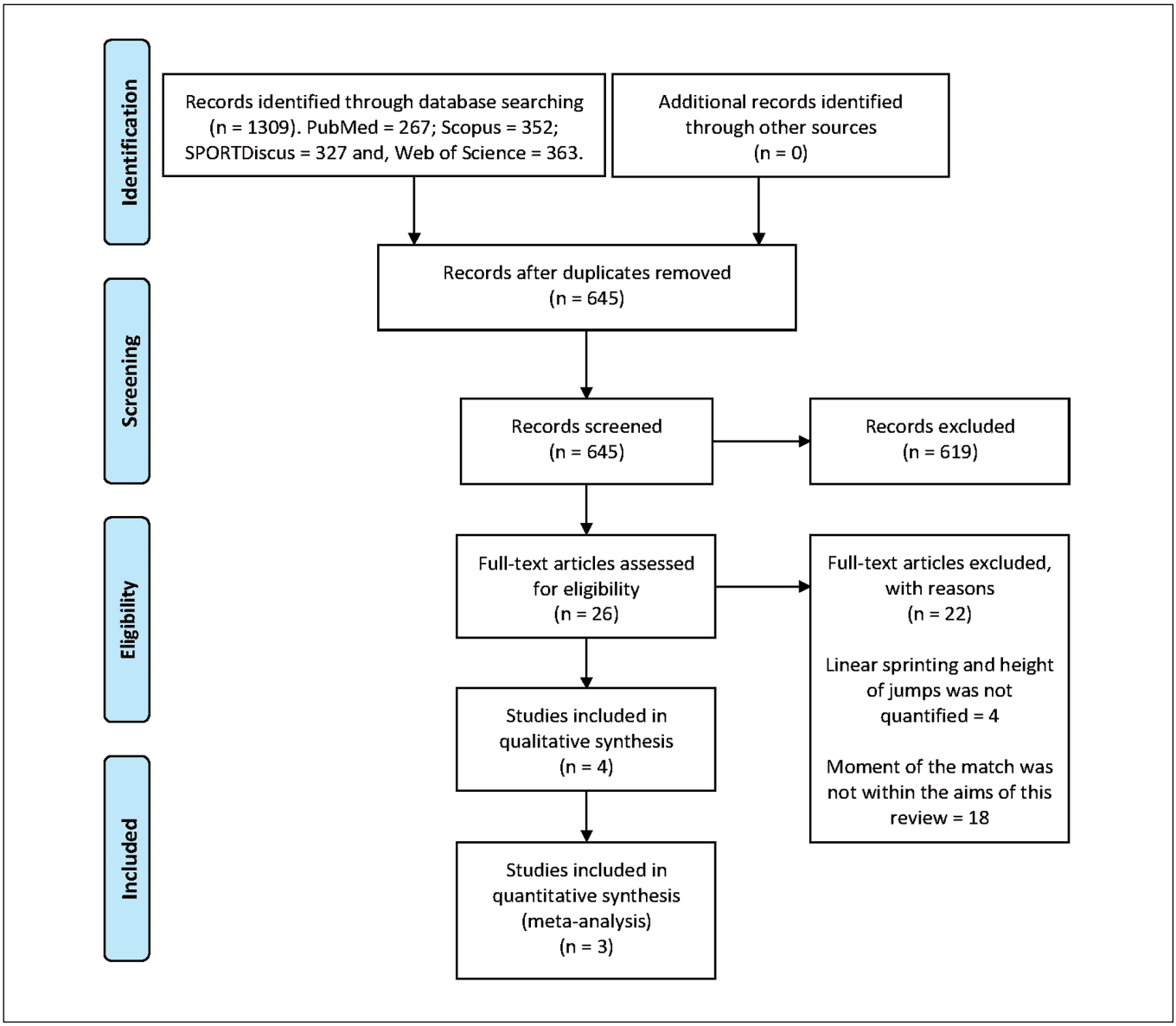


FIG. 1. PRISMA flow diagram highlighting the selection process for studies.

TABLE 2. Methodological assessment of the included studies.

Study	Outcome	D1a	D1b	D2	D3	D4	D5	DS	Overall
Edholm et al. [15]*	All	S	L	M	L	NI	M	M	S
Fashioni, Langley & Page [31]	All	SC	–	SC	H	L	SC	L	H
Lovell et al. [32]	All	SC	–	SC	L	L	SC	L	SC
Mohr et al. [9]	All	SC	–	SC	H	L	SC	–	H

Note. D1a: Randomization process; D1b: Timing of identification or recruitment of participants in a cluster-randomized trial; D2: Deviations from the intended interventions; D3: Missing outcome data; D4: Measurement of the outcome; D5: Selection of the reported result; DS: Period and carryover effects. C: Critical; H: High risk; L: Low risk; M: Moderate; NI: No information; S: Serious; SC: Some concerns. * Assessment from ROBINS-I: D1a: Bias due to confounding; D1b: Bias in selection of participants for the study; D2: Bias in classification of interventions; D3: Bias due to deviations from intended interventions; D4: Bias due to missing data; D5: Bias in measurement of outcomes; DS: Bias in selection of the reported result.

TABLE 3. Characteristics of selected studies

Study	Age (years) Mean ± SD	Sample size (*n*)	Level / Sex	RWU characteristics	Design	Outcomes	
						Vertical jump height	Sprint time
Mohr et al. [9]	27.0. ± 1.5	8♂ CG 8♂ EG	Male Soccer players competing in the Danish 4th Division	Re Warm Up1: 15′ rest (control) Re Warm Up2: 7′ rest + 7′ jog + exercises at 135 beat/ min	Randomized (participants) Parallel groups	–	Re Warm Up2 > Re Warm Up 1 *d* = −0.66 − 0.67% Test (Repeated sprint test. 30 m sprint)
Lovell et al. [32]	20 ± 1	10♂	Semi-professional male soccer players	Re Warm Up1: rest (control) Re Warm Up2: 9′ rest + 5′ Intermittent Agility Exercise Re Warm Up3: 9′ rest+5′ Whole Body vibration at 40 Hz	Counterbalanced Crossover design.	Re Warm Up2 > Re Warm Up 1 Test (CMJ)	Re Warm Up2 > Re Warm Up1 Test (10 m sprint)
Edholm et al. [15]	Range 18–33	22♂	Twenty-two male professional soccer players	Re Warm Up1: traditional half-time break Re Warm Up2: 7′ rest + 7′: jog and calisthenics	Crossover design.	Re Warm Up2 > Re Warm Up1 *d* = 0.29 3.02% Test (CMJ)	Re Warm Up2 > Re Warm Up1 *d* = −0.72 − 2.02% Test (10 m sprint)
Fashioni, Langley & Page [31]	23 ± 4	10♂	Male Amateur Soccer Players	Control Trial: 15-min Half Time Passive Re Warm Up Trial: 12 min + 3 min Re Warm Up.	Cross-over design.	Re Warm Up improvement in squat (d = 0.6; CON: 26.96 ± 5.00 CM; RWU: 30.17 ± 5.13) II) CMJ = (d = 07; CON: 28.15 ± 4.72 CM; RWU: 31.53 ± 5.43) Test (CMJ and AJ)	Re Warm Up improvement in 20 m sprint times. (d = 0.6; CON: 3.42 ± 0.20 S; RWU: 3.32 ± 0.12). Test (5 m, 10 m and 20 m sprint)

Characteristics of individual studies

The characteristics of the included studies and details of the RWU protocols can be found in Table 3.

Three out of the four studies followed a cross-over design [15, 31, 32], and the other one was a randomized parallel-groups study [9]. Regarding the participants, all studies were performed with male soccer players [9, 15, 31, 32]. The level of participants was amateur in two studies [9, 32], whereas one study included semi-professional players [15], and the other one involved professional players [31]. In addition, sample sizes varied from 10 participants [15, 32] to 22 participants [31]. The parallel-group study included 16 participants (eight in each group) [9]. Lastly, concerning the studies' RWU protocols, all studies employed a traditional RWU during the 15-min resting period between match halves while approaching the active RWU (7' rest + 7' jog + exercises at 135 beats/min [9], 9' rest + 5' intermittent agility exercises [15], 7′ rest + 7' jog and calisthenics [31] and 12' + 3' RWU [32]).

Sprint time was measured in all studies [9, 15, 31, 32], through repeated sprint test, 30 m [9], 10 m sprint [15, 32], and 5 m, 10 m and 20 m sprint [31]. Non-significant effects of RWU were found on 30 m sprint [9]. In fact, positive effects of RWU were found on 10 m sprint [15, 32]. Last, 20 m sprint improved after RWU, but non-significant effects were found on 5 m and 10 m [31].

Vertical jump height was assessed with CMJ [15, 31, 32] and squat jump (SJ) [31]. Significant positive effects of RWU protocols were found on CMJ [15, 31, 32] and SJ [31].

Effects of re-warm-up on vertical jump height

Three studies provided data for vertical jump height (pooled n = 104). Compared to a control condition, there was a moderate effect of RWU

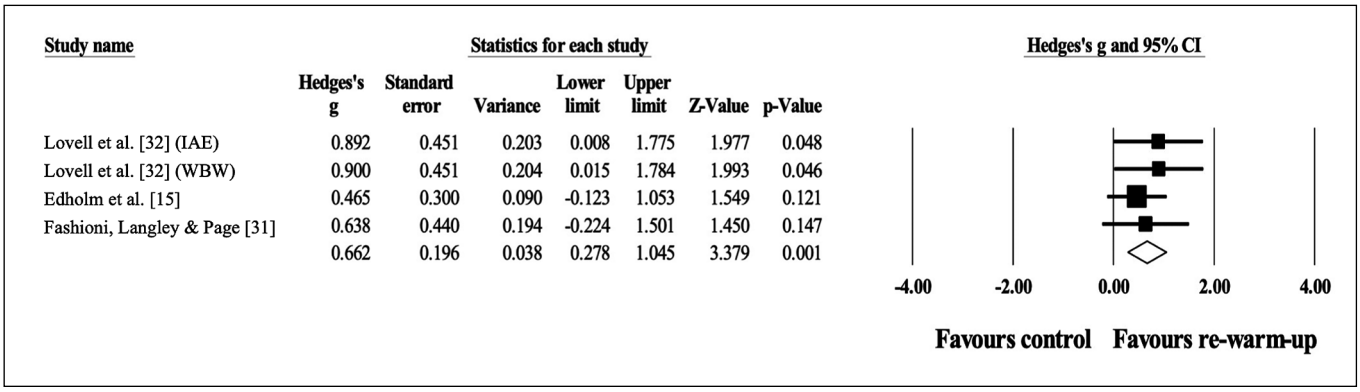


FIG. 2. Forest plot of effects of re-warm-up on vertical jump height compared to a control condition.

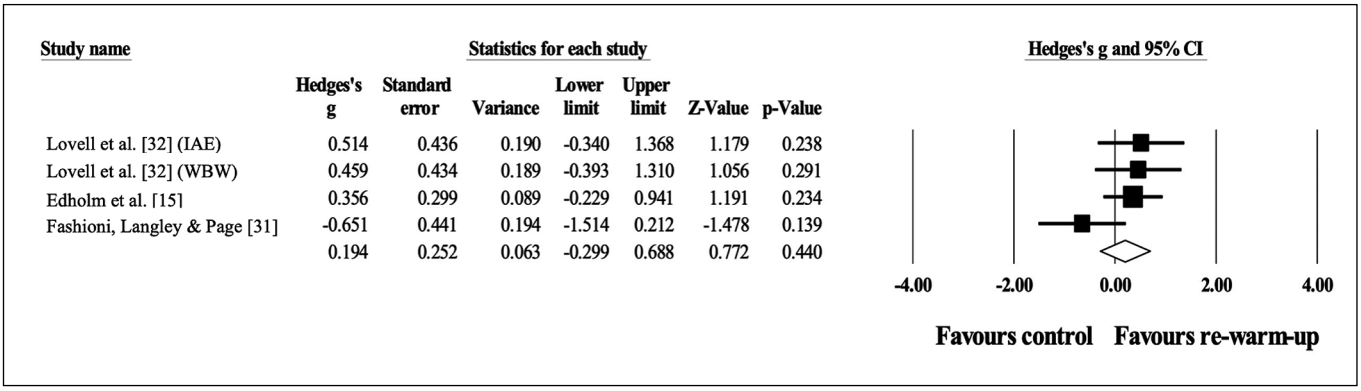


FIG. 3. Forest plot of effects of re-warm-up on sprint time compared to a control condition.

on vertical jump height with no heterogeneity (ES = 0.66; 95% CI = 0.28 to 1.05; $p = 0.001$; $I^2 = 0.0\%$; Egger's test $p = 0.098$; Figure 2). The weight used in each study in the analysis ranged from 18.8% to 42.5%.

Effects of re-warm-up on sprint time

Three studies provided data for linear sprint time (pooled n = 104). Compared to a control condition, there was a trivial effect of RWU on linear sprint time with moderate heterogeneity (ES = 0.19; 95% CI = -0.30 to 0.69; p = 0.440; $I^2 = 38.4\%$; Egger's test p = 0.692; Figure 3). The relative weight of each study in the analysis ranged from 21.8% to 34.0%.

DISCUSSION

The aim of this systematic review with meta-analysis was to determine the effects of RWU protocols on the vertical jump height and sprinting performance of soccer players. The meta-analysis revealed a significant and moderate beneficial effect of RWU on players' vertical jump height, although no significant benefits were found in sprinting performance.

Effects of RWU on vertical jump height

Traditionally, the countermovement jump (CMJ) has been explored in different ways (See Morin et al., 2019 for more information [33]), namely as a physical quality associated with lower-limb power [34] and as a readiness marker to detect the influence of fatigue on neuromuscular properties [35]. In the case of soccer, CMJ has also been confirmed as a determinant of other qualities such as sprinting or change of direction [36, 37]. Since CMJ is dependent on the recruitment of higher-order motor units, potentiation mechanisms, and/or muscle activation [38, 39], it can be expected that warming up plays an important role in immediate performance maximization.

The meta-analysis presented in this systematic review revealed moderate and significant beneficial effects of RWU protocols on CMJ. These changes were identified using the p-value and effect size. However, in a practical scenario, it would be necessary to analyse the raw data for the smallest worthwhile change. However, in this particular review, we did not have access to the raw data of included articles, which justifies the option for using the p-value and effect size to sustain the evidence of the beneficial effects of RWU on CMJ. Although the protocols of exposure to RWU were generally based on RAMP (raise, activate, mobilize, and potentiate), the effects were

large enough to signify the importance of using RWU to preserve players' jumping performance immediately before the match re-start. Although post-activation potentiation using heavy loads appears to represent a better neuromuscular stimulus for enhancing vertical jump [40], the protocols consisting of running, dynamic stretching, and straight sprinting [15, 31]; intermittent agility exercises [32]; or whole-body vibrations [32] had a favourable effect on the reduction the decremental effects of rest on vertical jump performance.

It is reasonable to hypothesize that elevated muscle temperatures improve the recruitment of motor units, possibly justifying the beneficial effects of RWU [15]. Additionally, considering that meaningful decreases in eccentric hamstring strength can be observed after inactivity during half-time [32], a re-activation before the second half of a match is also recommended to enhance vertical jump height, which requires the potentiation of muscles to increase players' performance.

Effects of RWU on sprint time

Sprinting is one of the most important high-intensity demands in soccer. Although it rarely occurs during matches [41], this action is crucial since it is related to decisive moments of matches that precede goal-scoring opportunities [42]. Usually, sprints last 2–4 s over distances shorter than 20 m [43]. Since sprinting performance depends on neuromuscular readiness and neural activation [44], the proper physiological conditions (e.g., induced by warming up) should be ensured [45]. Warming up is expected to immediately benefit sprinting performance, considering that it plays an important role in fully activating the working musculature and recruiting motoneurons to support the high magnitude of contractions [9, 46]. Considering that the half-time break presents a long period of rest/inactivity, it can induce a drop in muscle temperature (~1.5°C), thus negatively impacting sprinting performance [9].

The meta-analysis conducted in the current systematic review revealed a trivial and non-significant beneficial effect of RWU on sprinting performance. Among the included studies, Lovell et al. [32] and Edholm et al. [15] reported a beneficial and significant effect of RWU strategies in comparison to control conditions. Lovell et al. [32] stated that temperature was higher in the RWU group, possibly contributing to the players' muscle readiness for sprinting. However, neuromuscular facilitation caused by reflex potentiation could be another physiological cause of this benefit of RWU [46]. In a different study, the effects of RWU on sprinting performance were positive immediately after exposure, as well as ten and 15 minutes after exposure. Again, additional factors related to fatigue during the match could have impacted the comparisons [43]. Therefore, the literature provides relevant information about the requirements for high level soccer players and specific details to ensure the stability and solidity of second-half performance.

Generally, the individual studies emphasize the benefits of RWU for mitigating the decline in sprinting performance induced by the half-time rest period. Thus, from a practical point of view, coaches can choose to use a combined approach such as jogging, skipping, dynamic stretching, and straight sprinting [15, 31], or implement intermittent agility exercises [32], or use whole-body vibrations [32], or even selected alternative strategies such as potentiation-post activation based on lifting moderate-to-high loads [47] or short high cycling efforts [48].

Study limitations, future research, and practical implications

This systematic review has some limitations. One is the small number of included articles, which should be considered a limiting factor regarding the generalization of evidence. For example, the impact of heterogeneity (i.e., $I^2 = 0.0\%$) on the vertical jump height results was low. In contrast, a greater impact of heterogeneity (i.e., $I^2 = 38.4\%$) affected the linear sprint time findings. The limited number of studies available for meta-analysis may have magnified the impact of heterogeneity on linear sprint time findings. More high-quality studies, with homogeneous study designs, may help to clarify the potential benefits of RWU for linear sprint time. Another limitation is that only articles written in English were included; thus, some relevant literature may have been excluded. However, the results found are promising regarding the implementation of RWU strategies in soccer players. Eventually, short, moderate-to-high demanding activities should be ensured to maximize the increase in muscle temperature and neuromuscular activation in the shortest time possible, thus saving some time for the recovery during half-time [5].

Future research should consider determining the most adequate and practicable RWU strategies for soccer players, namely by comparing post-activation performance enhancement strategies, RAMP, whole-body vibration, or cycling. Duration of exposure and an analysis of this parameter's impact on the first minutes of the match should also be integrated into future reports. Determining the intensity and identifying thresholds should also be considered, namely for individualizing these strategies. As a consequence, more research is needed on the effects of RWU, as the dose-response effects on individual soccer players need to be better understood in order to achieve the best possible performance.

As example, the time of RWU is critical. As suggested in a study conducted in twelve amateur players comparing the effects of a 10- and 20-minute regular warm-up [49], a detrimental effect of the longer period on the muscular power output was found, followed by excessive thermal discomfort and fatigue. Similar evidence was found in a study comparing 8-, 15- and 25-minute warm-up protocols, in which only the condition of 8 minutes ensured significant improvements in the acceleration ability of soccer players [50]. Thus, considering these examples, time-efficient and optimal RWU strategies should be compared in crossover study designs. However, the saving of time should not compromise the effectiveness of RWU for improving some protective factors such as stabilization, balance, or extremity symmetries. As an example, a study using the regular warm-up of FIFA11+ revealed the potential of this condition for improving

unilateral jumping and dynamic balance and reducing lower limb extremity symmetries in female soccer players [51].

For now, it is possible to argue only that RWU strategies do not cause negative effects in comparison to control conditions and that they have a favourable effect on vertical jump height. For soccer coaching staff, more evidence is needed on the cost-benefit ratio of implementing an RWU in their match routines, eventually considering the extent of benefits to the first high-intensity demands occurring in the re-start of matches.

A practical application of this review is the improvement of substitution decision-making in high-performance matches [52, 53]. In fact, if soccer coaching staff have information about the evidence of RWU, they will be able to make much more effective player changes according to the specific tactics with which they intend to change the dynamics of a match (e.g., which player to send out when their team is trailing by one goal and there are 25 minutes left in the match). In this case, it would be appropriate to put players with high jumping power on the pitch, as this could be beneficial for finishing or heading shots.

In turn, this review provides key information when it comes to signing players and building a balanced squad, as the factors that have been shown to be positive can be taken into account to select the best players for a top-level team.

CONCLUSIONS

The most relevant contribution of this work is that there is a significant and moderate beneficial effect of RWU on vertical jump height, but not on sprinting performance, in soccer players. This information is crucial for soccer coaching staff to improve the performance of their teams. Given the small number of publications found, this research line can be described as emerging, as more studies are needed to consolidate the scientific evidence found.

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Conflicts of interest/Competing interests

The authors declare that they have no conflicts of interest relevant to the content of this review.

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Authorship Contributions

FTGF, HS, AIP and FMC lead the project, established the protocol and wrote and revised the original manuscript. RRC and SGV wrote and revised the original manuscript.

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Crucial workload variables in female-male elite Brazilian Beach Handball: An exploratory factor analysis

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ABSTRACT: This study aimed to identify the most important variables of male and female beach handball workload demands and compare them by sex. A total of 92 elite Brazilian beach handball players (54 male: age 22.1 ± 2.6 years, height 1.8 ± 0.5 m, weight 77.6 ± 13.4 kg; and 38 female: age 24.4 ± 5.5 years, height 1.7 ± 0.5 m, weight 67.5 ± 6.5 kg) were analyzed in 24 official matches during a four-day congested tournament. From 250 variables measured by the inertial measurement unit, fourteen were extracted for analysis using Principal Component Analysis as selection criteria. Five Principal Components (PC) were extracted that explained 81.2–82.8% of total variance (overview of workload demands during beach handball). Specifically, 36.2–39.3% was explained by PC1 ($Distance_{Expl,}$ Distance, $Distance_{4–7\,km/h}$, and Acc), 15–18% by PC2 (Acc_{Max}, $Acc_{3–4\,m/s}$, $Dec_{4–3\,m/s}$), 10.7–12.9% by PC3 ($Jumps_{Avg}$ Take-Off, $Jumps_{Avg}$ Landing and PL_{RT}), 8–9.4% by PC4 (Distance $_{> 18.1\,km/h}$, $Speed_{Max}$), and 6.7–7.7% by PC5 (HR_{Avg} and Step Balance). Sex-related differences were found in the PC distribution of variables, as well as in selected variables (HR_{Avg}, $Dec_{4–3\,m/s}$, $Acc_{3–4\,m/s}$, $Jumps_{Avg}$ Take-Off, $Jumps_{Avg}$ Landing, $Acc_{Max,}$ Distance, $Distance_{4–7\,km/h}$, Acc, $Speed_{Max}$) with higher values in male players ($p < .05$). In conclusion, the sex-related PC distribution and workload demands in beach handball should consider for training design and injury prevention programs.

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INTRODUCTION

Beach handball is a recently-created sport, which was developed from handball, and has become a popular discipline with the support from International to Regional Handball Federations [1]. The match consists of two sets of 10-minute where the draw results is resolved with a shoot-out to determine the winning team. Beach handball is practiced in sand surface with specific rules in order to be more spectacular and safer than indoor handball [2]. During the game, players have a specialized role (attack or defense), substitutions are made throughout the lateral band continuously during the game, and a double score for goals scored with 360º throwing, during flights, or by an attacking player dressed as a goalkeeper (specialist) are allowed [1]. These special characteristics do beach handball very attractive, unpredictable, and spectacular sport due to the multiple offensive technical possibilities [3].

The beach handball game model is cyclic, and composed by two alternative phases: (a) ball possession, where the attacking system is structured with numerical superiority due to the substitution of defensive players by offensive ones, and the substitution of the goalkeeper (gk) by the specialist (4 vs 3 + gk); and (b) turnovers, where the defensive system is structured with numerical inferiority, due to the substitution of offensive players by defensive players, and the specialist by the goalkeeper (3 + gk vs 4) [4]. In beach handball, the numerical superiority of the attacking team facilitates successive counterattacks, requiring a physical demand, characterized by fast-paced actions in which the two teams pass a ball with the aim of scoring goals [1]. During the game, a combination of high-intensity efforts (e.g. accelerations with short recoveries) are distributed along the

match duration [5]. As a result, players are exposed to intermittent demands of high- and low intensities, where appropriate levels of speed, sprint ability, strength, and power are required [1, 6]. Therefore, knowing the physical and physiological requirements is necessary for the adaptation of training sessions to competitive demands [5].

Numerous studies have been carried out to analyze workload demands in indoor handball through the use of inertial and tracking devices [7–9]. However, to date, beach handball is a relatively new sport and there is a lack of information related to its physical demands [2]. Two previous published studies [1, 6] have showed that players covered a total distance of between 1,000 and 1,200 meters. Most of the displacements are performed at low-intensity (0.5–13 km/h), and with low-intensity impacts (5-6G), demanding a moderate physiological response (71–80% of maximal heart rate [HR_{MAX}]), though internal and external workload demands depends on different contextual factors, such as competitive level, age or sex of the participants.

Indeed, sex-related differences were found in handball and beach handball with greater distance covered by female players, and higher impacts, accelerations, and high-intensity displacements in male players [1, 8]. Specifically in beach handball, female players covered higher total distance ($p = 0.049$, $d = 0.79$) and distance walking ($p < 0.001$, $d = 2.04$) in the first half, whereas in the second half females covered higher distance standing ($p = 0.008$, $d = 1.05$), obtaining a higher average speed than males ($p < 0.001$, $d = 2.28$) during the match. The number of accelerations distributed over different intensity categories (i.e. low-, moderate-, and high-intensity) was 43.2 ± 11.6, 9.4 ± 4.9, 0.8 ± 0.9 actions for male players, and 40.3 ± 12.7, 4.3 ± 3.0, 0.1 ± 0.3 actions for female ones, which is equivalent to one body acceleration every 23 s and 27 s, respectively [1].

Regarding the internal load variables, male and female players achieved a maximum heart rate (HR_{MAX}) of 173 ± 13, and 177 ± 13 bpm, maintained an average HR (HR_{AVG}) of 137 ± 12 and 138 ± 18 bpm, and spend a 20.3% and 29.2% of the total time in the anaerobic zone (81–90% HR_{MAX}), respectively [1]. In the same way, Gutiérrez-Vargas et al. [6] reported significant differences between male and female players in total distance ($p < 0.01$), average speed ($p < 0.01$), maximum speed ($p = 0.022$), total impacts ($p < 0.01$), body weight change (%) ($p = 0.038$), sweat rate ($p < 0.01$), and fluid intake (ml) ($p < 0.01$). In addition, a significant decrease was found in the maximum speed ($p = 0.05$) and body load ($p = 0.026$) in the second period in both sexes [6]. In this sense, the systematical register and analysis of internal and external workload can provide valuable information to characterize the competition demands and design training session adapted to them [10, 11].

For this systematical register, workload monitoring has become a crucial factor for optimizing players' performance in sport [12]. Since analyzing the specific requirements of each sport modality depends on the different contextual factors that could influence them, different non-invasive tools have been developed to quantify workload demands during the competition [13]. The workload quantification can be performed for internal [14] and external load through time-motion analysis in indoor [15, 16] and outdoor conditions [17, 18], tactical analysis [13], and neuromuscular load through accelerometry [19] in an objective and accurate way. These sensors allow recording of up to 400 variables per match [20, 21]. However, in a practical setting, fast evaluation of training/competition loads is necessary to assess performance and inform exercise prescription [22], and not all variables are decisive [23]. Therefore, variables that are not relevant or are redundant should be excluded from the assessment to provide more meaningful information to the coaches and athletes.

To address this point, different statistical methods have been applied and principal component analysis (PCA) has been shown to be a suitable approach [24, 25]. This method identifies the most relevant information to explain a phenomenon and excludes the components which are not essential to explain performance. The identification of the variables that explains the internal and external workload demands in beach handball could help team staff to reduce the big data provided by the EPTS, as well as a better understanding on physical and physiological requirements during the official games [21, 26]. Therefore, the purposes of the present study are to: (a) identify the variables that explain the variance of internal and external workload of elite-level male and female beach handball players, and (b) analyze the sex-related differences of the registered workload during an official tournament.

MATERIALS AND METHODS

Study Design

A cross-sectional design with natural groups was implemented to analyze locomotion demands of 6 male and 4 female elite Brazilian beach handball clubs during a 4-day congested fixture tournament using an electronic performance and tracking system (EPTS). A total of 24 matches were played in two days (13 male and 11 female matches), with a total of 152 records obtained from players. All matches were played under official rules and judged by federated referees, taking place in the same venue (Praia do Cabo Branco, João Pessoa, Brazil) in a two-court setting. The environmental conditions were substantially similar during the 4-day tournament, according to the Weather Forecasting and Climate Studies Center, from the Brazilian Government. Temperature ranged between 27.8 and 30.4ºC, the air humidity between 64 and 69% and the wind velocity between 2.57 and 3.08 m/s. The sand was uniformized with a squeegee before each game, to minimize possible sand depth differences. A Principal Component Analysis was used to extract the most representative variables to compare the external workload by sex.

Participants

Of a total of 92 players, 54 were male (age 22.1 ± 2.6 years, height $1.8 \text{ m} \pm 0.5 \text{ m}$, weight 77.6 ± 13.4 kg) and 38 females (age

24.4 ± 5.5 years, height 1.7 m ± 0.5 m, weight 67.5 ± 6.5 kg). They were selected from top elite Brazilian beach handball teams. The study was conducted according to the Declaration of Helsinki (World Medical Association, 2013) guidelines. All players were informed of the benefits and possible adverse consequences of participation in the study, and the protocol was approved by the Institutional Review Board of the University Federal of Paraiba (Register code: 02896918.1 .0000.5176).

Instruments and procedures

Time-motion variables were assessed using EPTS (WIMUPRO™, RealTrack Systems, Almeria, Spain) with a Ultra-Wide Band (UWB) radiofrequency tracking system. Participants were equipped with the EPTS 15-min prior to warm-up and asked to wear it during the matches at the height of the 2nd to 4th thoracic vertebrae using a special vest.

IMUs were calibrated following recent research criteria [27]. All data were measured using a sampling frequency of 18 Hz for positioning and 100 Hz for accelerometry-based variables. The accuracy and reliability of the system have previously been reported in different conditions [28].

As all matches were performed in the same venue, a six antennae UWB system setting was used to cover two side to side courts as shown in figure 1. Antennae were positioned 3.5-m from the floor and metallic material was avoided around the system. The antennae were fixed 4.5–5.5 m from the perimeter of the court in order to form a hexagon shape for better emission and reception of the signal, as shown in figure 1.

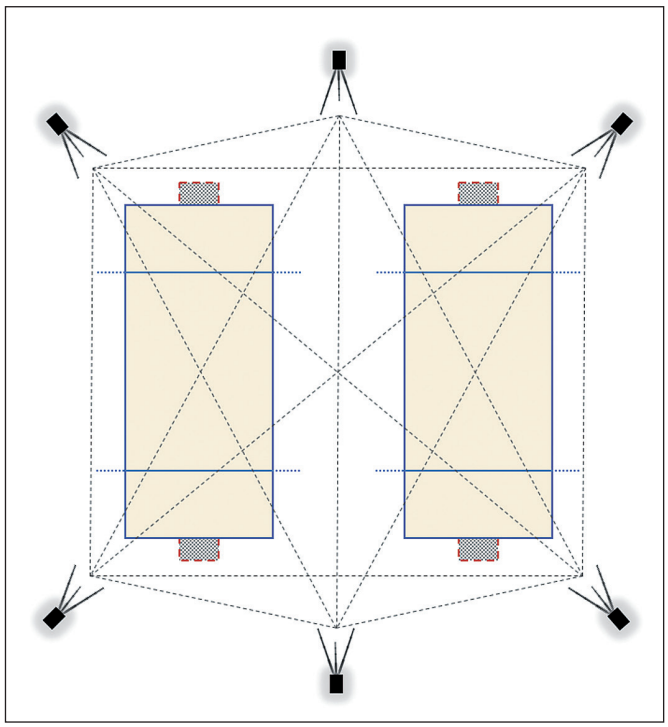


FIG. 1. Ultra-Wide Band setting in a two-court beach handball scenario.

All the data obtained from the matches were downloaded and exported immediately after each match finished using proprietary software (SPRO, RealTrack Systems, Almeria, Spain). The criterion to include players in the statistical analysis was participation in > 60% (> 12 min) of total playing time. All break pauses were considered in the analysis (e.g., ball out, fouls, free-throws, and others) in order to explore natural match behavior in an ecological manner, as adopted in other team sport studies [25]. Considering beach handball substitution particularities [8, 9], the software was programmed to automatically identify who was playing and which player was "on the bench". The software allows the court lines to be pre-set and delimited as well as identification of who is playing and who is resting outside the court (substitutes). In addition, goalkeepers were excluded from the study due to workload demands and technical-tactical actions differ to court players [29, 30].

Due to these particularities in substitution and changes in the position between players during the game, only relative variables expressed relative to time (e.g., relative distance, accelerations per min) and maximum values of a variable were included in the analysis. Considering these potential individual and peer differences by period, positioning and other situational variables there were no discrimination in the inclusion of one-person multiple data from different matches. The limits stablished by Pueo et al. [1] for distance (0–0.4; 0.5–4; 4.1–7; 7.1–13; 13.1–18; > 18.1 km/h), acceleration and deceleration (1–2, 2–3, > 3 m/s^2), impacts (5–6, 6–6.5, 6.5–7, 7–8, 8–10, > 10 g) and heart rate (< 60%, 61–70%, 71–80%, 81–90%, 91–95%, > 95% HR_{MAX}) were utilized. In addition, the acceleration and deceleration zones 3–4, 4–5, 5–6, 6–7, 7–8, 8–9, 9–10 and > 10 m/s^2 were included in the analysis. After PCA analysis, the fourteen variables extracted were: explosive distance as the distance covered at over 16 km/h ($Distance_{Expl}$, m/min), total distance covered per min (Distance, m/min), distance covered at 4.1–7 km/h ($Distance_{4.1–7\,km/h}$, m/min), distance covered over 18.1 km/h ($Distance_{>18.1\,km/h}$, m/min), total accelerations per min (Acc, n/min), maximum acceleration (Acc_{Max}, m/s), accelerations made between 3 and 4 m/s per min ($Acc_{3–4\,m/s}$, n/min), decelerations made between 4 and 3 m/s per min ($Dec_{4–3\,m/s}$, n/min), average g-force in the take-off ($Jumps_{Avg}$ Take-Off, g), average g-force when landing ($Jumps_{Avg}$ Landing, g), maximum speed ($Speed_{Max}$, km/h), average heart rate (HR_{Avg}, bpm), step balance percentage that determines the difference between left and right steps (Step Balance, %), and RealTrack player load per min that represented the accelerometry workload in the three planes of movement and was calculated according to Reche-Soto et al. (PL_{RT}, a.u./min) [31].

Statistical analysis

All the variables were reported using the mean and standard deviation. The procedure followed before and after the Principal Component Analysis (PCA) was developed according to previous similar papers

TABLE 1. Results of principal components analysis (orthogonal rotation) with % variance explained by sex

Variable	Men							Women							General					
	M ± SD (LL; UL)	Loading					M ± SD (LL; UL)	Loading					M ± SD (LL; UL)	Loading						
		PC1	PC2	PC3	PC4	PC5		PC1	PC2	PC3	PC4	PC5		PC1	PC2	PC3	PC4	PC5
Eigenvalue		5.8	2.4	1.6	1.4	1.1		5.4	2.7	1.9	1.3	1		5.9	2.2	1.8	1.2	1
%Variance		38.4	16.3	10.7	9.4	7.7		36.2	18	12.9	9.1	6.7		39.3	15	12.2	8	6.7
%Cumulative variance		38.4	54.7	65.4	74.8	82.4		36.2	54.1	67	76.1	82.8		39.3	54.3	66.5	74.6	81.2
$Distance_{Expl}$ (m/min)	4.4 ± 1.9 (0.1; 9.1)	0.62					2.9 ± 1.5 (0.1; 6.1)	0.72					3.6 ± 1.9 (0.1; 9.1)	0.72				
Distance (m/min)	37.7 ± 12.5 (4.1; 57.2)	0.91					28.3 ± 12.6 (4.8; 52.5)	0.92					32.7 ± 13.3 (4.1; 57.2)	0.91				
$Distance_{4–7\,km/h}$ (m/min)	11.3 ± 4.1 (0.5; 17.7)	0.88					8.2 ± 4 (0.8; 19.2)	0.87					9.7 ± 4.4 (0.5; 19.2)	0.88				
$Distance_{18–50\,km/h}$ (m/min)	0.1 ± 0.5 (0; 3.6)				0.94		0.2 ± 0.2 (0; 1.1)				0.95		0.2 ± 0.4 (0; 3.6)				0.89	
Acc (n/min)	15.3 ± 3.6 (5; 23)	0.72					13.4 ± 4.6 (2.6; 21.1)	0.79					14.3 ± 4.2 (2.6; 23)	0.8				
Acc_{Max} (m/s)	3.1 ± 0.5 (1.5; 4.2)		0.86				2.8 ± 0.5 (1.4; 3.8)		0.79				3 ± 0.6 (1.4; 4.2)		0.8			
$Acc_{3–4\,m/s}$ (n/min)	0.2 ± 0.3 (0; 1)		0.93				0.1 ± 0.1 (0; 0.5)		0.93				0.1 ± 0.2 (0; 1)		0.93			
$Dec_{4–3\,m/s}$ (n/min)	0.1 ± 0.2 (0; 1.2)		0.87				0.1 ± 0.1 (0; 0.5)		0.93				0.1 ± 0.2 (0; 1.2)		0.89			
$Speed_{Max}$ (km/h)	20.7 ± 8.1 (7.6; 39.1)				0.9		15.8 ± 2.8 (9.6; 28.8)				0.81		18.4 ± 6.6 (7.6; 39.1)				0.78	
HR_{Avg} (bpm)	162.2 ± 23.4 (93; 193)					-0.74	150.1 ± 24.9 (71; 195)	0.79					155.8 ± 24.9 (71; 195)	0.75				
Step Balance (%)	0 ± 0 (-0.2; 0.1)					0.8	0 ± 0 (-0.1; 0.1)					0.97	0 ± 0.1 (-0.2; 0.1)					0.96
$Jumps_{Avg}$ Take-Off (g)	2.8 ± 2.2 (0.8; 13.3)			0.94			1.9 ± 1.7 (0.5; 12.3)			0.89			2.3 ± 2 (0.5; 13.3)			0.92		
$Jumps_{Avg}$ Landing (g)	5.4 ± 2.3 (3; 13.2)			0.8			4.5 ± 1.6 (3.1; 12.2)		0.81				4.9 ± 2 (3; 13.2)			0.8		
PL_{RT} (a.u./min)	1.6 ± 5.1 (0.1; 29.8)			0.93			0.6 ± 1.5 (0.1; 12.7)			0.96			3.7 ± 1.1 (0.1; 29.8)			0.91		

Note. PC: Principal component; M: mean; SD: standard deviation; LL: lower limit; UL: upper limit; DistanceExpl: distance covered at over 16 km/h; Acc: Accelerations; Dec: Decelerations; HR: heart rate; PL: player load.

in sport [23, 25]. Prior to each PCA analysis (three PCA: general, male, and female), from a total of 250 variables, only maximum and relative variables (n = 129) were selected for correlation matrix exploration, and the variables with $r < 0.7$ extracted for PCA [32]. Variables were scaled and centered (Z-Score) and PCAs were suitable considering Kaiser-Meyer-Olkin values (KMO = 0.73–0.803) and when Barlett's Sphericity test was significant ($p < 0.01$) [33]. After PCA, eigenvalues greater than 1 were included for extraction of the respective principal component (PC) [33]. An orthogonal rotation using the VariMax method was used for identification of respective loadings in each PC; only loadings greater than 0.6 were retained for interpretation and the highest loading was reported when a cross loading was identified between PCs.

An independent *t*-test was used to compare the locomotion performance by sex. Cohen's *d* was used to report the magnitude of the differences, qualified as follows: $d < 0.2$ as trivial, $d = 0.2$ as small, $d = 0.5$ as moderate, and $d > 0.8$ as large effect size [34]. Alpha was prior set as $p < 0.05$. Data analysis was performed using the

Statistical Package for the Social Sciences (SPSS, IBM, SPSS Statistics, v.22.0 Chicago, IL, USA) and graphs were made using Prism software (GraphPad Software, San Diego, CA).

RESULTS

After general PCA, five different principal components (PC1, PC2, PC3, PC4, and PC5) were extracted (see table 1), which explained 81.2% of the total data set variance. According to respective loadings, the variables were grouped as follows: PC1 explained 39.3% of variance ($Distance_{Expl,}$ Distance, $Distance_{4–7\,km/h}$, and Acc), PC2 15% (Acc_{Max}, $Acc_{3–4\,m/s}$, $Dec_{4–3\,m/s}$), PC3 12.2% ($Jumps_{Avg}$ Take-Off, $Jumps_{Avg}$ Landing, and PL_{RT}), PC4 8% ($Distance_{>18.1\,km/h}$ and $Speed_{Max}$), and PC5 6.7% (HR_{Avg} and Step Balance).

In men, $Distance_{Expl,}$ Distance, $Distance_{4–7\,km/h}$, and Acc as PC1 explained 38.4% of total variance, Acc_{Max}, $Acc_{3–4\,m/s}$, $Dec_{4–3\,m/s}$ as PC2 explained 16.3%, $Jumps_{Avg}$ Take-Off, $Jumps_{Avg}$ Landing and PL_{RT} as PC3 explained 10.7%, $Distance_{>18.1\,km/h}$ and $Speed_{Max}$ as PC4 explained 9.4%, and HR_{Avg} and step balance as PC5 explained 7.7%. Slightly different distributions of variable loadings were found in women after running PCA, where PC1 explained 36.2% but HR_{Avg} was grouped in this first component, PC2 explained 18% but $Jumps_{Avg}$ Landing was part of this second component, PC3 explained 12.9%, PC4 explained 9.1%, and PC5 with only one variable explained 6.7% of total data set variance.

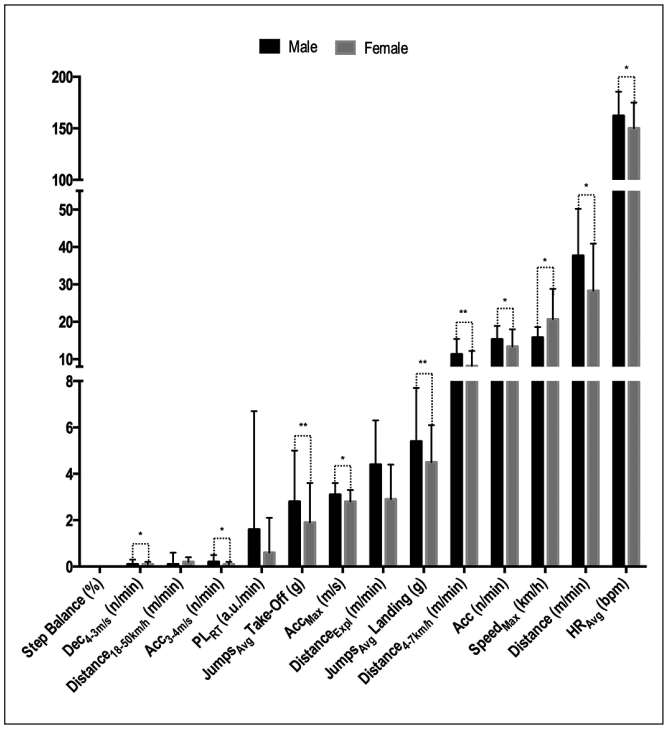


FIG. 2. Sex comparison of extracted external and internal workload variables. Significant differences: **p < 0.05, *p < 0.01.

There were significant sex-related differences in HR_{Avg} (t = 2.62, p < 0.01, d = 0.26 [small]), $Dec_{4–3\,m/s}$ (t = 2.31, p = 0.02, d = 0.24 [small]), $Acc_{3–4\,m/s}$ (t = 3.62, p < 0.01, d = 0.38 [small]), $Jumps_{Avg}$ Take-Off (t = 2.38, p = 0.02, d = 0.24 [small]), $Jumps_{Avg}$ Landing (t = 2.32, p < 0.02, d = 0.24 [small]), Acc_{Max} (t = 3.2, p < 0.01, d = 0.33 [small]), Distance (t = 4.13, p < 0.01, d = 0.43 [small]), $Distance_{4–7\,km/h}$ (t = 4.29, p < 0.01, d = 0.45 [small]), Acc (t = 2.63, p < 0.01, d = 0.27 [small]) and $Speed_{Max}$ (t = -4.35, p < 0.01, d = -0.45 [small]); but no significant differences were found in step balance (t = 0.62, p = 0.54, d = 0.06 [trivial]), $Distance_{>18.1\,km/h}$ (t = -0.51, p = 0.61, d = 0.06 [trivial]), PL_{RT} (t = 1.55, p = 0.12, d = 0.16 [trivial]) or $Distance_{Expl}$ (t = 0.34, p = 0.73, d = 0.04 [trivial]) (see figure 2.).

DISCUSSION

The analysis of specific workloads during competition should be considered in the training planning and recovery protocols to maintain the best physical condition of athletes [12]. Thanks to microtechnology, a large amount of data is obtained, however, in each sport modality it is necessary to select the variables that explain most of the behavior [22]. Through this process, the final report of the evaluation can be concise and rapidly available to team staff to make opportune decisions [21]. Therefore, this study aimed to identify the most important variables of male and female beach handball workload demands and to compare them between sexes. The main results showed that 81.2% of the total data set was explained by five principal components and that sex influenced the workload demands during official matches at elite level.

For the whole sample, five principal components explained 81.2% of the total variance observed. The first principal component is related to volume of demands, both in displacements (Distance, $Distance_{Expl}$, $Distance_{4–7\,km/h}$), changes of speed (Acc), and physiological demands (HR_{Avg}). The beach handball characteristics impose higher energetic and neuromuscular demands at the same running speeds compared to firm surfaces [35, 36]. Although there are many fewer body contacts (hits and pushes) compared to court handball, the players are required to walk/run on the unstable sand surface, and this fact may increase their physical demands.

Different contextual factors could influence the internal workload demands of the beach handball players. One of them is the level of players because Pueo et al. [1] found lower values in men and women players (137 ± 12 and 138 ± 18 bpm) in comparison with the results of the present study (162.2 ± 24.4 and 150.1 ± 24.9 bpm). Other factors previously identified that could influence the internal workload demands are the type of sand and heat stress. Less compact sand and higher values of temperature and humidity modify the heart rate requirements, requiring higher levels [37, 38]. To avoid the between-match effects, the environmental factors were substantially similar during the 4-days tournament (methods section for more details) and the sand was uniformized with an squeegee before each game. Therefore, it could evidence that the level of the players and

environmental factors directly influences the internal load demands during competition. It is important to address the requirements of beach handball players in specific conditions, being reference values for future championships with the same conditions.

The second principal component highlighted in the current study is related to high-intensity changes of speed (Acc_{Max}, $Acc_{3–4\,m/s}$, $Dec_{4–3\,m/s}$). In beach handball, the distances traveled while sprinting are shorter than on the court, since there is up to 15-m to run between the lines demarcating the goal areas. The high-intensity changes in speed (15%) are related to the game dynamics designed to perform counterattacks continuously, as well as having great influence on the decision-making ability of the athlete [30]. Thus, as a consequence, the acceleration speed on a sand surface needs to be addressed in ecological situations as it may be considered an important determinant of player´s capacity.

The third component observed is related to jump capacity and neuromuscular load ($Jumps_{Avg}$ Take-Off, $Jumps_{Avg}$ Landing and PL_{RT}). In the same way as changes in speed, jumps represent high importance in the locomotion demands in the game (12.2%) due to the double score for goals scored in flight or 360º [3]. Considering that landing following jumps produce high loads for athletes, being associated with injuries and overuse conditions [39], and landing was highlighted as a PC in the current study, future studies should further explore this variable and its impact on athletes' performance.

The fourth principal component, which explains 8% of the variance, is related to maximum intensity displacements ($Speed_{Max}$ and $Distance_{>\,18.1\,km/h}$). Due to the smaller beach handball playing space, the 15-meter "valid" court depth does not allow players to develop maximum speed [40]. This component has a low explanation in beach handball athlete performance compared with other sports with large dimensions, such as basketball (22.3%) [25] or soccer (36.2%) [23]. Therefore, it is important to focus training on the physical qualities of beach handball players related to competition demands.

Finally, the fifth component is related to step balance. This principal component analysis could be explained by the unstable surface where matches are played, and the large number of accelerations and decelerations performed in competition matches that explain 6% of beach handball behavior.

When analyzing male and female principal components, no differences were found between sexes. This fact could indicate that the game dynamics and key factors that explained the beach handball behavior are similar in both sexes. Instead, men performed greater demands in all external and internal workload demands, except in $Speed_{Max}$. Considering that male athletes are more effective when throwing, it is assumed that female matches are characterized by a greater number of counter-attack situations, which may increase their maximal speed performance during the match. Investigations in elite handball players showed similar results in both sexes related to the volume of displacements and actions, with higher demands for high-intensity actions in male compared to female beach handball players (high intensity impacts, collisions, and high-intensity accelerations and decelerations) [1, 40].

In the same way, these results were also confirmed in semiprofessional handball players in Costa Rica [6]. In this tournament, male players obtained higher values than female players in total distance, average speed, maximum speed, and total impacts. Therefore, although the variables that explain the performance in beach handball in women and men are similar, a difference in workload demands between sexes was found in the greater intensity of the actions performed by men.

To the best of the authors' knowledge, only three previous studies have analyzed the principal components related to external demands. These studies stated that explained variance is a combination of high-intensity actions, speed changes, jumps, and impacts in basketball and soccer [25, 41, 42]. Therefore, although basketball, soccer, and beach handball are all invasion team sports, their structures provoke that the explained variance of external workload variables obtained by PCA analysis differs between them. Based on the foregoing, and on the principle of specificity and individuality, it is essential to understand that each sport and team could have their own PCA results [21]. The evidence collected in this study is a key point parameter for the behavior of external load in elite handball competitions and is essential to consider for the design of training programs and recovery processes in beach handball players.

Limitations

The predominant strength of the present study is the use of a PCA approach based on the objectively and validated measurement of several internal and external variables to predict the workload of male and female elite beach handball players during matches. Nonetheless, our study has limitations that should be highlighted. No prior published studies were found which investigated elite beach handball players, making direct comparisons with other studies difficult. This clearly highlights the need for further examinations of the compositional nature of internal and external variables across several training demands and geographic locations. Moreover, assessments were performed over a tournament period, in which athlete´s performance could be affected depending on the match demands, as well as between 10-minutes sets and attack-defense team formation that cannot be analyzed due to data was facilitated by the tournament organizers. For these reasons, future research could explore the effect of sets, attack-defense team formation and effect of fatigue throughout the tournament to help the understanding of beach handball workload dynamics due to their influence in other team sports [31, 43, 44], as well as include technical-tactical indexes (e.g. throw or pass efficacy, type of goal scored, etc.) in principal component analysis to provide a global vision of performance in beach handball players [26]. Nonetheless, this could be a strong point, as all participants were high-level players.

CONCLUSIONS

Five principal components were extracted that explain the internal and external workload profile of elite beach handball players (PC1: $Distance_{Expl,}$ Distance, $Distance_{4–7\,km/h}$, and Acc; PC2: Acc_{Max}, $Acc_{3–4\,m/s}$, $Dec_{4–3\,m/s}$; PC3: $Jumps_{Avg}$ Take-Off, $Jumps_{Avg}$ Landing, and PL_{RT}; PC4: Distance $_{>\,18.1\,km/h}$ and $Speed_{Max}$; PC5: HR_{Avg} and Step Balance). The distribution of principal components differs between sexes, while selected variables are similar. In addition, although the variables that explain performance in beach handball are similar between sexes, the higher intensity of actions performed by males must be considered for specific dose-response of internal and external workload during training process.

Practical applications

Due to natural increases in interest in beach handball as an Olympic sport, its internal and external workload demands play an important role for coaches and sports professionals and represent an essential tool to exploit and sustain player technical and tactical qualities throughout the season. Sport scientist, athletes and coaches may understand that internal and external load in beach handball differ between sexes. Principal component analysis is a statistical technic that may help to understand global locomotion behavior in beach handball playing, identifying time-related distance, heart rate and accelerations as fundamental in beach handball physical-physiological load.

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Conflict of Interest Disclosure

None of the authors has a conflict of interest to declare, and all authors were involved in the study design, data collection and interpretation, and contributed to the writing of the manuscript. This manuscript is original and not previously published, nor is it being considered elsewhere until a decision is made as to its acceptability by journal Editorial Review Board.

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Relationships between weekly changes in salivary hormonal responses and load measures during the pre-season phase in professional male basketball players

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ABSTRACT: The aim of this study was to assess the relationships between weekly changes in external and internal load considered separately and jointly and salivary hormonal responses during the pre-season phase in professional male basketball players. Twenty-one professional male basketball players (mean ± standard deviation, age: 26.2 ± 4.9 years; height: 198.7 ± 6.7 cm; body mass: 93.2 ± 10.0 kg) were assessed during 5 weeks of the pre-season phase. External load was measured using microsensors and reported as PlayerLoad (PL) and PL/min. Internal load was calculated using the session rating of perceived exertion scale (sRPE-load), summated heart rate zones (SHRZ) and percentage of maximal heart rate (%HR_{max}). Salivary hormone responses were monitored weekly by measuring testosterone (T), cortisol (C), and their ratio (T:C). The relationships between weekly changes in load measures considered separately and jointly and hormonal responses were assessed using linear mixed model analysis. No significant ($p > 0.05$) relationships were evident between weekly changes in T, C or T:C with external and internal load measures considered separately (R^2-conditional = < 0.001–0.027) or jointly (R^2-conditional = 0.028–0.075). Factors other than measured loads might be responsible for weekly changes in hormonal responses and therefore external and internal load measures cannot be used to anticipate weekly hormonal responses during the pre-season phase in professional basketball players.

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INTRODUCTION

In basketball, the pre-season is a crucial phase during which coaches aim to prescribe optimal loads and a sufficient amount of sport-specific training for their players to obtain the best possible physical condition for the upcoming in-season phase [1–3]. The implementation of the aforementioned goals necessitates having precise control of the training and recovery process to avoid inappropriate loading that may lead to an insufficient physiological or psychological response, too high stress, increased risk of injuries, illnesses, overtraining or overreaching [4, 5]. Therefore, the prescription of appropriate loads and recovery interventions seems to be a key factor of the pre-season phase, thus emphasizing the importance of systematically monitoring the load sustained by the basketball players.

Load monitoring in basketball can be categorized as measures of external and internal load [5, 6]. External load is described as the imposed physical load, stimuli or dose, while internal load is considered as the physiological, psychological or perceptive response [5, 6]. Previously, the dose-response relationship between load measures during the pre-season and the in-season phases in semi-professional male basketball players has been investigated [6]. The findings revealed strong (r = 0.53–0.69) to very strong (r = 0.74–0.88) relationships between external (i.e. PlayerLoad [PL]) and internal (i.e. summated-heart-rate-zones model [SHRZ]; session rating of perceived exertion load [sRPE-load]) load measures, with stronger relationships occurring during training sessions (r = 0.69–0.88) than basketball matches (r = 0.53–0.69) [6]. These findings suggest a better anticipation of internal loads in response to the prescribed external loads and can enhance the possibility to organize properly the training and recovery process.

In addition, the analysis of hormonal responses in basketball has been suggested as fundamental to determine the level of stress and recovery, and in monitoring the risk of overtraining and non-functional overreaching [7]. Specifically, testosterone (T), cortisol (C), and their ratio (T:C) were indicated as useful markers to determine the balance between anabolic and catabolic processes [8], allowing a better understanding of training and recovery processes in basketball to be attained. Increased levels of T were reported to show an appropriate recovery, while decreased levels of T and increased levels of C indicate possible risk of overtraining, non-functional overreaching and reduced performance [9]. Consequently, the comprehension of the influence of changes in load measures on changes in

hormonal responses would help in the process of monitoring basketball players and designing and implementing sound training sessions during the pre-season phase.

Despite the relevance of this topic, only one study has analysed the relationships between changes in hormonal responses and changes in external and internal load measures in semi-professional, male basketball players during the in-season phase [10], with non-significant trivial-to-moderate ($p > 0.05$; $r = -0.01$–0.36) relationships found [10]. Nevertheless, the applicability of these results for professional male basketball players during the pre-season phase is questionable. Indeed, it was previously reported that professional male basketball players usually experience higher loads than do semi-professional male players [1]. Moreover, it was reported that the pre-season phase in male basketball is characterized by higher loads compared to the in-season phase [2]. Thus, in order to determine whether load measures can be used for anticipation of changes in hormone levels in other basketball populations during different phases of the season and specifically during the pre-season phase in professional male basketball players, it is important to assess whether weekly changes in hormonal responses are influenced by weekly changes in external and internal load measures. Therefore, the aim of this study was to assess relationships between weekly changes in external and internal load measures and salivary hormonal responses during the pre-season phase in professional male basketball players.

MATERIALS AND METHODS

Subjects

Twenty-five professional male basketball players from two teams competing in European level leagues (Team 1: FIBA Basketball Champions League, n = 12; Team 2: EuroCup Basketball League, n = 13) were recruited for the initial study sample. Due to attendance of training sessions being lower than 75%, four players (Team 1: n = 2; Team 2: n = 2) were excluded from the analysis and the final study sample consisted of 21 players (mean ± standard deviation [SD], age: 26.2 ± 4.9 years; height: 198.7 ± 6.7 cm; body mass: 93.2 ± 10.0 kg). All investigated players were over 18 years of age and were familiarized with the aims, procedures, requirements, possible risks, and benefits of the study, providing written consent before participating. Ethical approval was obtained from the Kaunas Regional Research Ethics Committee review board (No. BE-2-97).

Design

An observational study took place during 5 weeks of the pre-season phase for Team 1 (2019–2020 FIBA Basketball Champions League; August 16 to September 20, 2019) and Team 2 (2020–2021 EuroCup Basketball League; August 10 to September 13, 2020). Players were familiarized with all study procedures two weeks before the start of data collection. During the monitoring period, internal and external load measures were assessed across 45 training sessions and 6 pre-season matches (5 wins by 20.8 ± 16.6 points; 1 tie match) for Team 1 and 37 training sessions and 5 pre-season matches (3 wins by 35.3 ± 18.2 points; 2 losses by 13.0 ± 15.6 points) for Team 2. An experimental day for saliva collection was selected individually for both teams, considering their day 1 of the pre-season phase. Saliva samples were collected during an experimental day at the beginning of each week of the pre-season phase, and specifically, hormonal responses for Team 1 were monitored every Friday, and for Team 2 every Monday.

Procedures

Salivary analysis were conducted to measure weekly changes in T, C and T:C. To avoid any possible variation due to the circadian rhythm, saliva samples were collected at the same time of the day (17:00) [11]. Players were instructed not to eat, brush their teeth, or consume any drinks other than still water during the 90 min prior to saliva collection [12]. Before collection, players rinsed their mouth with distilled water [13], remained seated for 30 s, then spat all saliva from their mouth. Afterwards, players waited in a seated position for ~10 min before starting collection of the saliva sample by spitting into 15-ml ultrapure polypropylene SaliCap tubes through a polypropylene straw (IBL International, Germany) [14]. Collected saliva samples were stored at –20°C for subsequent analysis. T and C were determined in duplicate using an enzyme-linked immunoassay (IBL International, Germany) following the manufacturer's instructions. The intra-assay coefficient of variation for T and C was 2.35% and 3.14% for Team 1, and 2.51% and 3.22% for Team 2, respectively.

To assess external load during training sessions and matches, PlayerLoad (PL) and PlayerLoad per minute (PL/min) were measured using triaxial accelerometers ClearSky T6 (Catapult Innovations, Melbourne, Australia) sampling at 100 Hz to calculate instantaneous movement demands (in arbitrary units, AU) [6]. PL is a modified vector magnitude determined as the square root of the sum of the squared instantaneous rate of change in acceleration across three motion planes [6]. Data were processed using OpenField software (version 1.18, Catapult Innovations, Melbourne, Australia) and downloaded for statistical analysis.

The session rating of perceived exertion method (sRPE) was used for the assessment of internal load measures as previously used in basketball [15–17]. Approximately 30 min after each investigated training session or pre-season match, players were asked to rate their sRPE in the absence of peers using the modified Borg 10-point RPE scale (CR-10) [18] via cloud-based software (Google Docs, Microsoft, California, USA). Participants' compliance was 93% for both Team 1 and Team 2. Players' sRPE values and the total duration (min) of each investigated training session or pre-season match (including warm-up, breaks, and stoppage time in play) were used to calculate sRPE load (sRPE-load), using the following formula: sRPE-load = sRPE × total duration (min) [18].

Internal load was monitored using heart rate (HR) collected using Polar HR sensors and straps (Polar H10, Polar Electro, Kempele, Finland) at a sampling rate of 1 s, and with data downloaded and

processed using OpenField software. The summated-heart-rate-zones model (SHRZ) was then calculated as: SHRZ (AU) = (duration in zone 1 × 1) + (duration in zone 2 × 2) + (duration in zone 3 × 3) + (duration in zone 4 × 4) + (duration in zone 5 × 5), where zone 1 = 50%–59.9% of maximum HR (HR_{max}), Zone 2 = 60%–69.9% HR_{max}, Zone 3 = 70%–79.9% HR_{max}, Zone 4 = 80–89.9% HR_{max}, Zone 5 = 90–100% HR_{max}, and duration is time in min) [19]. The average $\%HR_{max}$ response was calculated for each training session and match. The HR_{max} was determined as the peak HR response during a 30–15 Intermittent Fitness Test performed prior to the monitoring period on a basketball court and updated using the peak response evident during training or matches if it exceeded that achieved during the testing session [20].

Statistical analysis

Mean and SD were calculated as descriptive statistics. Linear mixed model (LMM) analysis, which has been previously suggested to be suitable to assess the relationship across load measures in team sports [17, 21] was used to assess how weekly changes in different external and internal load measures affect separately (i.e. load measures considered singularly) and jointly (i.e. combining the internal and external load measures) weekly changes in hormonal responses. Weekly changes in T, C and T:C were used as dependent variables, while weekly changes in load measures indicating training volume (PL, sRPE-load and SHRZ) and weekly averaged values of load measures indicating training intensities (PL/min, $\%HR_{max}$) were used as fixed effects. Player was then used as a random effect with a random intercept and fixed slope. An alpha level of $p < 0.05$ was set *a priori* for statistical significance. All data were analysed using Jamovi software (version 1.2.27, 2020).

RESULTS

Descriptive statistics of weekly external and internal load measures and hormonal responses are presented in Table 1. The results of the effect of separate weekly changes in external and internal load measures on weekly changes in hormonal responses are presented in Table 2. The LMM analysis showed no significant effect of weekly changes in load measures on changes in hormonal levels.

The effect of weekly changes in joint load measures on weekly changes in hormonal responses are presented in Table 3. The LMM analysis showed that weekly changes in T, C and T:C responses are not affected by joint weekly changes in PL, PL/min, sRPE-load, $\%HR_{max}$ and SHRZ ($p > 0.05$).

DISCUSSION

This is the first study assessing the effect of separate and joint weekly changes in external (PL, PL/min) and internal (sRPE-load, $\%HR_{max}$, SHRZ) load measures on weekly changes in salivary hormone responses (T, C, T:C) during the pre-season phase in professional male basketball players. The LMM analysis revealed that weekly changes in T, C, and T:C responses are not affected by weekly changes in load measures considered separately or jointly.

The use of salivary markers as a tool to analyse the balance between anabolic and catabolic processes in different basketball training typologies has grown during the last decade [8, 11, 22–26]. High levels of T were characterized as an indicator for optimal recovery, whereas decreased levels of T and increased C concentrations were indicated as markers of overtraining and reduced performance [9]. Understanding whether load measures might play a role as potential predictors of hormonal responses might be important in order to help in the process of monitoring weekly load and

TABLE 1. Descriptive statistics of weekly load measures and hormone concentration.

Dependent variables	Week 1	Week 2	Week 3	Week 4	Week 5
Workload variables					
PlayerLoad™ (AU)	3495 ± 1009	3915 ± 782	3555 ± 706	3469 ± 835	3442 ± 780
PlayerLoad™/min (AU)	3.8 ± 0.6	4.3 ± 0.7	4.6 ± 0.6	4.0 ± 1.1	4.3 ± 0.7
sRPE-load (AU)	4991 ± 1913	5125 ± 811	4870 ± 966	5597 ± 1392	4875 ± 1306
SHRZ (AU)	1412 ± 528	1470 ± 405	1387 ± 303	1415 ± 426	1292 ± 323
$\%HR_{max}$ (%)	61.9 ± 3.9	61.5 ± 3.1	62.4 ± 4.0	60.9 ± 3.8	61.2 ± 3.0
Hormonal responses					
Testosterone (nmol/l)	0.25 ± 0.12	0.32 ± 0.14	0.28 ± 0.17	0.38 ± 0.17	0.39 ± 0.16
Cortisol (nmol/l)	3.49 ± 1.98	3.12 ± 1.54	2.71 ± 1.43	2.90 ± 1.48	2.58 ± 1.03
Testosterone:Cortisol	0.09 ± 0.06	0.14 ± 0.09	0.12 ± 0.08	0.15 ± 0.08	0.17 ± 0.12

Notes. Data presented as mean ± SD. sRPE-load – training load from session rating of perceived exertion scale; SHRZ – summated heart rate zones; $\%HR_{max}$ – average percentage value from attained maximum heart rate.

TABLE 2. The effect of separate weekly changes in external and internal load measures on changes in weekly salivary Testosterone, Cortisol and Testosterone:Cortisol levels.

Dependent variables	AIC	R-squared Conditional	Fixed effects	Estimate (95% CI)	SE	p-value
Testosterone	-70.000	$7.86e^{-4}$	PlayerLoad™	$-4.81e^{-6}$ ($-4.17e^{-5}$, $3.21e^{-5}$)	$188e^{-5}$	0.799
	-70.096	0.002	PlayerLoad™/min	-0.008 (-0.049, 0.032)	0.021	0.679
	-70.812	0.011	sRPE-TL	$-9.76e^{-6}$ ($-3.00e^{-5}$, $1.05e^{-5}$)	$1.03e^{-5}$	0.347
	-70.011	0.001	$\%HR_{max}$	-0.001 (-0.011, 0.010)	0.005	0.768
	-70.067	0.002	SHRZ	$-1.54e^{-5}$ ($-9.49e^{-5}$, $6.42e^{-5}$)	$4.06e^{-5}$	0.706
Cortisol	341.138	0.020	PlayerLoad™	$2.89e^{-4}$ ($-1.49e^{-4}$, $7.27e^{-4}$)	$2.24e^{-4}$	0.199
	342.329	0.006	PlayerLoad™/min	0.168 (-0.313, 0.649)	0.245	0.495
	340.816	0.024	sRPE-TL	$1.75e^{-4}$ ($-6.72e^{-5}$, $4.17e^{-4}$)	$1.23e^{-4}$	0.161
	342.529	0.003	$\%HR_{max}$	-0.029 (-0.142, 0.083)	0.057	0.606
	342.175	0.004	SHRZ	$2.65e^{-4}$ ($-6.88e^{-4}$, 0.001)	$4.86e^{-4}$	0.587
Testosterone: Cortisol	-148.761	0.011	PlayerLoad™	$-1.13e^{-5}$ ($-3.42e^{-5}$, $1.16e^{-5}$)	$1.17e^{-5}$	0.337
	-149.921	0.025	PlayerLoad™/min	-0.018 (-0.043, 0.006)	0.013	0.150
	-150.035	0.027	sRPE-TL	$-9.59e^{-6}$ ($-2.22e^{-5}$, $2.99e^{-6}$)	$6.42e^{-6}$	0.139
	-147.931	0.001	$\%HR_{max}$	$-9.36e^{-4}$ (-0.007, 0.005)	0.003	0.755
	-147.928	0.001	SHRZ	$-7.85e^{-6}$ ($-5.75e^{-5}$, $4.18e^{-5}$)	$2.53e^{-5}$	0.757

Note. AIC – Akaike information criterion; CI – confidence interval; SE – standard error. *Abbreviations*. $\%HR_{max}$ – percentage of maximum heart rate; SHRZ – summated-heart-rate-zones; sRPE-load – session rating of perceived exertion load.

TABLE 3. The effect of joint weekly changes in external and internal load measures on changes in salivary hormonal responses

Dependent variables	AIC	R-squared Conditional	Fixed effects	Estimate (95% CI)	SE	p-value
Testosterone	-64.268	0.028	PlayerLoad™	$3.54e^{-5}$ (-5.523-5, $1.26e^{-4}$)	$4.62e^{-5}$	0.446
			PlayerLoad™/min	-0.023 (-0.098, 0.052)	0.038	0.550
			sRPE-TL	$-2.42e^{-5}$ ($-5.83e^{-5}$, $9.91e^{-6}$)	$1.74e^{-5}$	0.168
			$\%HR_{max}$	$-5.83e^{-4}$ (-0.021, 0.020)	0.011	0.956
			SHRZ	$-1.09e^{-5}$ ($-2.09e^{-4}$, $1.87e^{-4}$)	$1.01e^{-4}$	0.915
Cortisol	347.504	0.039	PlayerLoad™	$-1.84e^{-4}$ (-0.001, $8.91e^{-4}$)	$5.49e^{-4}$	0.738
			PlayerLoad™/min	0.432 (-0.462, 1.325)	0.456	0.346
			sRPE-TL	$1.67e^{-4}$ ($-2.39e^{-4}$, $5.74e^{-4}$)	$2.07e^{-4}$	0.422
			$\%HR_{max}$	-0.080 (-0.324, 0.164)	0.124	0.521
			SHRZ	$4.27e^{-4}$ (-0.002, 0.003)	0.001	0.723
Testosterone: Cortisol	-146.237	0.075	PlayerLoad™	$1.77e^{-5}$ ($-3.73e^{-5}$, $7.26e^{-5}$)	$2.80e^{-5}$	0.530
			PlayerLoad™/min	-0.027 (-0.072, 0.019)	0.023	0.255
			sRPE-TL	$-2.08e^{-5}$ ($-4.15e^{-5}$, $-2.29e^{-9}$)	$1.06e^{-5}$	0.053
			$\%HR_{max}$	$-7.20e^{-4}$ (-0.013, 0.012)	0.006	0.910
			SHRZ	$1.38e^{-5}$ ($-1.07e^{-4}$, $1.34e^{-4}$)	$6.14e^{-5}$	0.823

Note. AIC – Akaike information criterion; CI – confidence interval; SE – standard error. *Abbreviations*. $\%HR_{max}$ – percentage of maximum heart rate; SHRZ – summated-heart-rate-zones; sRPE-load – session rating of perceived exertion load.

consequently planning basketball training sessions. To the best of our knowledge, no previous investigation has assessed whether weekly changes in load measures influence changes in hormonal responses during the pre-season phase in professional male basketball players. Our findings revealed that separate weekly changes in external (PL, PL/min) and internal (sRPE-load, $\%HR_{max}$, SHRZ) load measures have no influence on changes in salivary levels of T, C and T:C. These results are in line with a previous investigation on semi-professional male basketball players monitored during the in-season phase, in which trivial-to-moderate relationships were found between changes in levels of T, C, T:C and various external and internal load measures [10]. Interestingly, these similar outcomes indicate that

during both in-season and pre-season phases and for both levels of competition (i.e. semi-professional and professional players), changes in hormone concentrations and load measures possess a low commonality in basketball. It should be noted that our results are also in line with other studies investigating different sports [27–29]. Indeed, moderate ($p = 0.025$; $r = 0.551$) relationships between internal load (sRPE) and salivary C were found in high-level male and female middle and long-distance runners [27], and non-significant ($p > 0.05$) associations between internal load (sRPE) and weekly C levels were found in elite male Rugby Union players [28]. Moreover, one previous investigation documented no relationships between weekly measures of external and internal load variables and T and C levels in professional football players during the competitive season [29]. Overall, the results demonstrated that factors other than weekly changes in external and internal load measures considered separately are responsible for weekly changes in hormonal responses in team and individual sports athletes.

The second part of our study was designed to investigate whether weekly changes in load measures considered jointly might have an influence on weekly changes in hormonal responses. In fact, basketball players during training periods undergo different combinations of external and internal load measures that should be taken into account during the monitoring process [30]. Therefore, the use of several measures combined can be expected to provide a clearer picture about players' loads during specific training periods, and potentially might affect the hormonal responses. Nevertheless, similarly to the separate responses, no influence of joint weekly changes in external (PL, PL/min) and internal (sRPE-load, $\%HR_{max}$, SHRZ) load measures on weekly changes in T, C and T:C concentrations was found. Therefore, these findings imply that the investigated physical, physiological, and perceptive load measures have no influence on hormonal responses, suggesting that other measures such as psychological factors should be taken into consideration. Indeed, Moreira et al. [25] found an increase in C levels, despite a significant decrease in perceived exertion load (sRPE-load), during a 4-week in-season phase training period in professional male basketball players, suggesting that salivary hormone concentrations increased due to the high psychological stress of the upcoming playoff phase. Moreover, two review articles indicated that both acute and chronic hormonal responses to training are influenced by physiological (e.g. heart rate, oxygen consumption) and psychological (e.g. self-confidence, pressure) factors [5, 31]. Physiological, psychological, and behavioural stressors of sports training were indicated as the main factors activating or inhibiting the release of T and C [31]. Therefore, a possible explanation of our findings might be that changes in T, C and T:C levels are influenced by a combination of factors other than commonly used external and internal load measures, indicating that measures of hormonal responses might provide an additional insight about players' responses to the pre-season phase training. Overall, separately or jointly considered factors influencing changes in T, C and T:C levels remain unclear, requiring more investigations to reveal factors having an impact on changes in salivary hormonal levels during training periods in basketball.

Our investigation provides innovative and useful findings for basketball coaches and sports scientists, but there are some limiting factors that should be considered. Firstly, the investigated players participated in data collection after the off-season, in which their load was not monitored, making it difficult to compare the initial fitness level and adaptation progress in relation to its capacity between players, which might influence different internal and hormonal responses during the pre-season phase. Secondly, only external (PL, PL/min) and internal (sRPE-load, $\%HR_{max}$, SHRZ) load measures were included in the analysis, while other physiological and psychological factors, or changes in players' well-being, might be influencing changes in hormonal responses. Therefore, further research to analyse the effect of separate and joint weekly changes in other measures on changes in hormonal responses in professional male basketball players is required.

The findings of the current investigation provide some interesting practical recommendations. Firstly, basketball coaches and scientists should be aware that weekly changes in hormonal responses during the pre-season phase in professional male basketball players are independent from the separate and joint weekly changes in external and internal load measures. Therefore, changes in hormonal responses cannot be anticipated by load measures, and to have a full picture of players' responses to load, salivary analysis should be included in the process of monitoring basketball players as a separate monitoring tool.

CONCLUSIONS

The current investigation did not detect a significant relationship between separate and joint weekly changes in external and internal load measures and weekly changes in T, C and T:C during the pre-season phase in professional male basketball players, suggesting that other factors or a combination of them might affect hormonal responses. These results suggest that external and internal load measures cannot be used to anticipate weekly hormonal responses during the pre-season phase in professional male basketball players.

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Declaration of interest

The authors declare that they have no conflict of interest with the content of this original research article.

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Predictors of linear sprint performance in professional football players

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ABSTRACT: The purpose of this study was to analyze the relationship between sprint performance (time), and strength and power capabilities in football players. A total of 33 professional Portuguese football players performed isokinetic strength assessments, countermovement jumps (CMJ), squat jumps (SJ), and 10, 20 and 30 m sprints. Pearson's correlation (*r*) was used to determine the relationships between variables. Concentric knee extensor torque at $180^{\circ} \cdot s^{-1}$ was largely-to-very largely correlated with 10 m (r = -0.726), 20 m (-0.657) and 30 m sprints (r = -0.823). Moderate inverse correlation were observed between CMJ (r = -0.425 and r = -0.405) and SJ height (r = -0.417 and r = -0.430), and 20 m and 30 m sprint performance, respectively. Multiple linear regression combining KEcon $180^{\circ} \cdot s^{-1}$ and KFcon $180^{\circ} \cdot s^{-1}$ demonstrated that the model was significant for predicting 10 m sprint time (F (2, 8) = 5.886; R 2 = 0.595). The model combining SJ, CMJ and KEcon $180^{\circ} \cdot s^{-1}$ was also significant for predicting 20 and 30 m sprint times (F (3, 7) = 2.475; R 2 = 0.515 and F (3, 7) = 5.282; R 2 = 0.562; respectively). In conclusion, peak torque at higher velocities and vertical jump performance correlates significantly with linear sprint performance (time). For practitioners seeking to improve linear sprint performance in football players, evaluation of high speed strength and vertical jump indices should be undertaken.

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INTRODUCTION

Football matches involve activity of varying speeds, with high intensity efforts performed approximately every 60 seconds [1] and accounting for ~10% of total match running. Matches elicit a greater demand on the aerobic system, although, the decisive 'game defining' moments are largely covered through sprint actions that require anaerobic metabolism energy delivery [1]. Previous research suggests that 83% of goals scored in the German Bundesliga were preceded by a powerful action from either the assisting or scoring player [2]. The same study also found that players completed a straight-line sprint before 45% of goals scored in the highest competitive level of German football [2]. Furthermore, coaches and sports scientists seek practical and time-efficient methods to improve top running sprint performance and acceleration capabilities in team sport athletes [3]. Accordingly, determining the important physical characteristics of professional football players will enhance understanding of the underlying determinants that influence their sprint performance.

Actions such as changes of direction, jumping, tackling, accelerating and decelerating [4], require high-force muscular contractions [1]. These activities change every 5 seconds and are carried out around 1300 times per match with ~200 of these actions performed at high or maximum intensity [5]. Therefore, the sprint performance of the movement during competitive match-play is possibly associated with explosive strength and power production, but requires further investigation. To this end, identifying the key power and strength qualities that impact linear sprint performance could help inform individualized training programs that focus on improving the key elements that influence this variable.

Explosive force plays a fundamental role in football [6], which is influenced by the interaction of different morphological and neural factors. These include muscle cross-sectional area, muscle architecture, motor unit recruitment, fibre type distribution, and neuromuscular inhibition [7]. Measurable strength and power variables, such as knee flexor and extensor muscle strength and jumping performance may predict linear sprint performance and allow differentiation between professional and amateur players [8]. Laturco et al. [9] demonstrated that vertical jump ability is significantly associated with linear and curvilinear sprint performance. A separate investigation also found that professional football players possessing higher lower

extremity strength (i.e. maximum isometric knee extensor force and 1RM half squat) demonstrated superior sprint performance at 5 m and 30 m, and countermovement jump height (CMJ) [10]. Similarly, a positive relationship was found between knee extensor force ($240° \cdot s^{-1}$) and 30 m sprint performance in elite football players [6]. Contemporary research suggests that professional players need to significantly increase their strength to obtain slight improvements in certain running-based actions (sprint and change of direction speed) [11], controlling for strength deficits which appear to impair sprinting performance [12]. This may be due to fixture congested contemporary schedules, making it difficult to periodize strength training programmes and apply appropriate loads [13]. Therefore, due to equivocal data on predictors of linear sprint performance, more research is required.

Since the interaction between strength/power and speed is highly complex, further investigation seems warranted encompassing multiple predictor variables (e.g., jump measures and isokinetic measures) in the same multiple hierarchical linear regression models. Therefore, the objective of this study was to evaluate strength and power variables and their relationship with sprint performance (time) in professional players competing in the second highest professional division in Portugal to determine predictors of linear sprint performance.

MATERIALS AND METHODS

Participants

A total of 33 professional male football players from Portugal's second highest football division (LigaPro) participated in the study (age: 26.4 ± 4.8 years, stature: 180.9 ± 6.4 cm and body mass: 77.4 ± 8.4 kg). All participants were informed of the procedures and purpose of the study and their written informed consent was obtained. The study was approved by the Ethics Committee of the University of Coimbra (CE / FCDEF-UC / 00692021) and was carried out in accordance with the Declaration of Helsinki (2013).

Body composition

The bioelectrical impedance measurements were conducted using a valid, segmental, multi-frequency bioelectrical impedance analyzer (InBody770; Biospace, Seoul, Korea). Bioelectrical impedance has been shown to be reliable in both men and women. The intraclass correlation coefficients for body fat percentage (BF) ≥ 0.98, fat mass (FM) ≥ 0.98 and fat free mass (FFM) ≥ 0.99 and with a low standard error of measurement for BF (0.77% –0.99%), FM (0.54–0.87 kg) and FFM (0.58–0.84 kg) and a minimal difference for BF% (2.12% –2.73%), FM (1.49–2.39 kg) and FFM (1.60–2.32 kg). Participants' age, gender and height were initially input by the lead researcher. While participants adopted a standing position with minimal clothing and barefoot, body mass assessments were performed on the scale. The participant then grasped the handles with each hand for the impedance measurements. Total body water (L), fat mass (% and kg), muscle mass (kg), and dominant lower-limb fat (kg) were measured.

Isokinetic strength

Concentric and eccentric peak torque and mean torque (average of 5 repetitions) of the knee extensors and knee flexors were measured using an isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA). The isokinetic dynamometer is widely considered the gold standard of muscle strength testing [14] and possesses high validity and reliability [15]. Dynamometer calibration was performed as per manufacturer guidelines. A 5-min warm-up was performed, which involved participants pedaling between 50 and 60 rpm using a cycle ergometer (814E Monark, Varberg, Sweden) with a resistance corresponding to 2% body mass [16]. Participants were seated and straps were applied across the trunk, pelvis, and thigh to reduce excessive movement artefact. The crank axis of rotation was aligned to the lateral femoral epicondyle of the knee and the cuff on the padded lever arm was placed 5-cm proximal to the malleoli. Before isokinetic assessments, the tested limb remained passive and was weighed at 30° to correct for the effects of gravity [17]. The repetitions were performed through a range of 5–90° (5° close to full extension). A familiarization session was initially undertaken to minimize learning effects (three repetitions). Five repetitions were performed for each movement at angular velocities of 60 and $180° \cdot s^{-1}$. Outputs were analyzed with the *Acknowledge* software version 4.1 (Biopac Systems, Inc., Goleta, CA, USA). Each curve was inspected to consider true isokinetic torques within 95% confidence limits [18].

Countermovement Jump (CMJ) and Squat Jump (SJ)

Countermovement jump (CMJ) and squat jump (SJ) height were measured using a portable optical measurement system (Optojump, Microgate, Bolzano, Italy). The intraclass correlation coefficients (ICC) for this measurement protocol has demonstrated good reliability (ICC = 0.997–0.998). Test-retest reliability of the Optojump system has demonstrated excellent ICCs (0.982 to 0.989), low coefficients of variation (2.7% and 3.98%) and low random error (0.8 and 2.81 cm) [19, 20]. For CMJ, players were instructed to stand with their feet shoulder width apart and maintain hand-to-hip contract to negate the influence of arm swing on jump height. When prompted, participants descended rapidly into a ~60° squat position and immediately jumped vertically with maximum effort landing in the same position as takeoff. The SJ consisted of jumping from a fixed semi-squat position with the hands also placed on the hips. Whilst adopting a standing position, the participants were instructed to flex at the knees to ~90° and jump maximally. The participants had to avoid as much as possible any countermovement, and they were instructed to stop for 2 seconds at each phase. Three maximal efforts were performed for both jumps with 30 seconds passive recovery between jumps; the best score was retained for analyses.

Linear sprint performance (time) 10, 20 and 30 m shuttle

Linear sprint performance (time) was recorded for 10, 20, and 30 m sprint tests. Sprint times were recorded with three pairs of photocells (SpeedTrap II, Brower Timing Systems, Utah, USA). The

TABLE 1. Descriptive statistics and normality test considering age, experience, anthropometry, and body composition for the total sample (n = 33).

variables	units	mean			SD	Shapiro-Wilk	
		value	SEM	95% CI		value	*p*
Chronological age	years	26.4	0.8	(24.7 to 28.1)	4.8	0.957	0.224
Training experience	years	17.7	1.0	(15.7 to 19.7)	5.5	0.938	0.059
Stature	cm	180.9	1.1	(178.6 to 183.2)	1.1	0.972	0.565
Body mass	kg	77.4	1.5	(74.4 to 80.4)	1.5	0.954	0.189
Total body water	L	48.4	0.8	(46.6 to 50.1)	4.9	0.985	0.925
Fat mass	%	14.2	0.5	(13.2 to 15.3)	3.0	0.978	0.751
Fat mass	kg	11.1	0.5	(10.0 to 12.2)	3.0	0.962	0.318
Muscle mass	kg	37.8	0.7	(36.4 to 39.2)	3.9	0.980	0.803
Inbody dominant lower-limb fat	kg	1.66	0.1	(1.52 to 1.81)	0.4	0.945	0.098

Abbreviations: SEM (standard error of the mean); CI (confidence interval); SD (standard deviation).

TABLE 2. Descriptive statistics and normality test considering acceleration, speed/velocity, strength and jumping performance for the total sample (n = 33).

variables	units	mean			SD	Shapiro-Wilk	
		value	SEM	95% CI		value	*p*
Sprint 10 m	s	1.57	0.02	(1.52 to 1.61)	0.13	0.952	0.163
Sprint 20 m	s	2.99	0.03	(2.92 to 3.05)	0.03	0.937	0.063
Sprint 30 m	s	4.55	0.04	(4.46 to 4.63)	0.24	0.973	0.589
Squat jump (SJ)	cm	36.0	0.8	(34.4 to 37.6)	4.4	0.975	0.660
Countermovement jump (CMJ)	cm	37.2	1.0	(35.2 to 39.1)	5.5	0.969	0.483
KE isokinetic eccentric muscular action 60°/s	Nm	254.1	7.4	(238.9 to 269.2)	42.7	0.963	0.321
KF isokinetic concentric muscular action 60°/s	Nm	146.0	4.0	(137.8 to 154.2)	23.1	0.964	0.352
KE isokinetic eccentric muscular action 60°/s	Nm	317.0	13.4	(289.8 to 344.2)	76.7	0.983	0.887
KF isokinetic concentric muscular action 60°/s	Nm	197.4	6.5	(184.1 to 210.8)	37.6	0.957	0.224
KE isokinetic eccentric muscular action 180°/s	Nm	170.5	6.6	(155.6 to 185.3)	22.1	0.967	0.853
KF isokinetic concentric muscular action 180°/s	Nm	110.1	4.0	(101.1 to 119.1)	13.4	0.920	0.315
KE isokinetic eccentric muscular action 180°/s	Nm	285.9	15.2	(257.5 to 312.9)	45.6	0.921	0.404
KF isokinetic concentric muscular action 180°/s	Nm	170.5	7.6	(154.9 to 185.0)	22.7	0.972	0.915

Abbreviations: SEM (standard error of the mean); CI (confidence interval); SD (standard deviation).

TABLE 3. Bivariate correlations between strength and sprint performance.

Variable	units	Linear sprinting (s)					
		10 m		20 m		30 m	
		p	r	*p*	r	*p*	r
Squat jump (SJ) height	cm	0.198	–0.230	0.018	–0.417*	0.014	–0.430*
Countermovement jump (CMJ) height	cm	0.347	–0.169	0.015	–0.425*	0.022	–0.405*
KE isokinetic concentric muscular action 60°/s	Nm	0.895	0.024	0.089	–0.306	0.273	–0.200
KF isokinetic concentric muscular action 60°/s	Nm	0.230	0.215	0.203	–0.231	0.836	–0.038
KE isokinetic eccentric muscular action 60°/s	Nm	0.927	–0.017	0.388	–0.158	0.698	–0.071
KF isokinetic eccentric muscular action 60°/s	Nm	0.735	–0.061	0.472	–0.132	0.682	–0.075
KE isokinetic concentric muscular action 180°/s	Nm	0.011	–0.726*	0.028	–0.657*	0.002	–0.823**
KF isokinetic concentric muscular action 180°/s	Nm	0.014	–0.712*	0.387	–0.290	0.080	–0.549
KE isokinetic eccentric muscular action 180°/s	Nm	0.551	–0.230	0.186	–0.485	0.188	–0.483
KF isokinetic eccentric muscular action 180°/s	Nm	0.109	0.570	0.705	0.148	0.653	–0.175

Abbreviations: BD (bilateral difference); PT (peak torque); T (torque); KE (knee extension); KF (knee flexion). *p < 0.05; **p < 0.001.

TABLE 4. Unstandardized and standardized Beta values for each regression models.

Assessment	Variable	*B*	SE	*ß*
10 m sprint	Constant	2.476	0.261	
	KE isokinetic concentric muscular action 180°/s	–0.003	0.002	–0.440
	KF isokinetic concentric muscular action 180°/s	–0.004	0.003	–0.388
20 m sprint	Constant	4.106	0.521	
	Squat jump (SJ) height	0.019	0.033	0.411
	Countermovement jump (CMJ) height	–0.030	0.032	–0.710
	KE isokinetic concentric muscular action 180°/s	–0.004	0.003	–0.428
30 m sprint	Constant	6.633	0.566	
	Squat jump (SJ) height	–0.021	0.036	–0.330
	Countermovement jump (CMJ) height	0.018	0.035	0.312
	KE isokinetic concentric muscular action 180°/s	–0.011	0.003	–0.858*

* Standardized beta values are significant at the $P < 0.05$ level.

photocells were placed at the start and finish (10, 20 and 30 m mark). The tests were undertaken on natural turf and conditions were standardised between repeated measures. Each sprint was performed from a standing start position and was separated by 30 seconds of active recovery. The best sprints times taken at each distance were used for analyses.

Statistical analysis

Descriptive statistics (mean, standard error of the mean [SEM], 95% confidence interval [CI], and standard deviation [SD]) were carried out, and normality checked with the Shapiro-Wilk test. Two variables displayed non-normal distributions, and subsequently, these data were logarithmically transformed to counter the effects of non-normality. Therefore, for the first stage of data analysis, a two-tailed Pearson's correlation (*r*) was used, with 1000 bootstrap samples. For correlations, the following criteria, whether positive or negative, were used to interpret the magnitude *of r*: < 0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, and very large; 0.9–1.0, almost perfect [21]. All predictors that indicated a moderate (i.e., $r = \geq 0.3$) and significant correlation were kept for further analyses, while all other variables were omitted. Multiple hierarchical linear regressions were used as appropriate with the remaining predictor variables and their dependant variable correlates. Significance and relative contribution of predictors were determined using a combination of standardized Beta values, t-statistics (i.e., the predictor makes a significant contribution to the model), and 95% confidence intervals. Statements were made regarding the magnitude of change in the dependant variables resulting from a 1 SD change (increase or decrease) in the predictor variable. All analyses were performed using the Statistical Package for the Social Sciences version 26.0 (SPSS Inc., IBM Company, Armonk, NY, USA).

RESULTS

Table 1 presents the participants' morphological characteristics. Descriptive statistics for sprints, jump variations and isokinetic strength are presented in Table 2.

Moderate and significant correlations are outlined in Table 3 for four predictor variables (SJ, CMJ height, KEcon and KFcon). The multiple regression model combining KE and KF at 180°/s was found to be significant for predicting 10 m ($F(2, 8) = 5.886$: $p < 0.05$; $R^2 = 0.595$), 20 m ($F(3, 7) = 2.475$: $p = 0.146$; $R^2 = 0.515$) and 30 m sprint times ($F(3, 7) = 5.282$: $p < 0.05$; $R^2 = 0.562$) (Table 4).

DISCUSSION

Based on the notion that linear sprint time is key for success in professional football [2], the main objective of this study was to determine the relationship between linear sprint time and other physical performance predictors in elite football players. Large and very large relationships were found between 10 m sprint time and KEcon and KFcon at $180° \cdot s^{-1}$, 20 m sprint time and SJ, CMJ and KEcon at $180° \cdot s^{-1}$, and 30 m sprint time and SJ, CMJ and KEcon at $180° \cdot s^{-1}$. Multiple regression analysis evaluates the strength of the relationship between the dependent variable and several predictor variables to facilitate robust conclusions. Such data can be utilised by strength and physical conditioning practitioners to adapt training protocols and optomize linear sprint performance in professional football players.

The current findings that knee extensor strength at higher velocities was correlated with sprint speed are consistent with data derived from similar research [6]. This investigation demonstrated that there was a significant relationship between knee extensor peak torque at $240° \cdot s^{-1}$ and 30 m sprint performance. Knee

extensor peak torque is thought to be a key determinant for performing rapid knee extension during the swing phase while sprinting [22]. Sprint performance has also shown to better correlated with knee extensor peak torque at 240°·s^{-1} than the knee flexors [23]. Furthermore, a separate investigation reported stronger correlations with isokinetic knee extension strength with faster velocities (150 and 240°·s^{-1}) versus slower speeds of 60°·s^{-1} [24]. Therefore, it seems that the ability to produce greater knee extensor peak torque at high velocities is a positive factor for sprint performance. As such, knee extensor strength may need to be developed at higher speeds in order for sprint ability to be improved. Future research should assess whether training interventions targetting high velocity knee extensor peak torque translates to improvements in sprint performance.

The SJ and CMJ jump tests showed a moderate inverse correlation with 20 and 30 m sprint performance, but no associations with 10 m sprint performance were identified. These findings are similar to those published in previous studies, suggesting that relative peak power output during the bilateral CMJ is negatively associated with linear sprinting performance over 5, 10, and 20 m in English Premier League football players [25]. The findings are also somewhat analogous with another study evaluating 25 professional football players, with strong and negative correlations between CMJ and 30 m sprint performance, but no relationships with 10 m sprint performance [10]. Therefore, vertical jump height appears to be negatively correlated with sprint performance only at higher distances (i.e., 20 and 30 m). This notion may be related to how the transition from lower to higher speeds results in shorter stance phase duration, with a concomitant increase in maximum vertical force production [26, 27]. This inturn leads to an increase in flight time and stride length [28], but these factors may not have chance to influence sprint time over such short distances [26], perhaps explaining the lack of correlation for 10 m sprint performance. The ability to produce maximum force rapidly is a requirement for explosive jump performance – which is also a prerequisite for rapidly accelerating over short distances and reaching high speeds [10]. These actions are intergral moments in match-play and occur during the decisive phases of play [29]. Therefore, this information is important for practitioners with a training focus geared towards developing linear sprint and acceleration capacity.

The current study provides novel insights into the physical determinants of linear sprint performance in football although, the findings must be considered within the constraints of professional sports. Firstly, there are an absence of measures assessing horizontal jump performance, despite previous research demonstrating that horizontal ground reaction forces are more predominantly involved in top-speed acceleration [30]. Therefore, this must be considered a limitation since horizontal jumping and the associated force vectors may be better predictors of linear sprint performance than solely vertical jump performance and isokinetic strength. Additionally, football players rarely accelerate from a stationary position to maximum speed during matches [31] but are more likely to increase speeds from low-velocity movements. Therefore, the ecological validity of the sprinting mechanics with reference to their translational application in football may be questionable. Further studies should assess the predictive ability of horizontal ground forces across different positional roles in football.

CONCLUSIONS

The results in the present study suggest that strength and power variables at faster speeds are associated with linear sprint performance. Professional football players with greater torque at 180°·s^{-1} had faster sprint times at 10, 20 and 30 m. It is recommended that staff responsible for implementing training regimes should design training protocols that develop knee extensor strength at a higher rate to optimize running performance in professional football players. Another key finding demonstrated that SJ and CMJ are negatively correlated with 20 and 30 m sprint performance. Such relationships between vertical force generation and sprint times indicate that training protocols aimed at increasing lower extremity explosive strength should be incorporated into weekly football microcycles to maximize sprint performance. Future research avenues should explore the predictive capacity of reactive strength markers and horizontal jump indices in football players of different playing levels.

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Institutional Review Board Statement

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of University of Coimbra (code: CE/FCDEF-UC/0069202).

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Conflicts of interest

The authors declare no conflict of interest.

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Influence of game and quarter results on external peak demands during games in under-18 years, male basketball players

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ABSTRACT: To quantify and compare the external peak demands (PD) encountered according to game result (win vs. loss), quarter result (win vs. tie vs. loss), and quarter point difference (± difference in score) in under-18 years (U18), male basketball players. Thirteen basketball players had external load variables monitored across 9 games using local positioning system technology, including distance covered, distance covered in different intensity zones, accelerations, decelerations, and PlayerLoad™. PD were calculated across 30-s, 1-min, and 5-min time windows for each variable. Linear mixed models were used to compare PD for each variable according to game result (win vs. loss), quarter result (win vs tie vs loss), and quarter point difference (high vs. low). External PD were comparable between games that were won and lost for all variables and between quarters that were won and lost for most variables ($p > 0.05$, trivial-small effects). In contrast, players produced higher ($p < 0.05$, small effects) 1-min high-speed running distance and 5-min PlayerLoad™ in quarters that were won compared to quarters that were lost. Additionally, high quarter point differences (7.51 ± 3.75 points) elicited greater ($p < 0.05$, small effects) external PD (30-s PlayerLoad™, 30-s and 5-min decelerations, and 1-min and 5-min high-speed running distance) than low quarter point differences (-2.47 ± 2.67 points). External PD remain consistent (trivial-small effects) regardless of game result, quarter result, and quarter point difference in U18, male basketball players. Accordingly, external PD attained during games may not be a key indicator of team success.

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INTRODUCTION

Recent technological advances such as electronic performance tracking systems (EPTS), including inertial measurement units (e.g. accelerometers and gyroscopes) (IMU) [1, 2] and local positioning systems (LPS) [3] have allowed for basketball players to be monitored during training and games. There are several advantages to using this technology, including the capability to quantify the external loads of several players simultaneously to gather monitoring data efficiently in real time [4]. In this regard, external load is regarded as the physical load performed (e.g., duration, distance), which is determined by the organization, intensity, and quantity of exercise [5].

It is essential to quantify the external loads experienced during games among various samples of basketball players to develop training and recovery plans that are specific to player sex, competition level, and age. Regarding player age, quantifying external game loads among junior basketball players (< 18 years of age [U18]) is of particular interest given the importance of understanding the ratio of competition-to-training demands in optimizing the overall loading placed on young athletes across their development pathway [6]. In this way, external load data reported for U18, international, male basketball players (16.9 ± 1.1 years) show that basketball is an acyclic, high-intensity sport where playing time is mostly (93%) spent standing, walking (< 7 $km \cdot h^{-1}$), or jogging (7–14 $km \cdot h^{-1}$) [3]. These low-intensity movements are interspersed with high-intensity efforts [7, 8], during which players attain their peak demands (PD) [9–11]. Quantifying the external PD encountered by U18 basketball players during games is particularly important given the intensities detected can guide optimal training prescription to best prepare players to cope with most demanding scenarios experienced

during games [12] and to assist these young players in transitioning to adult competitions. External PD are considered the most intense activity periods experienced by basketball players for a selected variable across a specified timeframe of interest [11, 12].

Theoretically, the ability to achieve higher external PD during games could indicate players may be capable of attaining a superior playing pace at key stages across games. In turn, superior playing pace may indicate an ability to outplay opponents from a physical perspective and improve the likelihood of making successful plays, contributing to team success [13]. Alternatively, higher external PD during games may be reflective of game contexts in which a team, that is losing at the time, might elevate playing intensity to improve the score-line. However, it is currently unknown whether the external PD reached during games differentiate team success. Nevertheless, recent evidence exploring the average external intensities completed across entire games demonstrated that players in the bottom four teams completed significantly ($p < 0.05$) higher relative distances ($m \cdot min^{-1}$) than players in the top four teams during games in an U18, European male competition [14]. Similarly, separate research quantifying the average external intensities attained across entire games in adult, semi-professional, male basketball players showed players executed significantly ($p < 0.001$) more high-intensity accelerations per minute during games that were lost compared to won [15]. In turn, research examining external PD during games in adult, semi-professional, male basketball players showed consistent ($p > 0.05$, trivial-small effects) relative PlayerLoad ($AU \cdot min^{-1}$) across 15-s, 30-s, 1-min, 2-min, 3-min, 4-min, and 5-min sampling durations (i.e., peak intensities averaged across different time windows) were achieved between quarters that were won and lost [13]. Consequently, the existing research suggests losing teams likely experience greater average external intensities across games [14, 15], but the intensity of the most demanding game passages are comparable across quarters that are won and lost [13].

However, it should be noted that only one study [13] has quantified and compared external PD between quarters that were won and lost in basketball players. Furthermore, this previous study [13] used PlayerLoad™ as the only variable to quantify external PD, did not consider score-line margins, and examined adult basketball players. Further insight is needed regarding the PD encountered during basketball games according to team success using a wider selection of external load variables and specifically analyzing score-line margins. In this sense, game score-line has been shown to impact coaching substitution strategies [16] and therefore the active playing time of players, as well as team performance evidenced through improved score-line margins across game quarters when in a losing position at the start of the quarter [17]. Furthermore, separate research on this topic is needed in U18 basketball players for the generation of age-specific evidence given U18, male basketball players (16.8 ± 0.6 years) have been shown to cover more total distance ($p < 0.05$, moderate effect) and high-speed running distance > 18 $km \cdot h^{-1}$ ($p < 0.05$, small effect) across 1-min time windows than adult, male basketball players (19.6 ± 1.5 years) within a Euroleague academy setting [18].

Research ascertaining whether external PD differentiate team success across games and individual quarters considering the score-line margin will provide evidence for basketball practitioners to formulate training strategies to optimize player readiness for games and likelihood of team success. Therefore, the aim of this study was to quantify and compare the PD encountered according to game result (win vs. loss), quarter result (win vs. tie vs. loss), and quarter point difference (± difference in scores) across different time windows and external load variables in U18, male basketball players. Based on existing data [13, 14], it was hypothesized that losing teams would experience greater external PD across games and in individual quarters.

MATERIALS AND METHODS

Sample

Male basketball players from the same team competing in the highest regional division of an U18 Spanish basketball competition (n = 13, mean ± standard deviation [SD]: age 16.6 ± 1.0 years, height 197.6 ± 8.0 cm, body mass: 87.8 ± 7.7 kg) were monitored during nine official games played in the same stadium. For inclusion in the study, players had to complete at least 15 min of playing time in at least five of the nine games. Furthermore, to ensure adequate time windows for external PD variables could be calculated in each quarter, data from players who did not complete at least 5 min of playing time in a specific quarter were removed from individual quarter analyses but not entire game analyses. Playing time was classified as the time (min) each player was on the court during games, including stoppages (i.e., free-throws, fouls, out-of-bounds, rule infringements) but excluding warm-up, breaks between quarters, and time-outs. Consequently, three players originally recruited for the study did not meet the inclusion criteria and were excluded from final analyses, resulting in 13 players being retained in the study. Considering entire game analyses, 117 game samples were included in final analyses. Considering individual quarter analyses, 198 quarter samples were excluded due to players not attaining at least 5 min of playing time, resulting in 270 quarters samples across the 13 players remaining in final analyses. This study was conducted in accordance to the Declaration of Helsinki [19] and approved by the Institutional Review Board of the Polytechnic University of Madrid, Spain.

Procedures

This observational investigation was conducted across a 5-month period throughout the 2019–2020 season. Each player wore a device (Vector S7; Catapult Sports, Melbourne, Australia) in a bespoke pocket within a vest positioned on the upper thoracic spine between the scapulae. The devices contained an accelerometer (± 16 g, 100 Hz), magnetometer (± 4,900 μT, 100 Hz), gyroscope (up to 2,000 deg/sec, 100 Hz), and LPS. The ClearSky LPS (ClearSky S7, 10 Hz, firmware version 5.6.; Catapult Sports, Melbourne, Australia) is an

ultra-wide band, 4-GHz transmitting system equipped with 24 anchors positioned around the perimeter of basketball stadium that was used to collect LPS data. The technology used in this study has been supported as valid in measuring distance [20–23], speed, accelerations, decelerations [20, 21], and Player Load™ [24], while similar LPS technology has been shown to be reliable (coefficient of variation (CV) < 5%) in measuring distance and speed variables [23]. All players were familiarized with the monitoring technology, having worn the devices during training and games in the previous season. Each device was turned on ~20–40 min before the warm-up preceding each game. Players wore the same device throughout the study period to avoid inter-device variation in external load data outputs [25, 26].

To determine the external PD, first, the raw data was extracted in 1-s intervals for each player. Data were then exported to a custom-built Microsoft Excel (version 16.0; Microsoft Corporation, Redmond, WA) spreadsheet for further analysis. Data were analyzed across different time windows (30 s, 1 min, and 5 min) using rolling averages to find the peak value for each variable across each duration. This method is commonly applied when determining external PD [27] and has been previously used in several basketball studies [10, 11, 18, 28]. Data were analyzed from the beginning of each quarter to the end of the same quarter, with data across all quarters in the same game collated together for game analyses (i.e., the highest value for each variable across any quarter in a specific game was taken as the PD for that game).

Variables

PD were calculated for several distance variables including total distance (m) covered (TD) and distance (m) covered in different intensity zones including: standing-walking (S-W) ≤ 7 $km \cdot h^{-1}$; jogging (JOG) = 7–14 $km \cdot h^{-1}$'; running (RUN) = 14.01–18 $km \cdot h^{-1}$; and high-speed running (HSR) > 18 $km \cdot h^{-1}$, as previously used in basketball research [3]. Furthermore, accelerations (ACC) (count) performed > 2 $m \cdot s^{-2}$ (dwell time: 0.3 seconds), decelerations (DEC) (count) performed > -2 $m \cdot s^{-2}$ (dwell time: 0.3 s), and PlayerLoad™ (PL) (arbitrary units [AU]) were also measured. These dwell times were chosen given values between 0.3 and 0.4 s have been identified as the most readily used in basketball settings [10, 11, 29].

PL was calculated as the square root of the sum of the instantaneous rate of change in acceleration in the three movement planes (x-, y, and z-axis) using the following formula [11, 12]:

$$PlayerLoad™ = [\sqrt{(a_{y1} - a_{y-1})^2}$$

$$+\sqrt{(a_{x1} - a_{x-1})^2} + \sqrt{(a_{z1} - a_{z-1})^2}]/100$$

where fwd indicates movement in the anterior-posterior direction, side indicates movement in the medial-lateral direction, up indicates vertical movement, and t represents time.

Comparisons according to game result were made between games that were won (8 games, 244 samples) and games that were lost (1 game, 26 samples). Comparisons according to quarter result were made between quarters that were won (24 quarters, 183 samples), quarters that were tied (2 quarters, 14 samples), and quarters that were lost (9 quarters, 73 samples). Additionally, using a two-step cluster analysis for quarter point difference (± difference in score), the sample was split into two groups (average silhouette = 0.7) as shown in Table 1.

TABLE 1. Cluster analysis identifying groups based on quarter point difference during games.

Measure	Low difference	High difference
Quarter point difference	-2.47 ± 2.67	7.51 ± 3.75
Sample size (N)	94	176
Proportion of samples (%)	34.8%	65.2%
Bayesian information criterion	168.47	

Note: Quarter point difference groups presented as mean ± standard deviation for each group; sample size indicates the number of individual quarter samples included across all players.

Statistical analysis

The mean, standard deviation (SD), and coefficient of variation (CV) were determined for each PD variable across each time window and according to each factor (game result, quarter result, and quarter point difference). Linear mixed models (LMM) were used to compare each PD variable according to game result (i.e., win vs. loss), quarter result (win vs tie vs loss), and quarter point difference (i.e., high vs. low) across each time window. In each model, game result, quarter results, or quarter point difference was entered as the fixed term, and participant number was entered as the random term. Levene's equality of variances test was performed to assess for equal variances in the data. Cohen's effect size (ES) and the mean difference with 95% confidence intervals (CI) were determined for all pairwise comparisons and interpreted as: trivial ≤ 0.20; small = 0.20–0.59; moderate = 0.60–1.19; large = 1.20–1.99; and very large ≥ 2.00 [30]. All analyses were conducted using IBM SPSS for Windows (version 23, IBM Corporation, Armonk, New York), except ES, which were calculated using a customized Microsoft Excel spreadsheet (version 16.0, Microsoft Corporation, Redmond, WA).

RESULTS

Descriptive statistics for each variable across each time window according to each factor are presented in Tables 2–4. The estimated effects (ES ± 95% CI) for differences in pairwise comparisons according to each factor are presented in Figures 1–3.

TABLE 2. Descriptive statistics for external peak demand variables according to game result across different time windows.

30-s time window				1-min time window				5-min time window			
Variable	*Result*	*Mean ± SD*	*%CV*	*Variable*	*Result*	*Mean ± SD*	*%CV*	*Variable*	*Result*	*Mean ± SD*	*%CV*
TD (m)	*Win*	80.2 ± 8.7	10.8	**TD (m)**	*Win*	133.7 ± 14.6	10.9	**TD (m)**	*Win*	449.7 ± 69.4	15.4
	Loss	77.5 ± 7.6	9.8		*Loss*	129.3 ± 14.2	10.9		*Loss*	446.6 ± 66.2	14.8
PL (AU)	*Win*	10.4 ± 1.5	14.6	**PL (AU)**	*Win*	17.0 ± 2.6	15.7	**PL (AU)**	*Win*	53.3 ± 10.5	19.7
	Loss	10.1 ± 1.7	17.1		*Loss*	17.0 ± 3.0	18.1		*Loss*	51.1 ± 13.3	26.0
S-W (m)	*Win*	33.2 ± 6.3	18.9	**S-W (m)**	*Win*	57.5 ± 14.5	25.3	**S-W (m)**	*Win*	217.3 ± 69.7	32.0
	Loss	32.0 ± 4.5	14.1		*Loss*	53.5 ± 8.4	15.7		*Loss*	204.8 ± 52.6	25.7
JOG (m)	*Win*	44.5 ± 9.8	22.1	**JOG (m)**	*Win*	70.4 ± 20.6	29.2	**JOG (m)**	*Win*	200.2 ± 106.5	53.2
	Loss	41.7 ± 5.9	14.2		*Loss*	64.2 ± 9.6	14.9		*Loss*	180.0 ± 35.5	19.7
RUN (m)	*Win*	26.2 ± 9.2	35.2	**RUN (m)**	*Win*	35.4 ± 16.8	47.6	**RUN (m)**	*Win*	79.1 ± 74.0	93.6
	Loss	26.9 ± 5.3	19.8		*Loss*	35.0 ± 8.9	25.4		*Loss*	77.8 ± 19.3	24.9
HSR (m)	*Win*	17.2 ± 8.5	49.2	**HSR (m)**	*Win*	19.9 ± 10.3	51.9	**HSR (m)**	*Win*	33.9 ± 19.8	58.5
	Loss	16.1 ± 6.3	39.1		*Loss*	20.6 ± 10.1	49.2		*Loss*	34.0 ± 20.4	60.0
ACC (count)	*Win*	3.3 ± 1.2	38.2	**ACC (count)**	*Win*	4.0 ± 1.5	37.9	**ACC (count)**	*Win*	8.2 ± 3.4	41.6
	Loss	3.6 ± 1.2	35.3		*Loss*	4.4 ± 1.7	39.2		*Loss*	8.7 ± 3.3	38.8
DEC (count)	*Win*	2.0 ± 0.8	44.0	**DEC (count)**	*Win*	2.4 ± 1.0	43.2	**DEC (count)**	*Win*	4.3 ± 2.1	48.5
	Loss	2.0 ± 0.9	47.0		*Loss*	2.5 ± 1.3	53.5		*Loss*	4.3 ± 2.4	55.6

Abbreviations: TD = total distance, PL = PlayerLoad, AU = arbitrary units, S-W = standing-walking, JOG = jogging, RUN = running, HSR = high-speed running, ACC = accelerations, DEC = decelerations.

TABLE 3. Descriptive statistics for external peak demand variables according to quarter result across different time windows.

30-s time window				1-min time window				5-min time window			
Variable	*Result*	*Mean ± SD*	*%CV*	*Variable*	*Result*	*Mean ± SD*	*%CV*	*Variable*	*Result*	*Mean ± SD*	*%CV*
	Win	80.4 ± 8.9	11.1		*Win*	134.0 ± 15.2	11.3		*Win*	454.9 ± 68.9	15.1
TD (m)	*Tie*	81.4 ± 7.3	8.9	**TD (m)**	*Tie*	138.1 ± 10.8	7.8	**TD (m)**	*Tie*	458.5 ± 87.5	19.0
	Loss	78.3 ± 7.9	10.1		*Loss*	130.4 ± 13.3	10.2		*Loss*	433.9 ± 63.7	14.7
	Win	10.5 ± 1.5	14.9		*Win*	17.1 ± 2.8	16.4		*Win*	54.1 ± 10.9	20.1
PL (AU)	*Tie*	10.7 ± 1.3	12.5	**PL (AU)**	*Tie*	17.2 ± 1.9	11.4	**PL (AU)**	*Tie*	53.7 ± 11.6	21.5
	Loss	10.0 ± 1.5	14.9		*Loss*	16.5 ± 2.5	15.2		*Loss*	50.5 ± 10.2	20.2
	Win	33.0 ± 6.1	18.5		*Win*	57.1 ± 13.8	24.3		*Win*	216.7 ± 66.7	30.7
S-W (m)	*Tie*	33.4 ± 5.7	17.2	**S-W (m)**	*Tie*	56.7 ± 12.4	21.9	**S-W (m)**	*Tie*	222.7 ± 76.3	34.2
	Loss	33.1 ± 6.3	19.2		*Loss*	57.4 ± 15.1	26.4		*Loss*	213.4 ± 71.4	33.4
	Win	44.5 ± 10.0	22.6		*Win*	70.4 ± 21.2	30.2		*Win*	202.3 ± 107.6	53.1
JOG (m)	*Tie*	47.6 ± 8.2	17.3	**JOG (m)**	*Tie*	72.9 ± 12.1	16.6	**JOG (m)**	*Tie*	193.7 ± 50.4	26.0
	Loss	43.0 ± 8.4	19.6		*Loss*	67.7 ± 17.2	25.4		*Loss*	188.8 ± 95.1	50.3
	Win	26.6 ± 9.7	36.6		*Win*	36.2 ± 18.5	51.2		*Win*	82.8 ± 84.2	101.6
RUN (m)	*Tie*	24.4 ± 7.8	32.0	**RUN (m)**	*Tie*	33.3 ± 10.6	31.9	**RUN (m)**	*Tie*	69.7 ± 20.5	29.4
	Loss	25.8 ± 6.8	26.3		*Loss*	33.6 ± 9.5	28.4		*Loss*	71.1 ± 23.1	32.5
	Win	17.8 ± 8.7	48.9		*Win*	20.9 ± 10.8	51.8		*Win*	35.8 ± 20.8	58.3
HSR (m)	*Tie*	17.9 ± 8.5	47.4	**HSR (m)**	*Tie*	20.5 ± 10.1	49.4	**HSR (m)**	*Tie*	29.6 ± 16.2	54.6
	Loss	15.4 ± 7.0	45.8		*Loss*	17.4 ± 8.4	48.2		*Loss*	30.0 ± 17.3	57.7
ACC (count)	*Win*	3.3 ± 1.3	39.3	**ACC (count)**	*Win*	4.1 ± 1.6	34.6	**ACC (count)**	*Win*	8.3 ± 3.6	43.1
	Tie	3.0 ± 0.9	32.0		*Tie*	4.0 ± 1.2	39.9		*Tie*	8.3 ± 2.5	30.6
	Loss	3.4 ± 1.2	36.2		*Loss*	4.1 ± 1.4	34.6		*Loss*	8.0 ± 3.1	38.5
DEC (count)	*Win*	2.1 ± 0.9	42.8	**DEC (count)**	*Win*	2.5 ± 1.0	43.4	**DEC (count)**	*Win*	4.5 ± 2.1	47.1
	Tie	1.8 ± 0.9	51.0		*Tie*	2.5 ± 0.8	34.0		*Tie*	4.5 ± 1.9	42.6
	Loss	1.8 ± 0.8	46.2		*Loss*	2.2 ± 1.0	48.2		*Loss*	3.9 ± 2.1	55.6

Abbreviations: TD = total distance, PL = PlayerLoad, AU = arbitrary units, S-W = wtanding-walking, JOG = jogging, RUN = running, HSR = high-speed running, ACC = accelerations, DEC = decelerations.

TABLE 4. Descriptive statistics for external peak demand variables according to quarter point difference across different time windows.

30-s time window				1-min time window				5-min time window			
Variable	*Result*	*Mean ± SD*	*%CV*	*Variable*	*Result*	*Mean ± SD*	*%CV*	*Variable*	*Result*	*Mean ± SD*	*%CV*
TD (m)	*Low*	78.5 ± 7.7	9.81	**TD (m)**	*Low*	131.6 ± 12.8	9.7	**TD (m)**	*Low*	441.8 ± 70.1	15.8
	High	80.6 ± 9.0	11.21		*High*	134.1 ± 15.4	11.5		*High*	453.4 ± 68.2	15.0
PL	*Low*	10.1 ± 1.5	14.95	**PL**	*Low*	16.6 ± 2.4	14.8	**PL**	*Low*	51.5 ± 11.1	21.5
	High	10.6 ± 1.5	14.79		*High*	17.1 ± 2.8	16.4		*High*	53.9 ± 10.6	19.6
S-W (m)	*Low*	33.2 ± 6.3	19.11	**S-W (m)**	*Low*	57.9 ± 15.1	26.0	**S-W (m)**	*Low*	218.1 ± 73.1	33.5
	High	33.0 ± 6.0	18.35		*High*	56.7 ± 13.6	23.9		*High*	215.1 ± 65.7	30.5
JOG (m)	*Low*	43.6 ± 8.2	18.76	**JOG (m)**	*Low*	68.5 ± 16.1	23.5	**JOG (m)**	*Low*	190.7 ± 86.8	45.5
	High	44.6 ± 10.2	23.02		*High*	70.4 ± 21.6	30.6		*High*	202.2 ± 109.3	54.0
RUN (m)	*Low*	25.5 ± 6.8	26.84	**RUN (m)**	*Low*	33.8 ± 9.8	29.1	**RUN (m)**	*Low*	71.8 ± 23.7	32.9
	High	26.7 ± 9.8	36.98		*High*	36.2 ± 18.7	51.8		*High*	82.8 ± 85.6	103.4
HSR (m)	*Low*	16.1 ± 7.3	45.26	**HSR (m)**	*Low*	18.2 ± 8.6	47.4	**HSR (m)**	*Low*	30.6 ± 17.3	56.6
	High	17.7 ± 8.8	49.64		*High*	20.9 ± 11.0	52.6		*High*	35.7 ± 20.9	58.6
ACC (count)	*Low*	3.3 ± 1.2	36.04	**ACC (count)**	*Low*	4.1 ± 1.4	33.6	**ACC (count)**	*Low*	8.1 ± 3.0	37.8
	High	3.3 ± 1.3	39.38		*High*	4.1 ± 1.6	40.3		*High*	8.3 ± 3.5	43.0
DEC (count)	*Low*	1.8 ± 0.8	44.28	**DEC (count)**	*Low*	2.2 ± 1.0	44.8	**DEC (count)**	*Low*	4.0 ± 2.0	52.1
	High	2.1 ± 0.9	43.76		*High*	2.5 ± 1.1	43.9		*High*	4.5 ± 2.1	47.3

Abbreviations: TD = Total Distance, PL = Player Load, S-W = Standing-Walking, JOG = Jogging, RUN = running, HSR = High Speed Running, ACC = Accelerations, DEC = Decelerations.

Regarding game result, non-significant ($p > 0.05$), trivial to small differences were apparent in all variables across each time window between games that were won and lost. Differences in variables between games won and lost were mostly trivial in magnitude, with some variables reaching small effects in favor of wins (TD 30 s, PL 30 s, JOG 30 s, TD 1 min, S-W 1 min -0.28, JOG 1 min, and PL 5 min) or losses (ACC 30 s and ACC 1 min).

Concerning quarter result, significantly higher HSR ($p = 0.03$; ES = small) across the 1-min time window and PL ($p = 0.04$; ES = small) across the 5-min time window were evident during quarters that were won compared to lost. Non-significant ($p > 0.05$) differences were apparent in the remaining external PD variables across each time window. Differences according to quarter result (win vs. loss, win vs. tie, and tie vs. loss) were mostly trivial in magnitude, reaching small effects in favor of wins (vs. losses: TD 30 s, PL 30 s, HSR 30 s, DEC 30 s, TD 1 min, PL 1 min, HSR 1 min, DEC 1 min, TD 5 min, PL 5 min, HSR 5 min, and DEC 5 min; vs. ties: JOG 30 s, RUN 30 s, ACC 30 s, DEC 30 s, TD 1 min, and HSR 5 min) or ties (vs. losses: TD 30 s, PL 30 s, JOG 30 s, RUN 30 s, HSR 30 s, ACC 30 s, TD 1 min, PL min, JOG 1 min, HSR 1 min, DEC 1 min, TD 5 min, PL 5 min, and DEC 5 min).

Regarding quarter score-line, significantly greater PL ($p = 0.03$; ES = small) and DEC ($p = 0.02$; ES = small) across the 30-s time window, HSR ($p = 0.04$; ES = small) across the 1-min time window, and HSR ($p = 0.04$; ES = small) and DEC ($p = 0.03$; ES = small) across the 5-min time window were evident in quarters with high point differences between teams than quarters with low point differences. Non-significant ($p > 0.05$) differences were apparent in the remaining variables across each time window with mostly trivial effects and reaching small effects in favor of quarters with high point differences in some variables (TD 30 s, PL 30 s, DEC 30 s, HSR 1 min, DEC 1 min, PL 5 min, HSR 5 min, and DEC 5 min).

DISCUSSION

The aim of this study was to quantify and compare the external PD encountered during games according to game result (win vs. loss), quarter result (win vs. tie vs. loss), and quarter point difference (± difference in score) in U18, male basketball players. The outcomes indicated that: (1) external PD does not clearly differentiate team success based on game result; (2) quarters that were won or tied showed higher external PD (small effects) compared to quarters that were lost; and (3) high point differences in quarter score-lines elicited higher external PD (small effects) than quarters with low point differences.

Regarding game result, non-significant ($p > 0.05$) differences with predominantly trivial effects were apparent across variables in

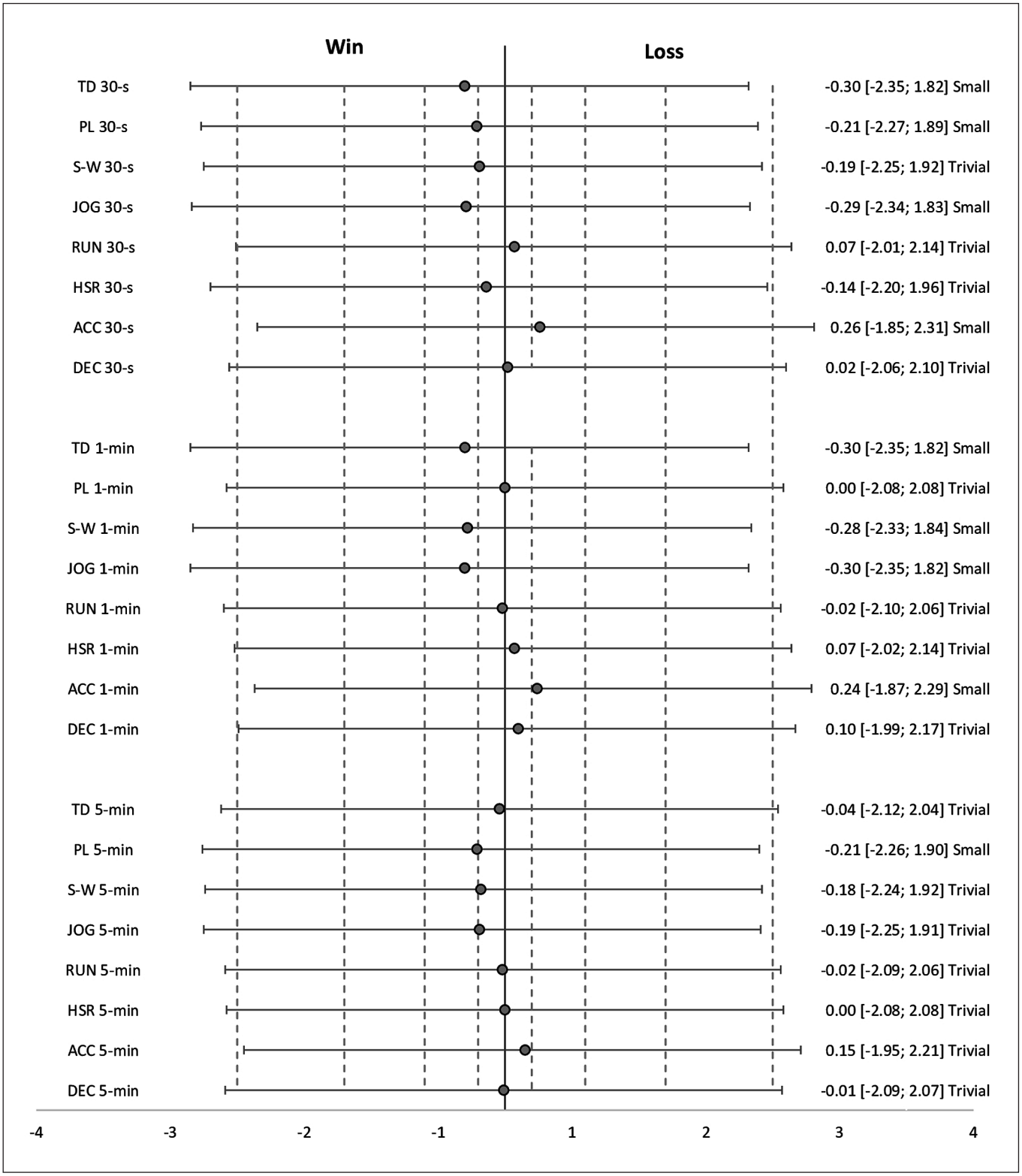


FIG. 1. Effect sizes with 95% confidence intervals for comparisons in external peak demand variables between games that were won and lost. *Abbreviations:* TD = total distance, PL = PlayerLoad, S-W = standing-walking, JOG = jogging, RUN = running, HSR = high-speed running, ACC = accelerations, DEC = decelerations. *Note: Dotted lines represent ES interpretation (trivial ≤ 0.20; small = 0.20–0.59; moderate = 0.60–1.19; large = 1.20–1.99 and very large ≥ 2.00).*

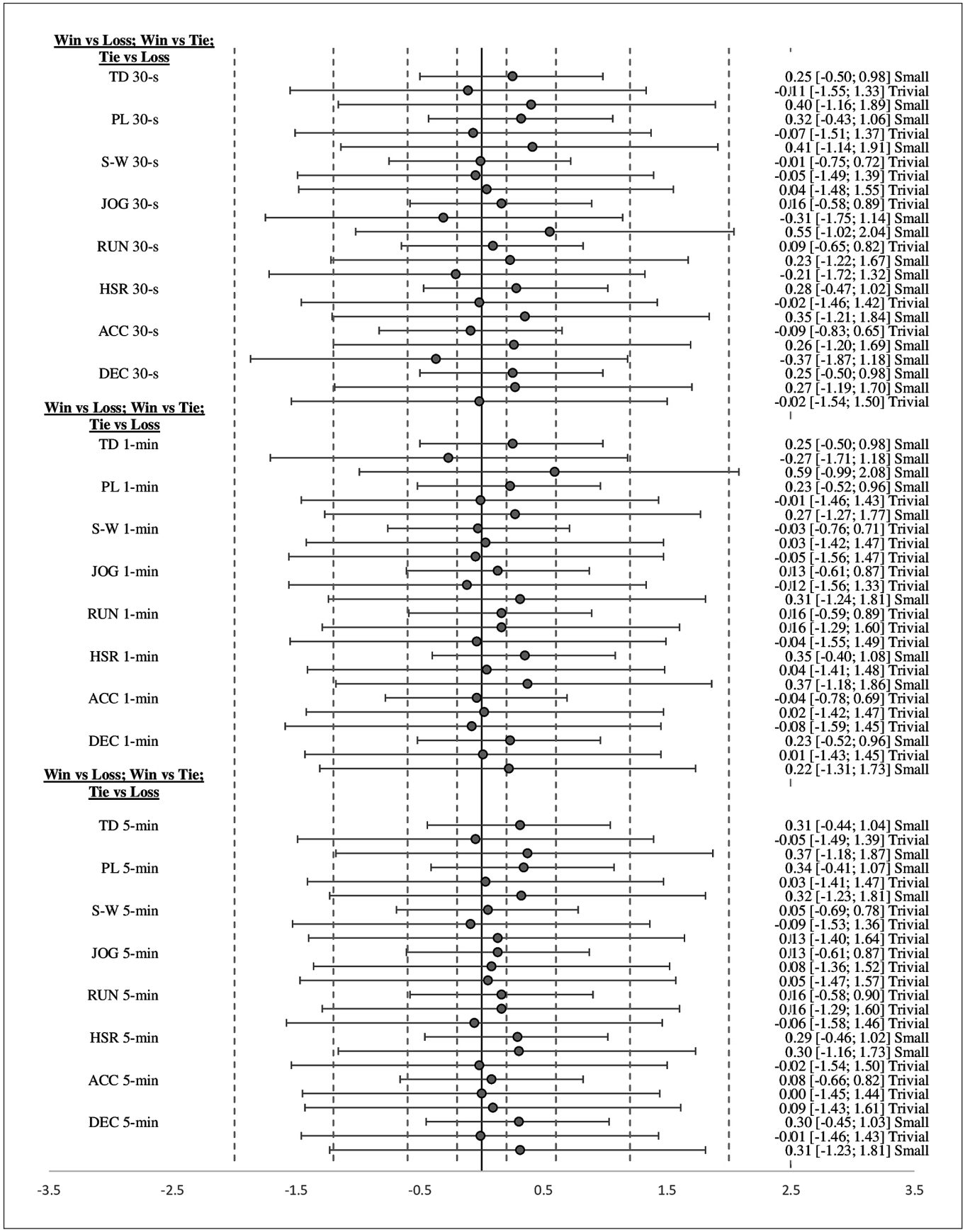


FIG. 2. Effect sizes with 95% confidence intervals for comparisons in external peak demand variables between quarters that were won and lost. *Abbreviations:* TD = total distance, PL = PlayerLoad, S-W = standing-walking, JOG = jogging, RUN = running, HSR = high-speed running, ACC = accelerations, DEC = decelerations. *Notes: Dotted lines represent ES interpretation (trivial ≤ 0.20; small = 0.20–0.59; moderate = 0.60–1.19 and large = 1.20–1.99). For each parameter the comparison followed is win vs loss; win vs tie; tie vs loss.*

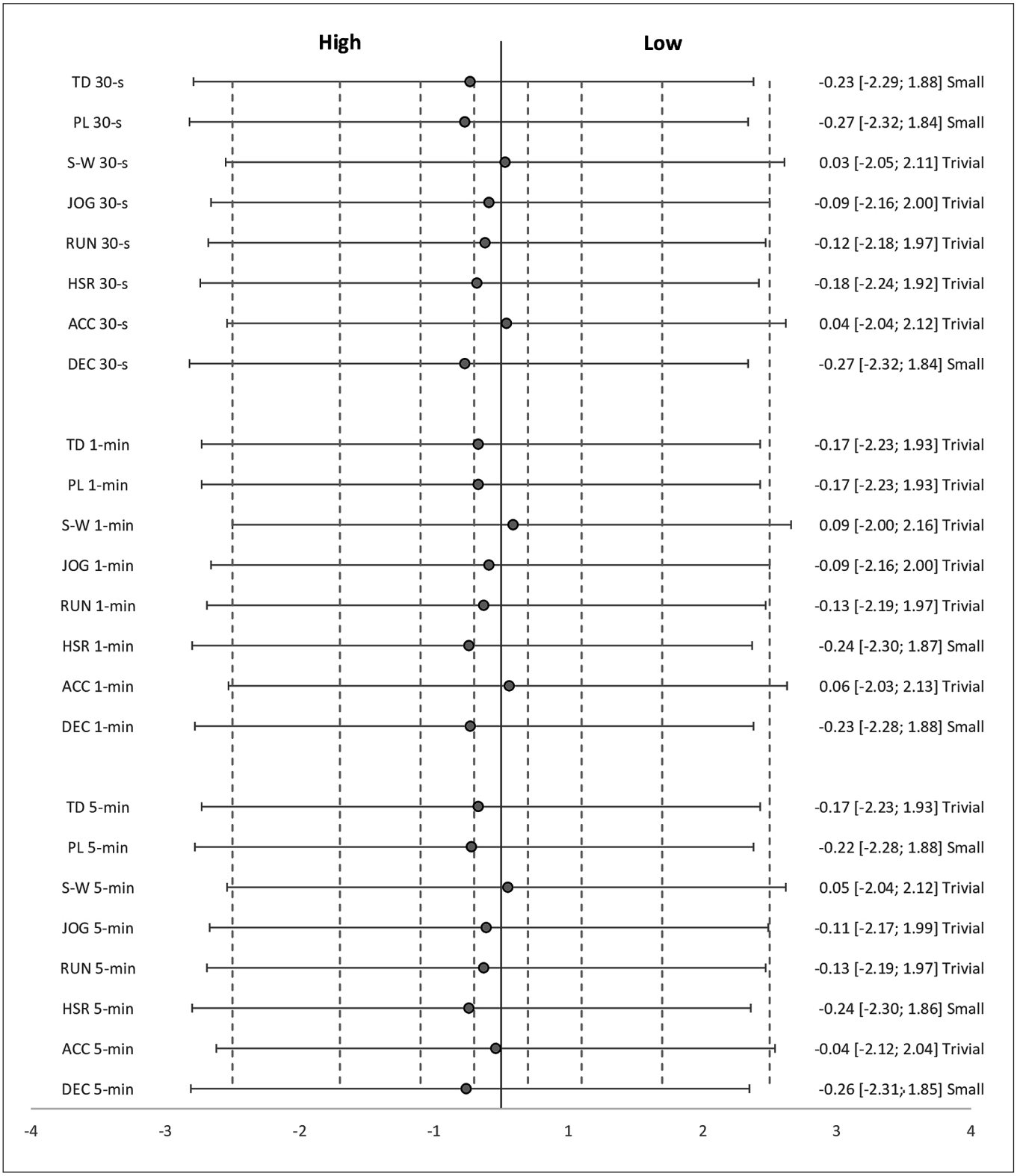


FIG. 3. Effect sizes with 95% confidence intervals for comparisons in external peak demand variables between quarters with low (-2.47 ± 2.67 points) and high (7.51 ± 3.75 points) score-line margins. *Abbreviations:* TD = total distance, PL = PlayerLoad, S-W = standing-walking, JOG = jogging, RUN = running, HSR = high-speed running, ACC = accelerations, DEC = decelerations. *Note: Dotted lines represent ES interpretation (trivial ≤ 0.20; small = 0.20–0.59; moderate = 0.60–1.19; large = 1.20–1.99 and very large ≥ 2.00).*

each time window between games that were won and lost. Our findings contrast those made previously in basketball research exploring average external load intensities across entire games among national-level, U18, male basketball players [14]. Specifically, previous data show U18, male basketball players in lower-ranked teams (placed fifth to eighth) completed significantly ($p < 0.05$) higher relative distances ($m \cdot min^{-1}$) than players in top-ranked teams (placed first to fourth) [14]. In turn, data provided for adult, semi-professional, male basketball players show they performed significantly ($p < 0.001$) more high-intensity accelerations per minute during games that were lost compared to won [15]. These previous data suggest that less successful teams may exert higher average intensities across games, which may be due to tactical inefficiencies in movements (i.e., they do not move effectively across the court and thus perform more activity to execute a specific movement phase) or perform at greater intensities in an attempt to reduce the deficit in score-line when in a losing position rather than slowing play to protect a lead [13]. In contrast to previous findings [13, 14], our data suggest when external PD are quantified across shorter epochs (30-s, 1-min, and 5-min windows) rather than averaged across entire games, similar intensities are reached regardless of game result among U18, male players. The consistent external PD across shorter epochs in our study may be explained by the chaotic nature of basketball producing comparable intense periods of play for winning and losing teams, and knowing that determinants of success are multi-factorial [31]. In this regard, there are several offensive and defensive technical-tactical performance indicators that have been shown to influence game outcome among various basketball player samples including rebounds [31], passing skills (e.g. ball coordination between inside and outside playing positions that enhance three-point shot opportunities) [32], perceptive and decision-making processes [33], and defensive preparation (e.g. personal fouls, steals) [34]. In turn, our data suggest identifying factors associated with team success in U18, male basketball players is not permissible using PD variables gathered from external load monitoring data in isolation [35], with a multidimensional approach considering other areas of performance likely needed.

Similar to what was found across entire games, quarter analyses showed non-significant differences in external PD across all variables and time windows except HSR across a 1-min window and PL across a 5-min window (higher values in quarters that were won). These findings contrast previous data provided for adult, semi-professional, male basketball players showing higher ($p > 0.05$, small effects) external PD for $PL \cdot min^{-1}$ (4-min and 5-min windows) during quarters that were lost compared to won [13]. Previously, Fox et al. [13] postulated that the higher peak $PL \cdot min^{-1}$ during quarters that were lost was potentially due to the team adopting an increased playing pace to maximize scoring opportunities and reduce the score-line margin [13]. In turn, the team analyzed in our study were not typically in a losing position (won 8 out of 9 games) and may have performed at high external intensities during game quarters that were won to establish the lead but reduced movement intensities in subsequent quarters (that were lost) to protect the lead or due to diminished motivation and concentration if the game result was clearly decided. In support of this notion, past research examining adult, professional, male basketball players indicates a greater difference in score-line at the beginning of each game quarter corresponds with a higher number of recovered points by the losing team in that quarter [17]. Further, the authors [17] postulated that players in a losing position may increase their work rate to score more points and heighten their defensive readiness, which may both exacerbate the external PD performed. Although this previous research was provided in adult, male basketball players, our data indicate similar scenarios may occur in U18, male basketball players; however, further research is encouraged exploring the motivational factors in young basketball players during different game scenarios to confirm this supposition.

A unique aspect of this study was the deeper analysis of quarter results through considering the score-line margin when examining external PD. In this regard, although greater external PD were attained (PL 30 s, HSR 30 s, 1 min and 5 min, and DEC 5 min) with high point differences than low point differences in score-line, the differences were small in magnitude. Nevertheless, these small differences support the notion that the U18, male basketball players in the examined team may have performed at higher external intensities across quarters to establish score-line leads involving high margins, but then reduced movement intensities given they were in a strong winning position yielding quarters with low score-line margins. Furthermore, the higher external PD for HSR across all time windows during quarters with high score-line differences may indicate fast break scenarios or elevated pace in transitions (given speeds $> 18\ km \cdot h^{-1}$ had to be reached for HSR to be detected) across the court can be key tactical strategies that promote pronounced leads in the score-line.

The limitations encountered in carrying out this study should be considered when interpreting our results. First, only external load variables were monitored, therefore internal PD (e.g., heart rate, rating of perceived exertion) were not explored and may show different patterns to those observed in our study for external PD. Second, due to the real-world context our observational analyses were conducted in, the reported outcomes were bound by the results of the included games and therefore games involving score-line margins outside of those seen in the present study may induce different trends in PD according to game and quarter results. Furthermore, the team won most games (8 out of 9 games) and therefore the data points were not distributed in a balanced manner for all factors investigated (game result, quarter result, and quarter point difference). Third, the sample size adopted in this study was small given a single basketball team was recruited, with the sample size for lost games only representative of a single game. Consequently, these findings may not translate to all basketball teams given the variations in success, tactical strategies, playing pace, and player fitness likely evident within and between competitions.

CONCLUSIONS

External PD appear to remain consistent regardless of game result in U18, male basketball players. In turn, although quarters that were won and involving high score-line margins elicited higher external PD than quarters that were lost or close in score-line, the observed effects were only trivial to small in magnitude. Accordingly, the external PD attained during games may not be a key indicator of overall team success in games. Further analyses using a wider range of variables in other areas such as technical-tactical parameters, psychology, team strategies, competition level, and player experience are recommended to identify the determinants of team success in young basketball players.

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Physical demands during 3 × 3 international male and female basketball games are partially impacted by competition phase but not game outcome

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ABSTRACT: Despite the increased popularity and number of international competitions for 3 × 3 basketball, the precise physical demands of this sport are not well described. Therefore, this study aimed to quantify the physical demands of 3 × 3 basketball games according to game outcome and competition phase. Following an observational design, video footage from 27 games were analysed from 104 international 3 × 3 basketball players (n = 52 male and n = 52 female players) belonging to 26 national teams (n = 13 male and n = 13 female teams) during the 2019 FIBA 3 × 3 World Cup. Manual frame-by-frame time-motion analyses were conducted to determine the relative frequency ($n \cdot min^{-1}$) and duration (% of live playing time) for several physical demand variables to make comparisons according to game outcome (win vs. loss) and competition phase (group games vs. finals games). Linear mixed models for repeated measures and effect size analyses revealed non-significant, *trivial-small* differences in physical demands between games that were won and lost. Regarding competition phase, male players completed more high-intensity activity (sprinting, high-intensity specific movements, and jumping) but spent a greater proportion of playing time jumping and performing recovery activities (standing/walking) during finals games than group games ($P < 0.05$, *small*), while female players performed more low-intensity activity (jogging and low-intensity specific movements) during group games than finals games ($P < 0.05$, *small*). These findings indicate that the physical capabilities of male and female 3 × 3 basketball players may not be the determining factor for team success in games and players can mostly maintain activity outputs across phases of tournament play conducted at the highest international standard.

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INTRODUCTION

Although 3 × 3 basketball is a global team sport adapted from the traditional 5 × 5 version of basketball, its unique characteristics likely impose specific demands on players compared to 5 × 5 basketball. In this regard, 3 × 3 basketball games are played on smaller courts (15 m × 11 m vs. 15 m × 28 m), with a reduced number of players competing at any one time (3 vs. 5), and following shorter overall live playing times (10 min vs. 40–48 min) and shot clock durations per possession (12 s vs. 24 s) compared to 5 x 5 basketball games. Accordingly, increased research is emerging exploring the demands of 3 × 3 basketball [1–8] so that team training plans and tactical strategies, as well as player technical skills and physical characteristics can be optimally developed to suit these demands.

Studies quantifying the demands of 3 × 3 basketball games have measured the technical-tactical demands [1–6], internal load [6–8], and external load [7, 8] of junior and adult players across both sexes competing at national and international levels. Existing data indicate 3 × 3 basketball games evoke high internal loads including heart rates of ~165 $beats \cdot min^{-1}$, blood lactate concentrations > 6.0 $mmol \cdot L^{-1}$, and ratings of perceived exertion > 5 arbitrary units (AU) using a modified Borg CR10 scale in male and female junior (under 18 years) and adult international players [6–8]. Regarding external load data during 3 × 3 basketball games, only two studies [7, 8] have quantified physical demands using positioning system and inertial sensor technology.

These studies [7, 8] have shown male and female players competing in the 2016 International Basketball Federation 3 × 3 under-18 World Championships, Senior European, and World Championships cover > 850 m and experience absolute PlayerLoads™ ranging from 116 ± 29 to 133 ± 28 AU and relative PlayerLoads™ ranging from 6.3 ± 1.4 to 6.8 ± 1.5 AU · min^{-1} during games. However, further data indicating the precise movement types and intensities completed by players during 3 × 3 basketball games is needed to provide practitioners with a more thorough understanding of the physical demands faced by players for enhanced translation to practice. In this way, video-based time-motion analysis (TMA) represents a valid [9–12] and reliable [9, 10, 12–15] method to provide detailed insight regarding the movements performed by players not captured with positioning system and inertial sensor technology such as stressful stationary activity (e.g., screens, boxing out opponents during rebounds, holding position on the court) [16]. Consequently, further research quantifying physical demands using approaches not adopted in the previous literature, such as video-based TMA, are needed to understand the complete requirements of players more comprehensively during 3 × 3 basketball games.

When quantifying player physical demands during basketball games, contextual factors should be considered given they may affect the activities performed by players [17]. Two key contextual factors that have received increased research attention when quantifying game demands in basketball players include game outcome (win vs. loss) [1, 17–22] and competition phase (group phase vs. final phase) [6, 7]. Regarding game outcome, previous research has only explored technical-tactical demands during 3 × 3 basketball games reporting winning male and female teams competing in the 2019 European Basketball Cup performed significantly better than losing teams in various metrics including scoring more efficiently (i.e., points per possession), securing more rebounds, committing fewer turnovers, and committing less fouls [3]. However, no data of this kind on physical demands according to game outcome are yet available for 3 × 3 basketball players. Regarding competition phase, research quantifying the technical-tactical demands of male and female players competing in 3 × 3 basketball games during the 2019 European Basketball Cup showed significantly greater scoring efficiency (i.e., points per possession) and less blocks were completed during group games compared to finals games [3]. In turn, research examining male and female players during the 2019 Australian National Basketball League 3 × 3 Pro Hustle demonstrated significantly less shots (semi-finals), more offensive rebounds (quarter-finals), and less steals (quarter-finals and semi-finals) were completed during finals games compared to group games. Further to technical-tactical demands, research exploring the internal responses of male and female players during 3 × 3 games found significantly higher ratings of perceived exertion (semi-finals and finals) and peak heart rates (semi-finals) during finals games compared to group games during the 2019 Australian National Basketball League 3 × 3 Pro Hustle. Nevertheless, no data exist directly comparing the physical demands of 3 × 3 basketball games between finals and group phases, with data only reported for individual games in male and female players across under-18 and senior international tournaments [7].

Due to the limited findings reported in the literature regarding the physical demands associated with 3 × 3 basketball games and considering no research has directly explored the impact of game outcome and competition phase on these demands, research on this topic is essential. Such data will assist basketball coaches and high-performance staff in identifying the most influential physical factors contributing to in-game success for the development of training plans that optimally prepare players for 3 × 3 basketball competition. Therefore, the aim of this study was to quantify the physical demands of 3 × 3 basketball games according to game outcome (win vs. loss) and competition phase (group games vs. finals games).

MATERIALS AND METHODS

Subjects

Data were collected from 104 international 3 × 3 basketball players (n = 52 male and n = 52 female players) belonging to 26 national teams (n = 13 male and n = 13 female teams), with each team comprised of four players. The study was approved by the Independent Institutional Review Board of MAPEI Sport Research Centre in accordance with the Helsinki Declaration (2013).

Design

An observational study design was used to assess the physical demands experienced during games in male and female players competing at the 2019 FIBA 3 × 3 World Cup according to game outcome (win vs. loss) and competition phase (group phase vs. finals phase). This competition featured 20 male and 20 female teams, that were divided into 4 groups of 5 teams, with teams seeded automatically based on the 3 × 3 FIBA world rankings. Separately in the male and female competitions, the top two teams in each group following the group phase progressed to quarter-final games. The winner of each quarter-final game progressed to the semi-final games, with winners of semi-final games progressing to the final. The games were played in accordance with the FIBA 3 × 3 basketball rules (https://fiba3x3.com/docs/fiba-3x3-basketball-rules-full-version.pdf). Video footage for each game was publicly accessible online via the tournament website (https://www.fiba.basketball/3x3WC/2019) or Youtube (https://www.youtube.com/c/FIBA3x3/playlists). A total of 27 official games out of the 96 games disputed during the 2019 FIBA 3 × 3 World Cup were included in final analyses. Specifically, all the games involving two teams not qualifying for the finals phase were excluded (n = 24 games) to reflect a similar distribution of games between competition phases for analyses. Then, games with more than 3% of total playing time not available for technical reasons (e.g., video interruption, commercial break, action replays) were excluded (n = 45 games). Specifically, 16 games during the group phase (male games, n = 8; female games, n = 8) out of 80 total games

during the group phase and 11 games during the finals phase (male games, n = 5 [final for first and second place, n = 1; semi-final, n = 1 and quarter-finals, n = 3]; female games, n = 6 [final for first and second place, n = 1; final for third and fourth place, n = 1; semi-finals, n = 2 and quarter-finals, n = 2]) out of 16 total games during the finals phase were analysed, thus resulting in a total of 216 (male games, n = 104 [group phase, n = 40; finals phase, n = 64] and female games, n = 112 [group phase, n = 48; finals phase, n = 64]) individual game samples being analysed.

Time-motion analysis

A manual frame-by-frame approach was used to determine player physical demands during games using established software (SICS VideoMatch Basket, version 5.0.5). As previously described [9, 14, 15], physical demands were quantified by identifying movements into one of eight categories as follows: (i) stand/walk: movement of no greater intensity than walking without any distinction between standing still and walking or between different intensities of walking; (ii) jog: forwards or backwards movement at an intensity greater than walking but without urgency; (iii) run: forwards or backwards movement at an intensity greater than jogging and a moderate degree of urgency but which did not approach an intense level of movement; (iv) sprint: forwards or backwards movement at a high intensity, characterised by effort and purpose at or close to maximum; (v) low-: (vi) moderate-: (vii) high-specific movements (SM): movements differing from ordinary standing, walking or running performed respectively at low intensity without urgency, at medium intensity with a moderate degree of urgency, and at high intensity with urgency; and (viii) jump: the time from the initiation of the jumping action to the completion of landing. SMs mainly included the stance position, shuffling, rolling, reversing, screening, and cross-over running activities [23]. Activities in each of these eight categories were then grouped more broadly according to their relative intensity as: (i) recovery (REC, i.e., standing/walking); (ii) low-intensity activities (LIA, i.e., jogging and low-SM); (iii) medium-intensity activities (MIA, i.e., running and moderate-SM); and (iv) high-intensity activities (HIA, i.e., sprinting, high-SM, and jumping) [9, 14, 15]. The frequency of occurrence and the duration of each activity were determined during live playing time (i.e., when the game clock was running). Activity frequencies were calculated as the total number of events (n) performed and normalised according to playing time ($n \cdot min^{-1}$) for each player to account for the varying exposures and substitution times across players. Activity durations were determined as a percentage (%) of the playing time for each player to account for the varying exposures and substitution times across players. The analysis was carried out by a single experienced video analyst. Intra-tester reliability was determined by having the observer analyse the relative frequency ($n \cdot min^{-1}$) and duration (s) of activities during an entire 2019 FIBA 3 × 3 World Cup 3 × 3 game for all players (n = 8) on two occasions separated by 7 days to minimise mental recall of video footage. The reliability of this approach through calculation of the intraclass correlation coefficient (ICC) and coefficient of variation (CV) were deemed acceptable and are reported in Table 1.

TABLE 1. Intra-tester reliability of video-based time-motion analysis variables reported in this study.

Variable	Movement category	ICC (95%CI)	CV% (95%CI)
Frequency of occurrence	REC	0.97 (0.87–0.99)	5.62 (3.68–11.78)
	LIA	0.98 (0.90–1.00)	3.92 (2.57–8.14)
	MIA	0.99 (0.94–1.00)	4.00 (2.63–8.31)
	HIA	0.99 (0.96–1.00)	2.90 (1.91–6.00)
	Sprint	0.99 (0.97–1.00)	5.14 (3.37–10.75)
	High-SM	0.97 (0.84–0.99)	6.60 (4.31–13.88)
	Jumps	1.00 (1.00–1.00)	0.00 (0.00–0.00)
Duration	REC	1.00 (0.98–1.00)	3.17 (2.09–6.56)
	LIA	0.99 (0.94–1.00)	3.52 (2.31–7.30)
	MIA	0.95 (0.76–0.99)	8.68 (5.66–18.46)
	HIA	1.00 (0.92–1.00)	2.04 (1.34–4.20)
	Sprint	0.98 (0.94–1.00)	8.41 (5.49–17.87)
	High-SM	0.98 (0.91–1.00)	5.10 (3.35–10.66)
	Jumps	0.99 (0.96–1.00)	5.09 (3.34–10.63)

Abbreviations: ICC, intraclass correlation coefficient; CI, confidence intervals; CV%, coefficient of variation as a percentage; REC, recovery; LIA, low-intensity activities; MIA, medium-intensity activities; HIA, high-intensity activities; SM, specific movements.

Statistical analysis

The TMA descriptive results are reported as means ± standard deviations (SD). Linear mixed models were constructed to examine differences in REC, LIA, MIA, HIA, total movements, sprint, high-SM, and jump data according to game outcome and competition phase, accounting for individual repeated measures. Linear mixed models were separately constructed for males and females where game outcome (2 levels: win and loss) and competition phase (2 levels: group phase and finals phase) were used as fixed effects and player as a random effect with a random intercept and fixed slope. All assumptions were met including assessing the normality of the residuals using the Kolmogorov-Smirnov test. Moreover, the magnitude of differences was assessed using effect size (ES) analyses with 95% confidence intervals and interpreted as: < 0.2 = *trivial*; 0.20–0.59 = *small*; 0.60–1.19 = *moderate*; 1.2–1.99 = *large*; and ≥ 2.0 = *very large* [24]. An alpha level of < 0.05 was set *a priori* for statistical significance. All data were analysed using Jamovi software (version 2.0.0.0, 2021).

RESULTS

Descriptive data and statistical analyses for physical demand variables during male basketball games according to game outcome (i.e., win vs. loss) and competition phase (i.e., group games vs. finals games) are presented in Tables 2 and 3. Regarding comparisons according to game outcome, no significant differences were evident in any physical demand variables between games that were won and lost in male players. Regarding comparisons according to competition phase, male players completed more HIA per minute ($P = 0.014$; *small* ES) and spent a greater proportion of playing time performing HIA during group games than finals games ($P = 0.018$; *small* ES) but spent a greater proportion of playing time performing REC during finals games than group games ($P = 0.012$; *small* ES). When considering singular high-intensity activities, male players performed more high-SM per minute and spent a greater proportion of playing time performing high-SM during groups compared to finals games ($P < 0.001$; *moderate* ES) but spent a higher proportion of playing time jumping during finals games compared to group games ($P = 0.009$; *small* ES). No significant interactions between fixed effects were evident for physical demand variables in male players ($P > 0.05$).

Descriptive data and statistical analyses for physical demand variables during female basketball games according to game outcome (i.e., win vs. loss) and competition phase (i.e., group games vs. finals games) are presented in Tables 4 and 5. Regarding comparisons according to game outcome, no significant differences were evident in any physical demand variables between games that were won and lost in female players. Regarding comparisons according to competition phase, female players performed more LIA per minute ($P = 0.018$; *small* ES) and spent a greater proportion of playing time performing LIA ($P = 0.010$; *small* ES) in group games than finals games. No significant interactions between fixed effects were evident for physical demand variables in female players ($P > 0.05$).

DISCUSSION

This study is the first to compare the physical demands encountered during 3 × 3 basketball games according to game outcome and competition phase. Furthermore, this study explored player demands in both male and female competitions during the World Cup, the highest international competition standard in 3 × 3 basketball. In turn, findings demonstrated no significant differences in physical demands between games that were won and lost in both male and female competitions. Comparisons in demands between competition phases revealed greater HIA bouts per minute, specifically high-SM, and a lower proportion of playing time spent in recovery and executing jumps were performed during group games compared to finals games in male players. In contrast, greater LIA were performed during group games compared to finals games in female players.

The similar demands between games that were won and lost during the 2019 FIBA 3 × 3 World Cup suggest that the activity outputs of players were homogenous across opposing teams and did not exert a dominant effect on dictating game results. Reasons for these findings may be related to the configurations of 3 × 3 basketball games limiting the extent to which differences in the physical capabilities of players manifest into the activity completed during games. Specifically, the short playing time (i.e., maximum 10 min) and small playing area (15 m × 11 m) likely restricts the activity outputs able to be generated (e.g., no transitions up and down a full court) and limits the effects of activity-induced fatigue during 3 × 3 basketball games [7], keeping activity demands relatively stable across teams. Furthermore, separate studies demonstrated players competing at the 2016 FIBA 3 × 3 World Championships possessed greater physical capabilities via clear differences in various fitness tests (males: aerobic capacity measured via the Yo-Yo Intermittent Recovery Test Level 1; females: change-of-direction speed via the Agility 505 Test) than players competing at the 2016 Under 18 World Championships [25], yet produced similar activity outputs during games measured using PlayerLoad · min^{-1} [8].

Comparisons to past research are difficult given the lack of research exploring physical demands according to game outcome in 3 × 3 basketball; however, findings from 5 × 5 basketball show similar trends. Specifically, previous data indicate semi-professional, male basketball players perform similar (*unclear* to *small* effects) external loads during games that were won and lost (PlayerLoad and PlayerLoad · min^{-1}) [17] and during quarters that were won and lost (peak PlayerLoad · min^{-1} across 15-s to 5-min sample durations and average PlayerLoad · min^{-1}) [17]. Nevertheless, while physical demands have not been quantified according to game outcome in 3 × 3 basketball, research has compared technical-tactical variables between winning and losing teams during 3 × 3 basketball games. Specifically, winning male and female teams competing in the 2019 3 × 3 European Basketball Cup performed scoring more efficiently, secured more rebounds, committed fewer turnovers, and committed less fouls than losing teams [3]. Indeed, similar findings have been consistently reported in 5 × 5 basketball competitions, with various

TABLE 2. Physical demands (mean ± standard deviation) according to game outcome (i.e., win vs. loss) and competition phase (i.e., group games vs. finals games [quarter-finals, semi-finals, and finals]) during the male 2019 FIBA 3 × 3 World Cup.

Dependent variables	Fixed effect			CV%	*P* value	Estimate	95% CI for estimate		ES	95% CI for ES		Interpretation
							Lower	Upper		Lower	Upper	
Frequency of occurrence (n/min)												
REC	Game outcome	Win	5.29 ± 1.75	33.08	0.156	-0.37	-0.88	0.14	0.25	-0.14	0.64	*Small*
		Loss	5.73 ± 1.83	31.94								
	Phase	Group	5.36 ± 1.91	35.63	0.213	-0.34	-0.86	0.19	0.20	-0.19	0.60	*Small*
		Finals	5.74 ± 1.59	27.70								
LIA	Game outcome	Win	14.71 ± 1.24	8.42	0.247	0.28	-0.19	0.76	-0.25	-0.64	0.14	*Small*
		Loss	14.33 ± 1.76	12.28								
	Phase	Group	14.46 ± 1.58	10.93	0.722	-0.09	-0.57	0.40	0.10	-0.30	0.50	*Trivial*
		Finals	14.61 ± 1.47	10.06								
MIA	Game outcome	Win	8.00 ± 1.55	19.38	0.338	-0.27	-0.82	0.28	0.14	-0.25	0.52	*Trivial*
		Loss	8.22 ± 1.70	20.68								
	Phase	Group	8.31 ± 1.57	18.89	0.282	0.31	-0.25	0.86	-0.32	-0.72	0.08	*Small*
		Finals	7.79 ± 1.68	21.57								
HIA	Game outcome	Win	11.47 ± 2.13	18.57	0.249	0.46	-0.31	1.22	-0.17	-0.55	0.22	*Trivial*
		Loss	11.10 ± 2.20	19.81								
	Phase	Group	11.73 ± 1.97	16.79	**0.014**	0.99	0.22	1.76	-0.56	-0.97	-0.14	*Small*
		Finals	10.56 ± 2.29	21.69								
Total	Game outcome	Win	39.46 ± 2.59	6.56	0.743	0.17	-0.85	1.19	-0.03	-0.41	0.36	*Trivial*
		Loss	39.38 ± 3.26	8.28								
	Phase	Group	39.87 ± 2.73	6.85	0.129	0.80	-0.22	1.83	-0.41	-0.80	0.00	*Small*
		Finals	38.70 ± 3.12	8.06								
Total time (%)												
REC	Game outcome	Win	15.24 ± 7.13	46.78	0.115	-1.65	-3.68	0.38	0.21	-0.18	0.59	*Small*
		Loss	16.73 ± 7.29	43.57								
	Phase	Group	14.59 ± 5.97	40.92	**0.012**	-2.73	-4.81	-0.66	0.51	0.10	0.92	*Small*
		Finals	18.20 ± 8.46	46.48								
LIA	Game outcome	Win	44.41 ± 4.77	10.74	0.182	1.19	-0.54	2.93	-0.34	-0.73	0.05	*Small*
		Loss	42.66 ± 5.52	12.94								
	Phase	Group	43.57 ± 5.19	11.91	0.592	0.48	-1.28	2.24	-0.02	-0.41	0.38	*Trivial*
		Finals	43.48 ± 5.30	12.19								
MIA	Game outcome	Win	16.74 ± 3.40	20.31	0.572	-0.35	-1.54	0.85	0.15	-0.24	0.53	*Trivial*
		Loss	17.28 ± 3.81	22.05								
	Phase	Group	17.41 ± 3.50	20.10	0.446	0.47	-0.74	1.68	-0.29	-0.69	0.11	*Small*
		Finals	16.37 ± 3.72	22.72								
HIA	Game outcome	Win	23.61 ± 4.53	19.19	0.496	0.59	-1.10	2.28	-0.06	-0.44	0.33	*Trivial*
		Loss	23.34 ± 4.99	21.38								
	Phase	Group	24.43 ± 4.41	18.05	**0.018**	2.09	0.39	3.79	-0.54	-0.95	-0.12	*Small*
		Finals	21.95 ± 4.92	22.41								

Abbreviations: CV%, coefficient of variation as a percentage; CI, confidence intervals; ES, effect size; REC, recovery; LIA, low-intensity activities; MIA, medium-intensity activities; HIA, High-intensity activities; SM, specific movements. *Notes*: Bolded *P* value indicates statistically significant difference ($P < 0.05$).

TABLE 3. High-intensity activities (mean ± standard deviation) according to game outcome (i.e., win vs. loss) and competition phase (i.e., group games vs. finals games [quarter-finals, semi-finals, and finals]) during the male 2019 FIBA 3 × 3 World Cup.

Dependent variables	Fixed effect			CV%	*P* value	Estimate	95% CI for estimate		ES	95% CI for ES		Interpretation
							Lower	Upper		Lower	Upper	
Frequency of occurrence (n/min)												
Sprint	Game outcome	Win	1.94 ± 0.79	40.72	0.581	0.08	-0.19	0.35	-0.15	-0.53	0.24	*Trivial*
		Loss	1.83 ± 0.70	38.25								
	Phase	Group	1.93 ± 0.86	44.56	0.404	0.12	-0.16	0.39	-0.17	-0.57	0.22	*Trivial*
		Finals	1.80 ± 0.72	40.00								
High-SM	Game outcome	Win	6.34 ± 1.42	22.40	0.239	0.28	-0.18	0.75	-0.17	-0.56	0.21	*Trivial*
		Loss	6.11 ± 1.29	21.11								
	Phase	Group	6.61 ± 1.19	18.00	**< 0.001**	0.87	0.41	1.34	-0.78	-1.21	-0.35	*Moderate*
		Finals	5.62 ± 1.38	24.56								
Jump	Game outcome	Win	3.18 ± 0.84	26.42	0.462	0.12	-0.20	0.45	-0.02	-0.41	0.36	*Trivial*
		Loss	3.16 ± 0.99	31.33								
	Phase	Group	3.19 ± 0.92	28.84	0.905	-0.02	-0.35	0.31	-0.06	-0.45	0.34	*Trivial*
		Finals	3.14 ± 0.91	28.98								
Total time (%)												
Sprint	Game outcome	Win	2.74 ± 1.18	43.07	0.504	0.14	-0.26	0.54	-0.16	-0.55	0.22	*Trivial*
		Loss	2.56 ± 1.01	39.45								
	Phase	Group	2.68 ± 1.14	42.54	0.670	0.09	-0.31	0.49	-0.08	-0.47	0.32	*Trivial*
		Finals	2.59 ± 1.04	40.15								
High-SM	Game outcome	Win	17.03 ± 4.12	24.19	0.779	0.21	-1.25	1.67	0.02	-0.37	0.40	*Trivial*
		Loss	17.10 ± 4.38	25.61								
	Phase	Group	18.17 ± 3.93	21.63	**< 0.001**	2.56	1.09	4.03	-0.72	-1.14	-0.29	*Moderate*
		Finals	15.30 ± 4.14	27.06								
Jump	Game outcome	Win	3.85 ± 1.05	27.27	0.270	0.22	-0.17	0.61	-0.15	-0.53	0.24	*Trivial*
		Loss	3.68 ± 1.19	32.34								
	Phase	Group	3.58 ± 1.06	29.61	**0.009**	-0.53	-0.92	-0.14	0.44	0.03	0.84	*Small*
		Finals	4.06 ± 1.17	28.82								

Abbreviations: CV%, coefficient of variation as a percentage; CI, confidence intervals; ES, effect size; SM, specific movements. *Notes*: Bolded *P* value indicates statistically significant difference ($P < 0.05$).

TABLE 4. Physical demands (mean ± standard deviation) according to game outcome (i.e., win vs. loss) and competition phase (i.e., group games vs. finals games [quarter-finals, semi-finals, and finals]) during the female 2019 FIBA 3 × 3 World Cup.

Dependent variables	Fixed effect			CV%	*P* value	Estimate	95% CI for estimate		ES	95% CI for ES		Interpretation
							Lower	Upper		Lower	Upper	
Frequency of occurrence (n/min)												
REC	Game outcome	Win	4.96 ± 1.59	32.06	0.237	0.28	-0.18	0.73	-0.08	-0.45	0.29	*Trivial*
		Loss	4.83 ± 1.67	34.58								
	Phase	Group	5.03 ± 1.61	32.01	0.310	-0.23	-0.68	0.22	-0.19	-0.56	0.19	*Trivial*
		Finals	4.72 ± 1.65	34.96								
LIA	Game outcome	Win	15.20 ± 1.74	11.45	0.407	0.24	-0.32	0.80	-0.02	-0.39	0.35	*Trivial*
		Loss	15.17 ± 1.53	10.09								
	Phase	Group	15.50 ± 1.58	10.19	**0.018**	0.70	0.13	1.27	-0.47	-0.85	-0.08	*Small*
		Finals	14.76 ± 1.61	10.91								
MIA	Game outcome	Win	8.08 ± 1.58	19.55	0.609	-0.14	-0.65	0.38	0.18	-0.20	0.55	*Trivial*
		Loss	8.35 ± 1.41	16.89								
	Phase	Group	8.04 ± 1.40	17.41	0.290	-0.28	-0.80	0.24	0.27	-0.11	0.65	*Small*
		Finals	8.45 ± 1.59	18.82								
HIA	Game outcome	Win	11.95 ± 2.57	21.51	0.464	-0.31	-1.13	0.51	0.05	-0.32	0.42	*Trivial*
		Loss	12.08 ± 2.27	18.79								
	Phase	Group	11.75 ± 2.59	22.04	0.476	-0.30	-1.14	0.53	0.26	-0.12	0.64	*Small*
		Finals	12.37 ± 2.12	17.14								
Total	Game outcome	Win	40.20 ± 3.43	8.53	0.952	-0.04	-1.22	1.15	0.06	-0.31	0.43	*Trivial*
		Loss	40.42 ± 3.41	8.44								
	Phase	Group	40.32 ± 3.50	8.68	0.827	0.13	-1.06	1.33	-0.01	-0.38	0.37	*Trivial*
		Finals	40.30 ± 3.31	8.21								
Total time (%)												
REC	Game outcome	Win	14.11 ± 6.38	45.22	0.170	1.29	-0.54	3.11	-0.12	-0.49	0.25	*Trivial*
		Loss	13.34 ± 6.51	48.80								
	Phase	Group	13.90 ± 6.30	45.32	0.108	-1.50	-3.31	0.31	-0.06	-0.44	0.31	*Trivial*
		Finals	13.48 ± 6.66	49.41								
LIA	Game outcome	Win	44.89 ± 5.87	13.08	0.707	0.36	-1.50	2.22	-0.08	-0.45	0.29	*Trivial*
		Loss	44.41 ± 5.76	12.97								
	Phase	Group	45.40 ± 6.02	13.26	**0.010**	2.52	0.65	4.40	-0.30	-0.68	0.08	*Small*
		Finals	43.66 ± 5.38	12.32								
MIA	Game outcome	Win	16.70 ± 2.84	17.01	0.651	-0.23	-1.25	0.78	0.16	-0.21	0.53	*Trivial*
		Loss	17.15 ± 2.90	16.91								
	Phase	Group	16.54 ± 2.86	17.29	0.192	-0.68	-1.71	0.34	0.31	-0.07	0.69	*Small*
		Finals	17.43 ± 2.82	16.18								
HIA	Game outcome	Win	24.30 ± 4.82	19.84	0.166	-1.11	-2.66	0.45	0.17	-0.20	0.54	*Trivial*
		Loss	25.10 ± 4.65	18.53								
	Phase	Group	24.16 ± 4.79	19.83	0.214	-1.00	-2.57	0.57	0.27	-0.11	0.65	*Small*
		Finals	25.43 ± 4.60	18.09								

Abbreviations: CV%, coefficient of variation as a percentage; CI, confidence intervals; ES, effect size; REC, recovery; LIA, low-intensity activities; MIA, medium-intensity activities; HIA, High-intensity activities; SM, specific movements. *Notes*: Bolded *P* value indicates statistically significant difference ($P < 0.05$).

TABLE 5. High-intensity activities (mean ± standard deviation) according to game outcome (i.e., win vs. loss) and competition phase (i.e., group games vs. finals games [quarter-finals, semi-finals, and finals]) during the female 2019 FIBA 3 × 3 World Cup.

Dependent variables	Fixed effect			CV%	*P* value	Estimate	95% CI for estimate		ES	95% CI for ES		Interpretation
							Lower	Upper		Lower	Upper	
Frequency of occurrence (n/min)												
Sprint	Game outcome	Win	1.96 ± 0.97	49.49	0.098	-0.28	-0.62	0.05	0.23	-0.15	0.60	*Small*
		Loss	2.20 ± 1.10	50.00								
	Phase	Group	1.94 ± 0.93	47.94	0.251	-0.20	-0.53	0.14	0.32	-0.06	0.70	*Small*
		Finals	2.27 ± 1.15	50.66								
High-SM	Game outcome	Win	6.57 ± 1.43	21.77	0.208	-0.30	-0.75	0.16	0.11	-0.26	0.48	*Trivial*
		Loss	6.72 ± 1.31	19.49								
	Phase	Group	6.45 ± 1.45	22.48	0.230	-0.28	-0.75	0.18	0.33	-0.06	0.70	*Small*
		Finals	6.89 ± 1.23	17.85								
Jump	Game outcome	Win	3.43 ± 1.00	29.15	0.148	0.25	-0.09	0.59	-0.28	-0.66	0.09	*Small*
		Loss	3.17 ± 0.85	26.81								
	Phase	Group	3.36 ± 1.00	29.76	0.291	0.19	-0.16	0.53	-0.16	-0.53	0.22	*Trivial*
		Finals	3.21 ± 0.85	26.48								
Total time (%)												
Sprint	Game outcome	Win	2.88 ± 1.43	49.65	0.061	-0.53	-1.08	0.02	0.30	-0.07	0.68	*Small*
		Loss	3.39 ± 1.84	54.28								
	Phase	Group	2.94 ± 1.53	52.04	0.368	-0.26	-0.81	0.30	0.27	-0.11	0.65	*Small*
		Finals	3.39 ± 1.80	53.10								
High-SM	Game outcome	Win	17.97 ± 3.86	21.48	0.165	-0.91	-2.19	0.37	0.17	-0.20	0.54	*Trivial*
		Loss	18.63 ± 3.81	20.45								
	Phase	Group	17.87 ± 3.89	21.77	0.123	-1.03	-2.32	0.27	0.26	-0.12	0.64	*Small*
		Finals	18.87 ± 3.72	19.71								
Jump	Game outcome	Win	3.45 ± 1.07	31.01	0.063	0.34	-0.01	0.69	-0.37	-0.74	0.01	*Small*
		Loss	3.09 ± 0.85	27.51								
	Phase	Group	3.35 ± 1.02	30.45	0.213	0.23	-0.13	0.58	-0.18	-0.56	0.19	*Trivial*
		Finals	3.17 ± 0.91	28.71								

Abbreviations: CV%, coefficient of variation as a percentage; CI, confidence intervals; ES, effect size; SM, specific movements. *Notes*: Bolded *P* value indicates statistically significant difference ($P < 0.05$).

technical-tactical variables significantly favouring winning compared to losing teams in the Euroleague (i.e., assists, blocked shots, fouls, turnovers, shots made, and shooting percentage) [26], Australian National Basketball League (i.e., shots made, defensive rebounds, blocked shots, assists, steals, fouls, and turnovers) [27], and FIBA Asian and European Women's Championships (i.e., shots made, rebounds, blocked shots, assists, steals, and turnovers) [28]. Consequently, past findings combined with those in this study indicate that tactical and/or skill differences might differentiate team success more than physical outputs in high-level basketball games following 3 × 3 and 5 × 5 formats. In turn, technical-tactical elements may be particularly important to consider when developing and/or selecting players for 3 × 3 basketball competitions. However, given that existing technical-tactical data for 3 × 3 basketball games were indicative of the 2019 European Basketball Cup [3] and the physical data provided in this study were indicative of the 2019 World Cup, further research exploring technical-tactical and physical demands collectively in the same 3 × 3 basketball competition are encouraged to confirm this notion.

Unlike game outcome, significant differences emerged in the physical demands encountered during group games compared to finals games. More precisely, in the male competition at the 2019 World Cup, the lower HIA and high-SM bouts per minute and greater proportion of playing time spent in recovery and jumping in finals games compared to the group phase might be attributed to an increased defensive pressure being applied in finals games. In this regard, teams may have adopted tighter defensive structures during finals games compared to group games, limiting the freedom of opponents to move at high intensities as well as contested shots more effectively resulting in more jumping activity (i.e., attempting to block shots, shooting over defender's hands, and securing rebounds). In contrast to male players, female players at the 2019 3 × 3 World Cup performed significantly less LIA during finals games compared to group games, suggesting increased activity was dispersed among moderate and high intensities to a greater extent in finals games. This trend in activity for female players may be expected given the increased opponent quality faced in finals games may evoke higher activity demands and/or players may place increased importance on finals games given the proximity to deciding the competition outcome [29] and consequently work at greater activities intensities than during group games. Nevertheless, it should be noted that the significant differences in physical demands in male and female players between group and final games were *small* in magnitude, with many variables not reaching significance. In this regard, past research examining a large sample of male (n = 250) and female (n = 201) basketball players competing in the 2016 FIBA 3 × 3 under-18 World Championships, Senior European and World Championships, and selected FIBA World Tour events showed no clear change in external load (i.e., Player-Load · min^{1}) or internal load (i.e., blood lactate concentration and average heart rate) variables from the first group game to the championship game [7]. Likewise, few technical-tactical demand variables were shown to differ between group and finals games (i.e., higher points per possession and less blocked shots during finals) in male and female teams competing in the 2019 3 × 3 European Basketball Cup [3]. Consequently, the collective 3 × 3 basketball research suggests the physiological, physical, and technical-tactical demands are rather consistent across competitions phases. Thus, the present findings should not be overstated as it appears that competition phase may only partially impact (i.e., have *small* effects) the physical demands experienced by players in the context of the 2019 3 × 3 World Cup.

The novel findings presented in this study should be interpreted while considering the associated limitations. First, male and female competitions in the 2019 3 × 3 World Cup were examined in this study, so the reported data may not be indicative of other 3 × 3 competitions. Second, physical demand variables were determined using video-based TMA with subjective tester interpretation of video footage, so further research complementing these analyses with objective approaches to quantify the physical demands (e.g., local positioning system or inertial sensor technologies) and internal stress imposed on players according to each contextual factor are encouraged to provide a more holistic indication of the demands encountered during 3 × 3 basketball games. Third, key contextual factors in the form of game outcome and competition phase were selected for analyses in this study given they have been examined in previous basketball research [17, 18, 30] to provide useful insight for end-users. However, other contextual factors shown to impact the physical demands placed on basketball players during games such as opponent quality [31], game location [17], and score-line [17] warrant consideration in future research. Fourth, the video sourced online had a small portion of footage missing (< 3%) for some games; however, it is anticipated that due to the brief footage missed for a selection of games, the overall physical demands reported were not adversely impacted. Finally, games were removed from analyses where lower-ranked teams (i.e., teams that did not make the finals phase) played one another to permit more even comparisons between group and finals phases in the present study. Consequently, the comparative analyses presented in this study are indicative of better-ranked teams who reached the finals phase at the 2019 3 × 3 World Cup.

Practical applications

The present findings hold useful practical applications in various ways. The similar physical demands experienced in games that were won and lost suggest team success may not be predicated on physical capabilities in international 3 × 3 basketball competition. In turn, players competing at the highest standard of play (i.e., World Cup) may possess rather homogenous physical capacities given the elite level of competition. Nevertheless, it is essential that the physical preparation of players is given adequate consideration alongside technical-tactical skills through appropriate training and recovery plans to ensure players reach the requisite level of fitness needed to

compete in 3 × 3 international basketball competition. In this regard, it appears that the reduced playing area associated with 3 × 3 compared to 5 × 5 basketball limits the ability of players to perform sprints on a repeated basis, with most high-intensity activity captured in the present study consisting of basketball-specific movements (i.e., stance position, shuffling, rolling, reversing, screening, and cross-over running). Consequently, our data support previous recommendations advocating the need to develop acceleration, deceleration, and change-of-direction attributes through appropriate strength and conditioning approaches in 3 × 3 basketball given the reduced running demands compared to traditional 5 × 5 basketball [8]. Furthermore, our data emphasise 3 × 3 basketball players require well-developed vertical power expression with > 3 jumps performed per minute on average during games, including significantly greater playing time spent jumping in finals games compared to group games in male players. Despite some variations in physical demands between group and finals games, most variables were consistent between competition phases similar to external and internal load data reported in other international 3 × 3 basketball competitions [7]. These data suggest players may have adequate fitness capacities and/or adopt effective recovery strategies between games to offset an accumulative fatigue and maintain activity outputs across competition phases in light of the short game durations and tournament setting during the 2019 3 × 3 World Cup.

CONCLUSIONS

The present findings add to the limited knowledge surrounding the physical demands encountered during 3 × 3 basketball game-play, providing foundation data specifically during the 3 × 3 World Cup. In turn, physical player demands were consistent irrespective of whether teams won or lost in both male and female competitions. Furthermore, although physical player demands differed for some variables during finals games compared to group games in male players (HIA and high-SM decreased while jumping duration decreased in finals) and female players (LIA decreased in finals), these effects were mostly *small* in magnitude with many variables remaining consistent between competition phases.

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Conflict of interest declaration

The authors report no conflict of interest for this manuscript.

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Nap improved game-related technical performance and physiological response during small-sided basketball game in professional players

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ABSTRACT: The effect of 40-min nap (NAP) opportunity on psycho-physiological outcomes and technical performance during small-sided basketball game (SSG) was examined in ten professional basketball players. Nocturnal sleep and naps were monitored by actigraphic recording and sleep diaries. Nocturnal total sleep time (TST), time in bed (TIB), sleep efficiency (SE), sleep onset latency (SOL) and wake after sleep onset (WASO) were analyzed. Subjective sleep quality was assessed with visual analogue scale (VAS). Profile of mood state (POMS) and simple reaction time (SRT) were measured before and after Nap and no-nap (CON) conditions. During both test sessions, participants played 10-min SSG. Technical and tactical performances were assessed using Team Sport Assessment Procedure. Volume of play (VP), attack with ball (AB), efficiency index (EI) and performance score (PS) were determined. Heart rate (HR) was measured during SSG, and rating of perceive excretion (RPE) after. Lower HR ($p \leq 0.03$, $d \geq 0.78$) and RPE ($p = 0.007$, $d = 1.11$) were obtained in NAP compared to CON. There was no significant difference in TIB, TST, SE, WASO and VAS between CON and NAP conditions. AB, EI and PS were higher in NAP compared to CON ($0.0002 \leq p \leq 0.001$, $1.3 \leq d \leq 1.8$). A significant reduction was observed in POMS' fatigue ($p = 0.005$, $d = -1.16$, $\Delta = -53.6\%$), anxiety ($p = 0.02$, $d = -0.9$, $\Delta = -32.1\%$), anger ($p = 0.01$, $d = -0.94$, $\Delta = -30.3\%$), and an improvement in vigor ($p = 0.01$, $d = 0.99$, $\Delta = +23.8\%$); which may reflect better readiness after nap and more concentration to start a game-situation. In summary, NAP reduced fatigue, anger, anxiety and enhanced vigor, allowing better technical and tactical performances during basketball SSG.

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INTRODUCTION

Basketball is considered as an intermittent high-intensity sport characterized by the repetition of short (≈ 2 seconds) high-intensity (i.e., average work-to-rest ratio of 1:3.6 during competition) movements (i.e., runs, shuffles, sideway runs and jumps) [1, 2]. Studies analysing the physiological determinants of success in basketball revealed the importance of both aerobic and anaerobic pathways [1–5]. Indeed, the limited recovery time between high intensity actions and the need to maintain a high quality of these actions to win matches highlights the need for a well-developed (i) anaerobic system to be able to perform short duration high-intensity movements and (ii) aerobic metabolism allowing rapid recovery between intense efforts [1, 4]. Moreover, basketball players should have a good aerobic capacity to cover a distance of approximately 7.5 km per match [1]. While, explosive actions, such as changes of direction, jumps, sprints and movements at maximum intensity, depend on the anaerobic routes [6, 7]. Further, it has been reported that aerobic capacity is strongly correlated with high-intensity running during matches, and has been identified as one of the determinants of repeated sprint ability [3]. Besides, due to its complexity and mixed physical-technical-tactical nature, the game of basketball requires great attention to determining the physical demands and the required technical skills [8]. Several studies investigated physical demands in basketball [6, 7, 9–12]. However, technical demands remain poorly investigated [13, 14]. In this context, small-sided games (SSG) are widely used by basketball coaches in an attempt to simultaneously develop technical

and tactical skills under high physical loads [2, 5, 14–17]. Furthermore, International Basketball Federation (FIBA) has shown increasing interest in SSG with 3 × 3 (10 min gameplay) becoming an Olympic sport since Tokyo 2020 games.

Recently, a growing body of evidence suggests that napping enhances physical and cognitive performances. It has been reported that a diurnal nap opportunity improved endurance [18, 19] and short term physical performance (*i.e.,* jump [19], sprint [20], postural control [21] and strength [22, 23]). Interestingly, several studies showed improvement in repeated-sprint ability following various nap opportunities (*e.g.,* 20-min [24–26], 25-min [27, 28], 35-min [27], 40-min [23], 45-min [27]…). Due to the importance of repeated-sprint ability and the aerobic-anaerobic aspect of basketball during competition, it would be of interest to investigate the effect of napping on real-situation games.

The only study that investigated the effect of sleep extension on basketball athletes showed that the increase in sleep duration was associated with improvements in reaction time, sprint speed, shooting accuracy, free throw percentage, and three-point field goal percentage [29]. It is important to mention that naps were allowed in this study during control and sleep extension conditions; however, data about nap's exact duration was not reported. Thus, it might be useful to measure nightly sleep episodes and daytime naps separately to get more insight about nap's effect. In addition, the game-related technical aspect was not evaluated in this study [29]. To the best of authors' knowledge, no study examined the effect of napping on technical performance during small-sided basketball games.

Therefore, the aim of the present study is to examine the effect of 40-min nap opportunity on cognitive outcomes and technical performance during SSG in professional basketball players. We hypothesized that diurnal napping would (i) improve technical game-related performance and (ii) enhance physiological response of athletes during SSG situations.

MATERIALS AND METHODS

Participants

Ten high-level professional basketball players (age, 27.6 ± 4.7 years; height, 194.2 ± 7.3 cm; mass, 89.6 ± 11 kg; body mass index, 23.4 ± 1.8 m·kg^{-2}; body fat, 13.71 ± 2.5%, expertise, 18 ± 5 years, normative retiring and rising times: 22:57 ± 0:22 h: min and 07:00 ± 0:48 h: min, respectively) volunteered for this study. Verbal explanation of the experimental procedure was provided to each individual. Then they provided written informed consent before participating in the study. All of them were non-habitual nappers. They trained regularly 6 to 8 times per week (≈ 2 h/practice) since they signed a professional contract (*i.e.,* professional career, 9 ± 4 years). They were asked to sustain from consuming tobacco, alcohol or caffeine and were not allowed to nap during the experimental days. Based on the Horne and Ostberg self-assessment Morningness–Eveningness Questionnaire (MEQ) [30], participants who presented an

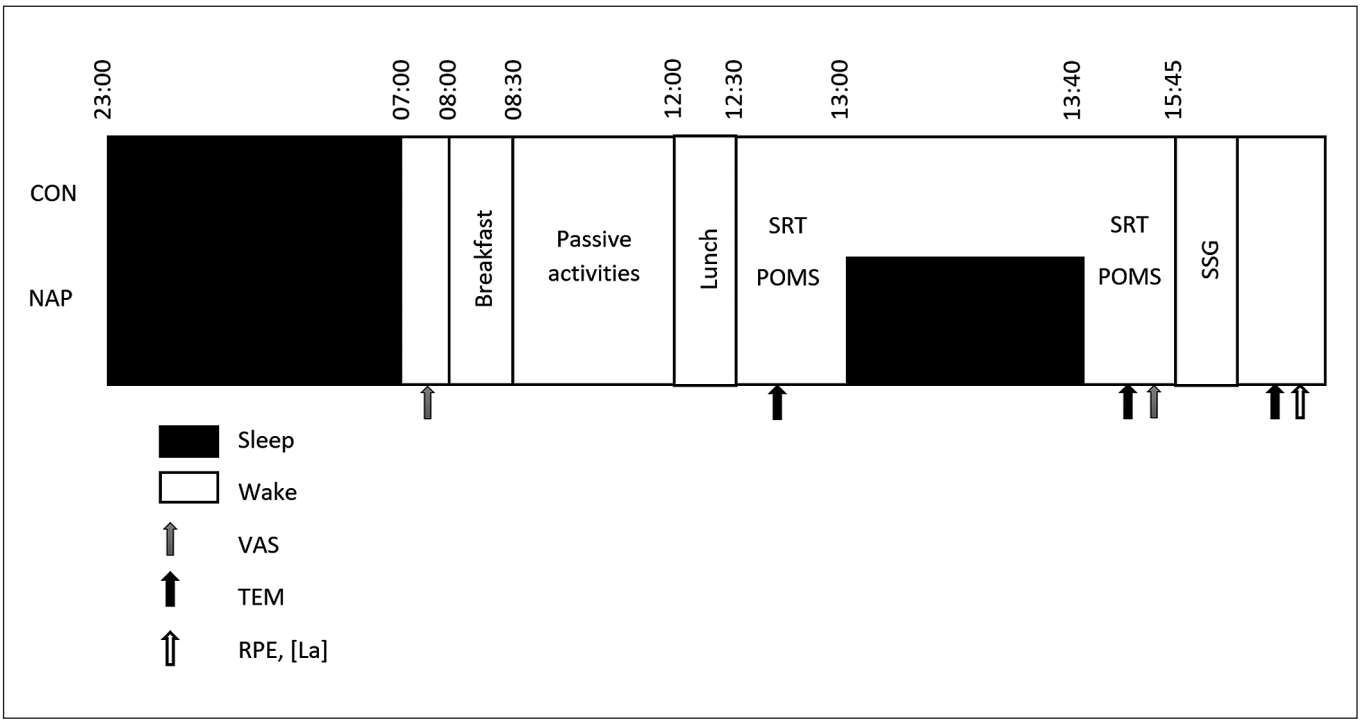


FIG. 1. Experimental protocol. ESS indicates Epworth Sleepiness Scale; POMS, Profile of Mood State; RPE, rating perceived of exertion; SRT, simple reaction time; TEM, temperature; VAS, visual analog scale; [La], blood lactate concentration.

extreme morning or extreme evening type were eliminated (MEQ mean score = 56 ± 3.1). The protocol of the present study was approved by the local Institutional Review Board (CPP SUD N° 0339/2021) and complied with Helsinki's declaration for human experimentation.

Procedure

A randomized crossover design was used. The participants were asked to visit the physiology laboratory on three separate occasions. During the first visit, anthropometric data were collected and participants were familiarized with the experimenters, laboratory, used material/devices, the sleeping room, tests, questionnaires and the experimental procedures. The experimental design is described in Figure 1.

Two weeks after the familiarization session, 2 test sessions were undertaken, 72 h apart, after normal sleep night. In both test sessions, participants arrived at the laboratory at 7:30. They subjectively rated their last night sleep on a visual analog scale and ate a qualitatively and quantitatively standardized breakfast at 08:00 h. Then participants stayed awake doing passive activities (*e.g.,* surfing on the internet, watching television, playing video games, reading) until noon; when they ate an isocaloric lunch. Afterwards, they were assigned to experience both nap (NAP) and no-nap (CON) conditions (*i.e.,* 13:00 h – 13:40 h) in a randomized order. Before and after each condition, simple reaction time (SRT) and intra-aural temperature (TEM) were measured and the profile of mood state questionnaire (POMS) was administrated.

In the NAP condition, participants entered the comfortably warm, fully dark, and quiet sleeping room at 12:45 h. Nap opportunity started at 13:00 h, after 10 min of acclimatization in bed, and lasted 40 min. The nocturnal sleep and naps were monitored by actigraphic recording and sleep diaries. In the CON condition, participants spent the same time (*i.e.,* 13:00 h – 13:40 h) seated on a comfortable chair watching television.

In both conditions, participants completed a 15 min standardized warm-up at 15:30 h. The warm-up consisted of a 5 min jog at a self-selected comfortable pace, followed by a 10 min of dynamic stretching (*e.g.,* lunges, butt kicks, hip flexion/extension, hip abduction/adduction), and five progressive sprints. Then, participants played a 10 min SSG. Heart rate (HR) was assessed during SSG, and blood lactate concentration [La], rating of perceived exertion (RPE) and TEM were assessed after the game for both NAP and CON conditions.

Measured Variables

Eliteness of athletes

Eliteness' mean score was 9.16 ± 1.2. Based on Swan et al.[31]' categories, athletes belong to the second-highest qualification, i.e., successful elite.

Actigraphy and sleep diaries.

For objective sleep measurements, participants wore GT3X activity monitors on their non-dominant arm (Actigraph, Pensacola, FL, USA), the night before each experimental day and during daytime napping opportunities. This non-invasive and cost-effective device was evaluated as a valid tool to assess sleep and wake behaviors compared to the gold standard polysomnography [32]. The GT3X data was downloaded and analyzed using Actilife 6 (version 6.13.7) software. A high-level sensitivity was used for the estimation of sleep-wake patterns in 60-s epochs. Actigraphic records were edited with information listed in the subjective sleep diaries. The following sleep parameters were derived and analyzed: total sleep time (TST), time in bed (TIB), sleep efficiency (SE), sleep onset latency (SOL) and wake after sleep onset (WASO).

Subjective sleep quality

The subjective sleep quality was evaluated using the visual analogue scale (VAS) [33]. An important related advantage of VAS is that, unlike whole numbers and words, they provide an unlimited number of possible responses along a single continuum [34]. The sleep

TABLE 1. Team sport assessment procedure components of Game Play

Components	Definitions
	Gaining possession of the ball
Conquering the ball (CB)	Interception. Stealing the ball from the opponent, or recapturing the ball after an unsuccessful shot on goal or near loss to the other team.
Receiving the ball (RB)	Receiving the ball from a teammate and not immediately losing control of it.
	Disposing of the Ball
Playing a neutral ball (NB)	Passing the ball to a teammate, or any pass that does not put the other team in jeopardy.
Losing the ball (LB)	Losing the ball to the other team without having scored a goal.
Influent passes (P)	Passing the ball to a partner, thus pressuring the other team, which most often leads to a shot on goal.
Executing a successful shot (SS)	Scoring or maintaining possession of the ball following the execution of a shot.

Note: Adapted from Gréhaigne et al. [36].

quality evaluation – VAS scale is a 10-cm scale. The scale shows "Very bad sleep quality" on the left side, and "Very good sleep quality" on the right side. The sleep value of the VAS is determined by measuring the distance between the marked point and the far-left end of the scale. VAS was administrated after both, nocturnal sleep and nap opportunity.

Team sport assessment procedure (TSAP)

TSAP has been used widely by students, teachers, coaches and researchers [35, 36]. In basketball, TSAP's validity was ascertained through inter-observer reliability and test-retest method [37]. Further, TSAP was used to analyze the effect of different SSGs on technical and tactical performance among youth basketball players of different levels, i.e., U14 and U16 [13].

TSAP focus on the offensive on-ball aspects of the game, assessing how a player gains the balls possessions, recording the number of Conquered Balls (CB) and Received Balls (RB); and how a player disposes of the ball, recording the number of Lost Balls (LB), Neutral Balls (NB), Influent Passes (P) and Success Shots (SS) (Table 1).

Observational analysis was conducted after video collection by two authors (MS and MJS), separately, using a sample of a variable recording sheet [36]. The authors that performed TSAP analysis had between 15 and 20 years of basketball's experience. All the variables were computed and used to calculate the indexes of "Volume of Play", "Attack with ball", "Efficiency index" and "Performance Score", using different formulas (Table 2). Cohen's k coefficient value (k = 0.86) reveals an almost perfect inter-observer agreement among all the observations [36].

Profile of mood state (POMS)

POMS standard validated psychological test [38] was administered pre and post nap/rest. It consists of 65-items classified into seven different subscales; anxiety-tension, anger-hostility, confusion-perplexity, depression-discouragement, fatigue-inertia, vigor-activity and interpersonal relationship.

TABLE 2. Formulas for calculating team sport assessment procedure variables outcomes.

Outcome variables	Calculation
Volume of play (VP)	CB + RB
Attack with ball (AB)	P + SS
Efficiency index (EI)	AB / (10 + LB)
Performance score (PS)	(VP /2) + (EI × 10)

Abbreviations: CB = conquering the ball; LB = losing the ball; P = Influent Passes; RB = receiving the ball; SS = executing a successful shot; VP = volume of play.

Intra-aural temperature (TEM)

TEM was measured using ThermoScan® 7 (Braun, IRT6520WE, Germany) equipped with Age Precision® technology which provides more precise temperature measurements depending on age. TEM was measured pre and post nap/rest, and at the end of SSG.

Simple reaction time (SRT)

SRT was assessed using software Reaction, INRP free software (4.05 version). Participants were asked to respond as quickly as possible to a visual stimulus (Blue Square) presented systematically at the center of the computer screen. SRT was measured before and after nap/rest.

Heart rate (HR)

The physiological demand was assessed using HR monitor chest belts (Team System 2, Polar, Kempele, Finland). HR beats were exported and analyzed using Excel software (Microsoft Corporation, Redmond, WA, USA). SSG' HR data were expressed as mean (HR_{mean}) and peak (HR_{peak}) HR as a percentage of each subject's individual HR_{max} (%HR_{max}).

Rating of perceived exertion (RPE)

RPE scores were collected at the end of SSG using the Borg 15-grade scale [39], which is considered a valid method to evaluate players' training load in team sports and has been widely used during basketball ball-drills [2, 14]. This psycho-physiological scale given score represents the exertion that the athlete experiences during the exercise [40].

Blood lactate concentration [La]

[La] was measured at the end of SSG using the Lactate Pro 2 portable blood lactate meter (Arkray, Kioto, Japan) on micro blood samples drawn from the tip of the index finger according to the manufacturer's instructions.

Statistical analysis

The following analyses were performed using Excel (Microsoft Office, v.2016) and SPSS Statistics (IBM, v.23) softwares. All data were expressed as means ± standard deviations (SD).

The Shapiro-Wilk W-test revealed that TEM, POM'S variables, VP, AB, PS, EI, HR_{mean}, HR_{peak}, RPE and [La] were normally distributed. TEM and POMS were analyzed using a two-way repeated-measures ANOVA [2 conditions (CON and NAP) × 2 times (pre and post rest/nap)] for POM'S, [2 conditions (CON and NAP) × 3 times (pre and post rest/nap and after SSG)] for TEM. All ANOVA effect sizes were calculated as partial eta squared (np^2). When significant main or interaction effects were observed, pairwise comparisons were performed using Bonferroni post-hoc test.

Paired samples t-test was used to determine differences of VP, AB, PS, HR_{mean}, HR_{peak}, RPE and [La] between CON and NAP conditions. Effect sizes were calculated using Cohen (*d*) test [41].

Wilcoxon test was used to compare differences between CON and NAP conditions for SOL, SE, TIB, TST, WASO and VAS. Statistical significance level was set at $p < 0.05$.

RESULTS

Objective and subjective sleep Parameters

There was no significant difference during the night before experimental days in TIB ($p = 0.3$), TST ($p = 0.5$), SE ($p = 0.5$), SOL ($p = 0.4$), WASO ($p = 0.3$) and VAS ($p = 0.5$) between CON and NAP.

TSAP

Although no significant difference was reported in VP, statistical analysis revealed a significant improvement for AB, EI and PS in NAP compared to CON condition (Table 3).

TABLE 3. Mean values (± SD) for observational variables of technical and tactical performance collected by the Team Sport Assessment Procedure.

		Mean ± SD	P	*d*	Δ (%)
VP	CON	21.70 ± 2.79	NS	–	–
	NAP	23.40 ± 4.01			
AB	CON	5.80 ± 2.20	0.001	1.57	+ 45.3
	NAP	10.60 ± 3.34			
EI	CON	0.33 ± 0.12	0.0002	1.80	+ 54.8
	NAP	0.73 ± 0.25			
PS	CON	14.16 ± 2.15	0.003	1.30	+ 25.3
	NAP	18.96 ± 3.86			

Abbreviations: AB = attack with ball; CON = control condition; EI = Efficiency index; NAP = nap condition; PS = performance score; VP = volume of play.

POMS

Two-way repeated measures ANOVA revealed a significant interaction for anxiety ($F_{(1,9)} = 17.8$, $p = 0.002$, $\eta p^2 = 0.66$), anger ($F_{(1,9)} = 11.5$, $p = 0.008$, $\eta p^2 = 0.56$), depression ($F_{(1,9)} = 9.9$, $p = 0.01$, $\eta p^2 = 0.52$), fatigue ($F_{(1,9)} = 16.5$, $p = 0.003$, $\eta p^2 = 0.64$), and vigor ($F_{(1,9)} = 6.8$, $p = 0.02$, $\eta p^2 = 0.42$). Scores are presented in Table 4.

Scores were significantly lower after nap compared to values before nap for anxiety ($p = 0.02$, $d = -0.9$, $\Delta = -32.1\%$), anger ($p = 0.01$, $d = -0.94$, $\Delta = -30.3\%$) and fatigue ($p = 0.005$, $d = -1.16$, $\Delta = -53.6\%$). In addition, POMS' fatigue ($p = 0.002$, $d = -1.32$, $\Delta = -55.7\%$) and anxiety ($p = 0.003$, $d = -1.26$, $\Delta = -42.4\%$) values were significantly lower after NAP compared to values after CON condition. In CON condition, Bonferroni post-hoc test revealed an increase in fatigue ($p = 0.01$, $d = 0.9$, $\Delta = + 29.2\%$), anxiety ($p = 0.005$, $d = 1.2$, $\Delta = + 30.8\%$) and depression ($p = 0.04$, $d = 0.8$, $\Delta = + 22.2\%$) scores after CON compared to values before CON. Furthermore, vigor' scores improved after nap compared to both, pre nap ($p = 0.01$, $d = 0.99$, $\Delta = + 23.8\%$) and after CON ($p = 0.03$, $d = 0.8$, $\Delta = + 28.6\%$) values.

TEM

Repeated measure ANOVA revealed a significant effect of time ($F_{(2,18)} = 69.5$, $p < 0.0005$, $\eta p^2 = 0.88$) and a significant interaction ($F_{(2,18)} = 12.3$, $p < 0.0005$, $\eta p^2 = 0.59$).

Bonferroni post-hoc test revealed that TEM was significantly lower in NAP after nap/rest compared to pre nap ($p = 0.001$, $d = 1.61$, $\Delta = 2.4\%$) and compared to CON condition ($p = 0.005$, $d = 1.16$, $\Delta = 2.1\%$) (Figure 2).

SRT

There was no significant effect of conditions ($F_{(1,9)} = 0.5$, $p > 0.05$, $\eta p^2 = 0.006$) or time ($F_{(1,9)} = 0.03$, $p > 0.05$, $\eta p^2 = 0.05$) on SRT.

TABLE 4. Mean (± SD) values for POMS' scores (anger, anxiety, confusion, depression, fatigue, and vigor) before and after nap and control conditions.

	CON		NAP	
	Pre	Post	Pre	Post
Anger, au	14.0 ± 7.27	15.1 ± 7.03	17.8 ± 6.32	12.4 ± 4.33 **
Anxiety, au	9.0 ± 4.97	12.5 ± 3.98 **	10.6 ± 5.32	7.2 ± 4.71 **, ##
Confusion, au	9.4 ± 5.13	9.5 ± 4.74	10.3 ± 4.79	8.9 ± 4.31
Depression, au	7.0 ± 5.23	9.0 ± 6.58 *	8.0 ± 5.96	4.9 ± 3.11
Fatigue, au	8.5 ± 5.46	11.5 ± 5.5 **	11.0 ± 5.16	5.1 ± 2.81 **, ##
Vigor, au	17.4 ± 5.5	15.2 ± 6.37	16.1 ± 4.53	20.6 ± 4.30 **, #

Significant difference compared to pre nap/rest: *P < 0.05, **P < 0.01. Significant difference compared to control (CON) condition, #P < 0.05, ##P < 0.01.

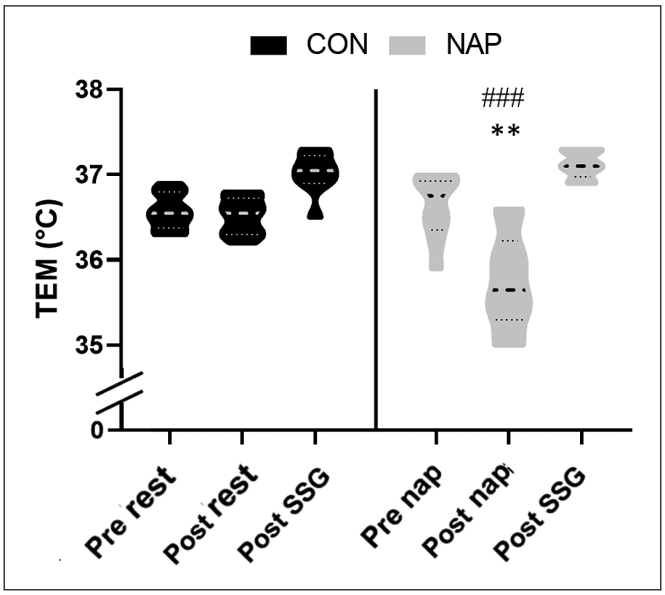


FIG. 2. Violin plot for intra-aural temperature (TEM) before and after nap/rest and after SSG in CON and NAP conditions. Significance was assessed with Two-way repeated-measures analysis of variance and Bonferroni post hoc tests. Horizontal and vertical bars represent the group means and SDs, respectively. SSG indicates small sided games. Significant difference compared to CON condition: **P < 0.01. Significant difference compared to pre nap/rest: ###P < 0.001.

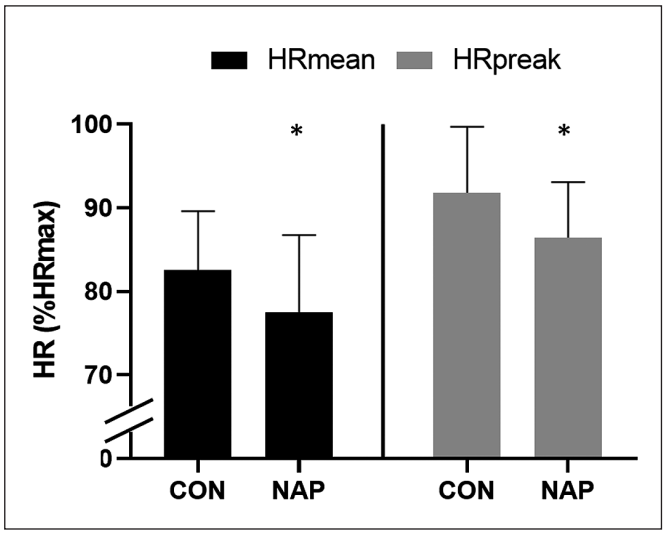


FIG. 3. Mean values (± SD) for HR_{mean} and HR_{peak} during SSG in CON and NAP conditions. Significant difference compared to CON condition: *P < 0.05.

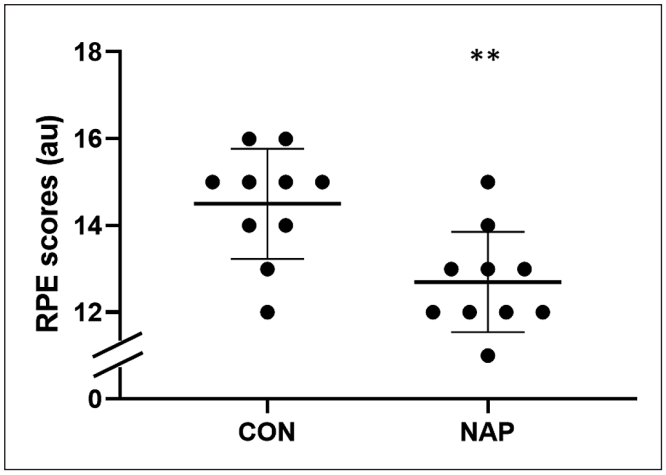


FIG. 4. Individual values for RPE scores in CON and NAP conditions after SGG. Significant difference compared to CON condition: **P < 0.01.

HR

The pairwise comparison revealed a significant effect of nap on HR. Results showed lower values in NAP compared to CON condition for HR_{mean} ($p = 0.03$, $d = 0.78$, $\Delta = 6.2\%$) and HR_{peak} ($p = 0.02$, $d = 0.83$, $\Delta = 5.8\%$) (Figure 3).

RPE

Statistical analysis revealed a significant effect of nap on RPE scores. Results showed lower values in NAP compared to CON condition ($p = 0.007$, $d = 1.11$, $\Delta = 12.4\%$) (Figure 4).

[La]

The paired Student t-test did not reveal a significant effect of nap on [La].

DISCUSSION

Although napping is commonly used as a strategy to improve human's physical and cognitive performances during separated exercise, to our knowledge, the present study is the first to evaluate the effectiveness of napping on (i) technical and tactical performance and (ii) physiological responses during real-situation game. Accordingly, the main findings of the current study were that NAP improved observational variables (AB, EI and PS) and physiological responses, decreased RPE, anger, fatigue, anxiety and intraoral temperature, and increased vigor. Importantly, in addition to the mean score of eliteness (i.e., 9.16 ± 1.20), body fat percentage (i.e., 13.7%) gives an additional argument regarding the high level of the athletes included in the present study. Indeed the average percentage of professional basketball players' body fat for men is 13.5 ± 2.9% [42].

There was no significant difference during the night before experimental days in sleep parameters (i.e., TIB, TST, SE, SOL and WASO) and subjective sleep quality – VAS the night preceding testing between CON and NAP conditions. About 7 h of TST and 85% of SE was obtained in each condition, which is the lowest recommended

sleep duration for athletes (7–9 h; [43]) and the lowest SE recommended for healthy adults to promote health (85%; [44]. Indeed, athletes require more sleep than the general population due to the imposed training load [45]. Evidence suggest that 8–9 h of TST are needed for athletes for optimal waking functioning [29, 46].

Interestingly, a major result in this study was that NAPO improved AB, EI and PS, while no significant difference was reported for VP between both conditions. It is important to mention that VP is the sum of conquered balls and received balls. As mentioned above TSAP focus on the offensive on-ball aspects of the game, assessing (i) how a player gains the balls possessions, recording the number of conquered balls and received balls and (ii) how a player disposes of the ball, recording the number of lost balls, neutral balls, influent passes and success shots. Therefore, the results of the present study showed that NAPO had a positive impact on the part of how the player disposes of the ball by improving AB, EI and PS. In this vein, according to Lastella et al. [47], the ability to make fast and accurate decisions in team sports is just as important as executing skills efficiently during competitions. Accordingly, our results are probably due to better decision making [48] and mastery of technical skills [49]; which implies better control of the ball, less turnovers and less mistakes on offense.

Otherwise, our results showed that RPE mean values during SSG were 12.4% lower after NAP compared to CON condition. These results are essentially the same as previous studies that reported a decrease in RPE mean values by 12.4% [23] and 16.7% [50] following 40-min NAPO and 19.6% following 45-min NAPO [27]. It is important to mention that shorter NAPO (i.e., $20 \leq$ NAPO ≤ 35 min) had minor (i.e., $1 \leq \Delta$ RPE $\leq 6\%$) [27] or even no effect on RPE scores [24, 28]. Thus, it could be posited that the participants performed better in NAP because they perceived the exercise to be less strenuous compared to CON condition. Moreover, in the present study RPE results were confirmed by a decrease in HR mean values, i.e., HR_{mean} and HR_{peak} (by 6.2% and 5.8%, respectively). To our knowledge, this is the first study to investigate the effect of daytime napping on HR response during physical effort. Further, we did not report any significant effect of nap on [La] measured after SSG. Prior investigations revealed higher [La] following 20 min NAPO after PSD [24] and NSN [51]; whereas, in the line with our results, no significant effect was reported following 90 min NAPO for both studies [24, 51]. It is possible that longer NAPO (i.e., NAPO $\geq$ 40 min) resulted in a greater aerobic contribution in energy synthesis compared to short NAPO [51]. In view of these results, it could be argued that improvement of technical and tactical performance during SSG is likely due to the better physiological response. This may increase the active recovery, and thus prepare the players for high intensities and to restart in the following offensive process. In this context, it was suggested that non-rapid eye movement (NREM) sleep is the time in which body actively repairs and restores itself [52]. This could explain the positive impact of napping on physiological response. Additionally, slow wave sleep – also known as deep NREM sleep – is thought to play an important role in cerebral restoration and recovery [53], which might explain the improvement of decision making.

Furthermore, mood states estimated by the POM'S (i.e., fatigue and anxiety) were significantly lower after NAP compared to CON. Additionally, nap improved vigor scores. In this context, it has been reported that mood state and physical performance have a direct relationship with sleep quality and quantity [23, 24, 51]. In agreement with presents findings, Boukhris et al. [23] revealed that 40 min NAPO decreased fatigue ($\Delta = 31.7\%$) and anxiety ($\Delta = 27.5\%$), and increased vigor ($\Delta = 16.6\%$) of fourteen amateur team sport players. Thus, the improvement of technical and tactical performance during the SSG after nap could also be explained by a reduction in fatigue and an increase in vigor. Importantly, for the same NAPO duration (i.e., 40 min), we reported higher percentages of improvement 55.7%, 42.4% and 28.6% (for fatigue, anxiety and vigor, respectively). This could be related to the fact that participants in our study are professional basketball players and probably carrying a greater sleep dept compared to participants in Boukhris et al. [23] study. In fact, athletes are known to experience chronically shortened sleep duration [54]. Elite athletes' sleep may be more disturbed than normal due to reasons such as jetlag, altitude, early morning training, increases in training load and traveling to sport meetings which might involve getting up early in the morning or retiring late at night [55]. In addition, a recent systematic review focused on the effect of sleep extension in athletes and concluded that the most important factor is athlete's normal sleep pattern and whether he/she is getting adequate sleep [56].

Besides, despite being in the ascending phase of temperature's circadian rhythm, current data showed a marked drop in TEM following NAPO. These results are in the line with prior investigations showing that napping decreased body temperature [20, 24, 51]. In this context, it has been reported that starting exercise with a lower core body temperature increases the duration of the exercise and delays fatigue onset [57]. In fact, hyperthermia causes a decrease in cerebral perfusion, which alters the evacuation of heat from the brain and reduces cerebral oxygenation during exercises [58]. However, in the present study we didn't have a significant effect of nap on TEM after SSG. The lack of a significant difference between the conditions could be related to the short duration of exercise (i.e., 10 min). Therefore, napping could be suggested as precooling technique to enhance endurance performance during long duration exercises. Nevertheless, further researches are required to investigate thermoregulatory response including long duration exercises.

Limitations

First, a small sample size was included in the present study. Second, napping is often seen as a response to insufficient nocturnal sleep, the current study shows a positive effect of napping in professional basketball players with normal sleep. However, it is well

known that sleep disturbances are frequent amongst athletes, which implies poorer sleep duration and lower sleep quality [55]. Thus, these results cannot be systematically generalized to all populations, and larger studies are still needed to confirm the veracity of the present findings. Third, the selected participants were non-habitual nappers. It was reported that non-habitual nappers displayed heavier sleep inertia at the awakening compared to habitual nappers [59]. Thus, results could be different if habitual nappers were included instead of non-habitual nappers especially for SRT in which no significant result was reported. Finally, future researches should consider the use of objective sleep measures (e.g., polysomnography) during nap opportunities in order to get more insight of sleep stages and nap duration.

CONCLUSIONS

The results of the present study showed that 40 min nap opportunity has a beneficial effect on technical and tactical performance, physiological responses and perceived exertion during a real game situation among elite athletes. In addition, napping may be an effective strategy for reducing fatigue, anxiety, anger and TEM, and enhancing vigor following a reference night. From a practical point of view, these findings can be placed in a professional context by implementing napping in athletes' schedule. Accordingly, basketball players are advised to plan a nap before practice and/or competition in order to improve their technical and tactical performance. Noting that, these results may suit the players' goals, and without violating doping regulations.

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Relationships between training load and wellbeing measures across a full season: a study of Turkish national youth wrestlers

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ABSTRACT: The two aims of this study were: (i) to analyse the correlations between weekly acute workload (wAW), chronic workload, acute/chronic workload rate (wACWR), training monotony and strain and the weekly (w) reports of delayed onset muscle soreness, wFatigue, wStress, wSleep quality, and the Hooper indicator (wHI); (ii) to analyse the relationships between early, mid and end preparation season (PS) and the full PS. Ten elite young wrestlers participated in this study. The subjects who were included in this research were wrestlers participating in competitions organized by the National Turkish Wrestling Federation. The subjects were monitored for 32 weeks and were divided into three time periods: early PS, W1 to W11; mid PS, W12 to W22; and end PS, W23 to W32. Very large correlations were found for wAW and wACWR with wFatigue and wHI during end PS. Also, the same workload parameters were significantly correlated with wStress ($r = 0.66$; $P = 0.03$), wSleep ($r = 0.78$; $P = 0.004$), and wHI ($r = 0.72$; $P = 0.01$) during mid PS. The results of this study offer new perspectives for specialists regarding the perceived level of load and the variations of wellbeing during a PS at the level of elite young wrestlers.

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INTRODUCTION

In elite sport practice and in research, the analysis of internal and external training loads has become a critical issue. In this regard, monitoring the athletes' internal training loads is important for understanding whether athletes are positively adapting to their training programme. Bourdon et al. (2017) stated that the measures of training load can be categorized as either internal or external, where external training loads are objective measures of the work performed by the athlete (speed, volume, acceleration, etc.) [1]. Internal training load is defined as the relative physiological and psychological stressors imposed on the athlete during training or competition. The same authors stated that there exist various methods for measuring internal load, such as rating of perceived exertion (RPE), session RPE (sRPE), training impulse (TRIMP), heart rate indices, blood lactate, oxygen uptake and/or psychological scales and questionnaires [1–3]. At present, especially the sRPE [2, 3] and the acute:chronic workload ratio (ACWR) [4] methods are being discussed, whereas sRPE has been extensively investigated and seems to be a valid tool for measuring internal training load in a variety of sports [3], especially in swimming [5].

Complementary, subjective daily wellbeing questionnaires have become increasingly prominent as a quick and easy method of understanding an athlete's readiness to train and can incorporate questions surrounding an athlete's sleep, stress levels, fatigue, etc. [6]. There is a large body of studies demonstrating the change in wellbeing questionnaires over the course of a pre- or full-season period [7]. Fullagar et al. [9] found that the perceptions of wellbeing variables (i.e., sleep quality, delay onset muscle soreness [DOMS], energy, and overall wellness) fell to the lowest level the day after a rugby league or American football match, but did not recover to baseline levels for at least four days after the match [7]. Furthermore, research has shown that a drop in perceptions of wellbeing can lead to reductions in external training load output in elite adult soccer and Australian rules players [8]. Additional, this study failed to quantify the association between training load and wellbeing in adolescent athletes [9].

In a study performed by Rossi et al. [10] on 22 elite soccer players, in 160 training sessions and 35 matches during the 2015/2016 season, it was found that the training workloads performed in the

previous week had a strong effect on perceived exertion and training load. On the other hand, the analysis of this prediction showed higher accuracy for medium RPE and S-RPE values compared with the extremes.

Additionally, the relationship between players' wellness profile and training load has received growing interest in recent years. The literature provides significant interactions between DOMS, stress, fatigue perception, and sleep quality [11].

However, regarding our study, there is no recent research analysing the relationship between the training load and wellbeing of youth wrestlers, which justifies this research. We found only a study conducted in Turkey, where they measured the level of anxiety in 50 wrestlers [11], or the somatotype and anthropometric assessment of wrestlers. A similar study by Lupo et al. [12] on five female and four male taekwondo athletes did not reveal any difference for gender. The internal training loads of competitive sessions (Edwards: 228 ± 40 arbitrary units, AU) were higher than those of pre-competitive sessions (192 ± 26 AU; $P = 0.04$). Although all data collections achieved significant correlations between Edwards' and session-RPE methods, a strong relationship ($r = 0.71$, $P < 0.001$) emerged only for PC sessions evaluated at 30 minutes of the recovery phase.

Based on the above observations, this study aimed: (1) to analyse the correlations between weekly acute workload (wAW), weekly chronic workload (wCW), wACWR, weekly training monotony (wTM), weekly training strain (wTS) and the weekly reports of delayed onset muscle soreness (DOMS), fatigue, stress, sleep quality, and the Hooper indicator (HI); (2) to analysis the relationships of early, mid and end preparation season (PS) with the full PS.

MATERIALS AND METHODS

Participants

Participants were ten elite juvenile wrestlers (mean ± standard deviation (SD); age, 16 ± 0.7 years; height, 163 ± 4.8 cm; body mass, 57.7 ± 9.0 kg; VO_{2max}, 48.7 ± 1.4 ml·kg^{-1}·min^{-1}), who were preparing to participate in competitions in the National Turkish Wrestling Federation. Inclusion criteria for the youth wrestlers recruited for this study were: (i) to have taken part in ≥ 90% of the training sessions of the whole PS; (ii) to not participate in separate exercises throughout the PS; (iii) to attend the national team camp during the PS. Hence, the type of feeding, rest, sleep, and accommodation temperature were the same for all wrestlers during the PS. PS training days included the following: (i) wrestling-specific technical and skills with moderate-intensity aerobic training; (ii) wrestling-specific technical and skills with anaerobic training; (iii) hypertrophy training for muscular neuromuscular adaptation; (iv) containing special moves in wrestling tactical and full body-weight training, plyometric training; (v) rest day; (vi) velocity and power training; (vii) and finally, competitive wrestling within the team. These wrestlers had at least 6 years of training experience. Before the start of the study, all wrestlers were enlisted, and with their parents were notified of the study's stages, and consent was signed by all of them. This study was approved by the Ethics Committee of the Afyon Kocatepe University. The entire study follows the Helsinki Declaration regarding human experimentation.

Sample size

Previous studies have reported large to very large correlations of workload variables with wellbeing in youth athletic and individual sports [13–16]. To obtain the sample size, the results were analysed with a minimum power of 0.80. Consequently, assuming the distribution to be two-tailed, with an α error of less than 0.05 and a large size effect, 10 wrestlers are required to reach 83.9% actual power to correlate workload variables with wellbeing.

Study design

The present study is a longitudinal descriptive study on under-17-year-old elite wrestlers of the Turkish national team in the 2017–2018 season. Daily information was collected in each training session for 32 weeks during the full PS. The whole monitoring was divided into three periods: early PS, W1 to W11; mid PS, W12 to W22; and end PS, W23 to W32 (Table 1). Throughout the PS, the minimum number of exercises recorded per week was three sessions. All wrestlers had three years of self-reported (RPE and HI) history of the Hooper Questionnaire and training load. HI 30 minutes before each training session and RPE 30 minutes after each training session by wrestlers were individually reported to the researchers [3]. The RPE number multiplied by the training time of each session was used to calculate the training load of the s-RPE. From this variable, the other indicators of training load – AW, CW, ACWR, TM, TS [2, 3] – were calculated

TABLE 1. During monitoring in full season.

Years	2017																								2018							
W (n)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
TS (n)	7	6	6	7	7	3	7	6	7	6	7	7	7	7	6	7	7	7	7	6	7	7	7	7	7	6	7	6	7	7	7	5
Months	July				August				September				October				November				December				January				February			
Periods	Early-PS												Mid-PS												End-PS							

Note: W, week; TS, training session; Early-PS, Early-preparation season, Mid-PS; Mid-preparation season; End-PS, End-preparation season.

for the whole PS. Information about the health status (i.e., HI) of juvenile wrestlers was obtained by asking them individually before each session [17, 18]. This included: quality of sleep, feeling exhausted (fatigue), contusion, DOMS, and stress status [13, 19]. These variables were calculated on a weekly basis and afterward were used for analyses. The unit of all variables of this study is the selected arbitrary unit (AU). Intermittent Fitness Test 30–15 ($IFT_{30–15}$) was used to calculate the VO_{2max} of the subjects. After performing the test, the formula specific to $IFT_{30–15}$ was used to obtain the VO_{2max} [20]. For this test, test-retest reliability was performed and afterward the intra-class correlation coefficient was calculated and was 0.81.

Procedures

Anthropometrics: Anthropometric measurements were taken once in the morning before the study [13, 21]. Standing height and body mass were measured (Seca 654, Hamburg, Germany). The accuracy of the height gauge was ± 5 mm and that of the scale was 0.1 per kg. These measurements followed the International Society for the Advancement of Kinanthropometry advanced instructions [22]. All measurements were repeated twice and their means were recorded. If the technical error measurement between the two assessments was above 3%, then the measurement was performed for the third time and the median of these three replications was finalized and recorded [13, 15].

Monitoring internal training loads: The internal loads were calculated by means of the s-RPE. In particular, the daily training load was quantified by means of the Borg scale re-designed by Foster [23]. To obtain the RPE score of each wrestler, the following question was regularly asked: "How do you feel about practising?" The announced number was recorded by RPE according to the Borg questionnaire (0 to 10). According to previous studies by Borg and Foster [16, 24, 25], the RPE score was obtained between 20 and 30 minutes after the end of the training sessions [26]. The score obtained by the athletes in RPE were then multiplied by the time of the session in minutes, thus providing the s-RPE measured in arbitrary units (A.U.) [27]. Wrestlers had been experienced in reporting RPE for at least 3 years.

Calculate workload indices: wAW is equal to the sum of the total weekly training loads [28]; the wCW is equal to the average training load in the last three weeks. Due to the use of this formula, this variable is available from the third week [29]. The wACWR was calculated using the uncoupled formula as in previous studies [13, 29, 30]. Due to the use of this formula, this variable is available from the fourth week. For example, wACWR for week 5 is equal to wAW5/0.333 × (wCW in the previous 3 weeks); wTM is equal to the average training load obtained per week divided by the SD of the training load per week. wTS is equal to wAW divided by wTM [28, 31].

Wellbeing status monitoring: The HI is a four-variable questionnaire (stress, fatigue, DOMS, and sleep quality) with seven points. Studies have shown that it can monitor an athlete's wellbeing status [17, 32]. This questionnaire was used before the training sessions of athletes to record the situation in the above four variables. Number 1 in this questionnaire means good condition and number 7 means bad condition in that index for the athlete. The accumulated data weekly of these variables were analysed: wStress, wFatigue, wDOMS, wSleep, and wHI. Wrestlers had experience using this questionnaire in previous years. All questions were asked individually. The daily data register was made in Excel.

Statistical analysis

SPSS (version 22.0; IBM, Armonk, NY) was used for computations. Descriptive statistics are presented as mean and SD. Additionally, the weekly changes and coefficients of variation are shown as percentages. Data normality and homogeneity were checked applying the Shapiro-Wilks and Levene's tests, respectively. After that, the associations between training workload measures and wellbeing variables were evaluated using the Pearson correlation test (r). Correlation thresholds were defined as follows [33]: ≤ 0.1, trivial; > 0.1 to ≤ 0.3, small; > 0.3 to ≤ 0.5, moderate; > 0.5 to ≤ 0.7, large; > 0.7 to ≤ 0.9, very large; and > 0.9, nearly perfect. The correlations were always presented with the 95% confidence interval (CI). The alpha level was set at $P \leq 0.05$. To calculate an a-priori estimation of power and sample size, the statistical software G-Power (University of Dusseldorf, Dusseldorf, Germany) was applied. The selected study design: t tests – Correlation: Point biserial model.

RESULTS

Figures 1 and 2 show the summary of every season period for training load variables (wAW, wCW, wACWR, wTM and wTS) and wellbeing variables (wDOMS, wFatigue, wStress, wSleep and wHI), respectively.

Within-week coefficient of variation (CV) and between-week variation (%) values for wAW, wCW, wACWR, wTM and wTS during in PS periods are presented in Figure 3. The maximum (41%) and lowest (9%) CV occurred in w18 and w12, respectively (Figure 3A). The greatest between-week change happened from w6 to w7 (Figure 3A). The highest (19%) and minimum variation (6%) was observed in w6 and w14, respectively for wCW (Figure 3B). For wACWR, the maximum (40%) and minimum (6%) CV was recorded in w18 and w12, respectively (Figure 3C). The greatest between-week variations occurred from w8 to w9 for wCW and w6 to w7 in wACWR (Figures 3B and 3C). The largest increase in between-week variation was observed from w6 to w7 for wTM, and from w7 to w8 for wTS. wTM and wTS presented the greatest CV (w11-TM: 62%; w6-TS: 46%) and smallest (w32-TM: 10%; w26-TS: 14%) (Figures 3D and 3E).

Figure 4 shows the within-week CV and between-week variations (%) for wellbeing categories across the PS. The CV in wDOMS was observed to be highest in w18 (42%) and lowest in w26 (9%) (Figure 4A). The greatest between-week change happened from w25 to w26 (Figure 3A). The highest CV was observed in w3 (40%) and the minimum variation (11%) in w8 for wFatigue (Figure 3B). wStress

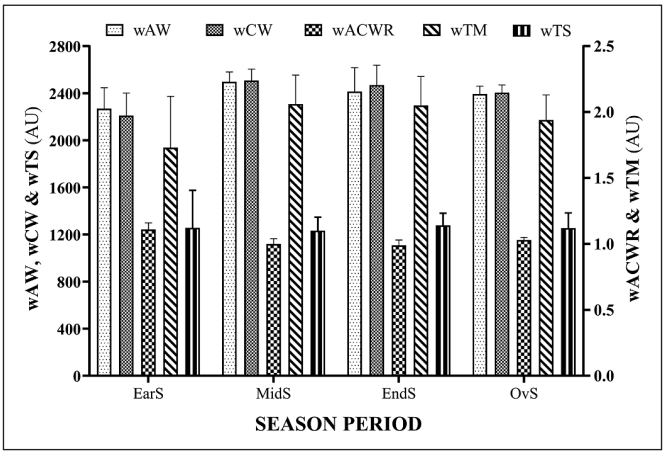


FIG. 1. Summary of every season period for training load variables: weekly acute workload (wAW), weekly chronic workload (wCW), weekly acute/chronic workload ratio (wACWR), weekly training monotony (wTM) and weekly training strain (wTS) Arbitrary Units (AU), Early-preparation season (EarS), Mid-preparation season (MidS), End-preparation season (EndS), Overall-preparation season (OvS=Full season).

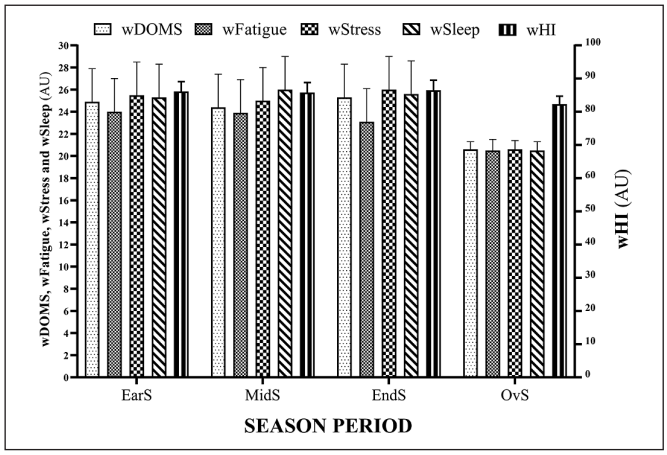


FIG. 2. Summary of every season period for wellbeing variables: weekly sleep quality (wSleep), weekly delayed onset muscle soreness (wDOMS), weekly fatigue (wFatigue), weekly stress (wStress) and weekly Hooper indicator (wHI). Arbitrary Units (AU), Early-preparation season (EarS), Mid-preparation season (MidS), End-preparation season (EndS), Overall-preparation season (OvS=Full season).

had the CV maximum in w15 (46%) and minimum in w5 (12%); see Figure 4C. The greatest between-week variation occurred from w18 to w19 for wFatigue, and w15 to w16 for wStress (Figures 4B and 4C). The percentage change in between-week variation showed the largest increase from w4 to w5 for wSleep, and w18 to w19 for wHI. Ultimately, wSleep and wHI presented the maximum CV (w15-sleep: 43%; w18-HI: 35%) and insignificant (w21-sleep: 8%; w13-HI: 5%) (Figures 4D and 4E).

Associations of wAW, wCW, and wACWR with wellbeing variables for the early-, mid- and end-PS periods and the full PS are presented in Figure 5. Overall, wAW had significant very large correlations with wFatigue (r = 0.77; 95% CI: 0.26 to 0.94; P = 0.01) and wHI (r = 0.73; 95% CI: 0.19 to 0.93; P = 0.02) during end PS (Figure 5A). wACWR had significant very large and large correlations with wFatigue (r = 0.73; 95% CI: 0.19 to 0.93; P = 0.02) and wHI (r = 0.69; 95% CI: 0.09 to 0.92; P = 0.03) during end PS. Workload parameters with meaningful correlations were wStress (r = 0.66; 95% CI: 0.10 to 0.90; P = 0.03) with a large correlation, wSleep (r = 0.78; 95% CI: 0.35 to 0.94; P = 0.004) with a very large correlation, and wHI (r = 0.72; 95% CI: 0.22 to 0.92; P = 0.01) with a very large correlation during mid PS (Figure 5C). There were no significant correlations between wCW and wellbeing variables during full-PS periods (Figure 5B).

The relationship between wTM, wTS and wellbeing status is shown in Figure 6. wTM showed a large correlation with wFatigue during end PS (r = 0.65; 95% CI: 0.04 to 0.91; P = 0.04) and a moderate correlation with wSleep in the overall PS (r = 0.40; 95% CI: 0.06 to 0.66; P = 0.03). wTS presented a large correlation with wStress during early PS (r = 0.61; 95% CI: -0.88 to -0.01; P = 0.048). wTS showed a very large correlation with wDOMS during mid PS (r = 0.77; 95% CI: 0.32 to 0.94; P = 0.005) (Figure 6B).

DISCUSSION

The objectives of this study were: (1) to analyse the relationships among wAW, wCW, wACWR, wTM, wTS, DOMS, fatigue, stress, sleep quality, and HI; (2) to analyse the relationships in different periods of the early, mid and end PS with the full PS.

In our study higher variation of wAW, fatigue, stress and HI was observed in the end PS. The most significant variation in wCW and fatigue was observed in the early PS, but the most significant reduction was observed at the mid PS. The largest increase and reduction in wACWR were observed in the early PS, where there was also the largest reduction in wTM, wTS, wDOMS, wStress and wHI. It is in concordance with previous studies; Clemente et at. also found the highest reduction of wDOMS, wStress and wHI during the early season. It seems that during the beginning of the season there are fewer decisive matches and this could improve the wellbeing [29].

wTM, wTS, wSleep and wDOMS showed the greatest variation in mid PS. The highest value of between-week variation for wTS was w8 to w9, and the lowest reduction for wACWR was between w9 and w10. The highest within-week variation was found for wACWR in w18, and the lowest for wCW in w19. The results of this study are somewhat different from previous studies in young soccer players [13]. Nobari et al. reported that the highest values of variation of wCW and wTS were observed in the mid season, while the lowest values were found in the early season. They also observed that the highest values of wFatigue, wDOMS, and wStress corresponded to the end season, and the lowest values of wSleep and wStress were in the early season, while the lowest values of wFatigue and wDOMS

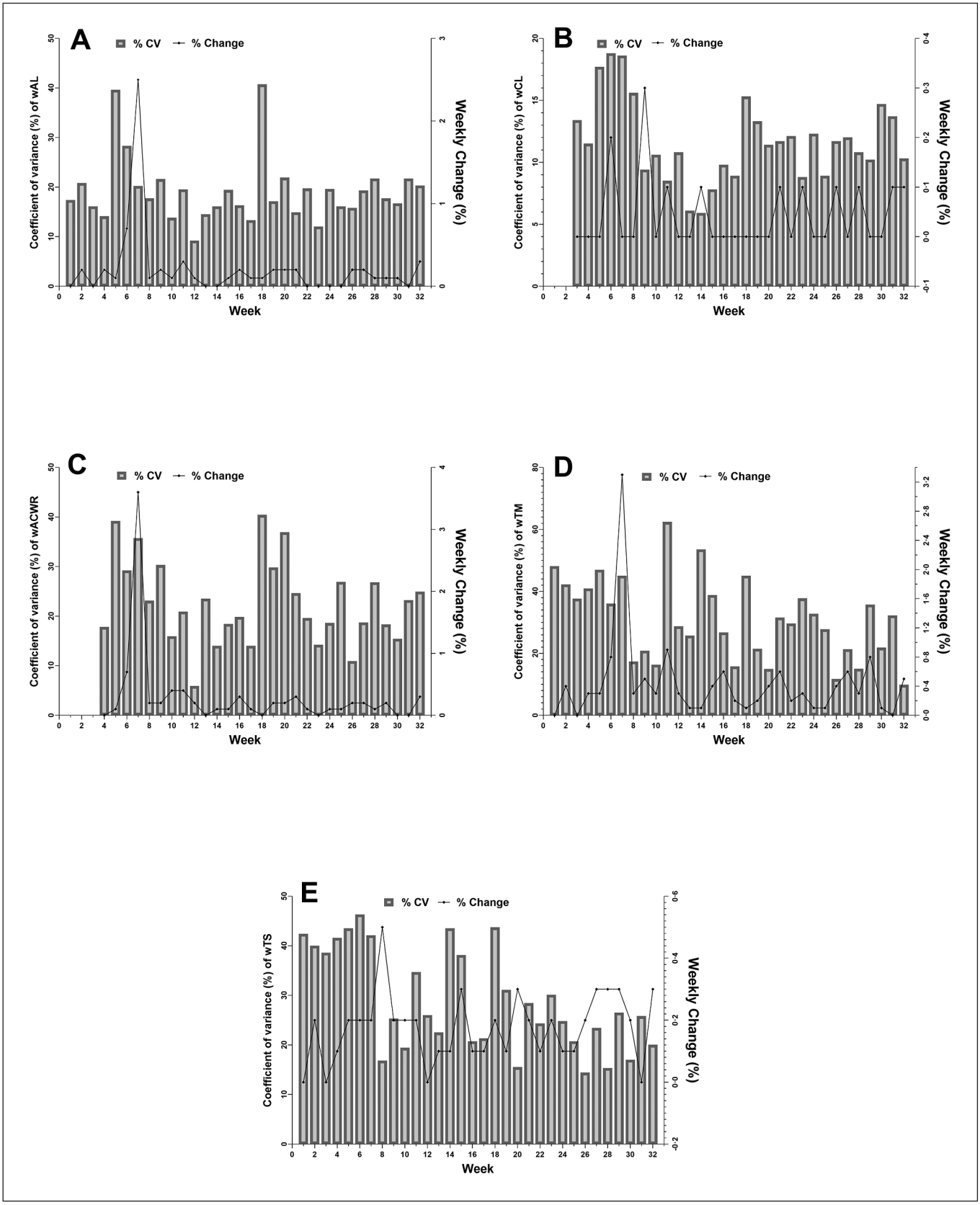


FIG. 3. Within-week coefficient of variations (CV) and between-week variations (%) for A) acute workload (AW), B) chronic workload (CW), C) weekly acute/chronic workload ratio (wACWR), D) weekly training monotory (wTM) and E) weekly training strain (wTS) across the season.

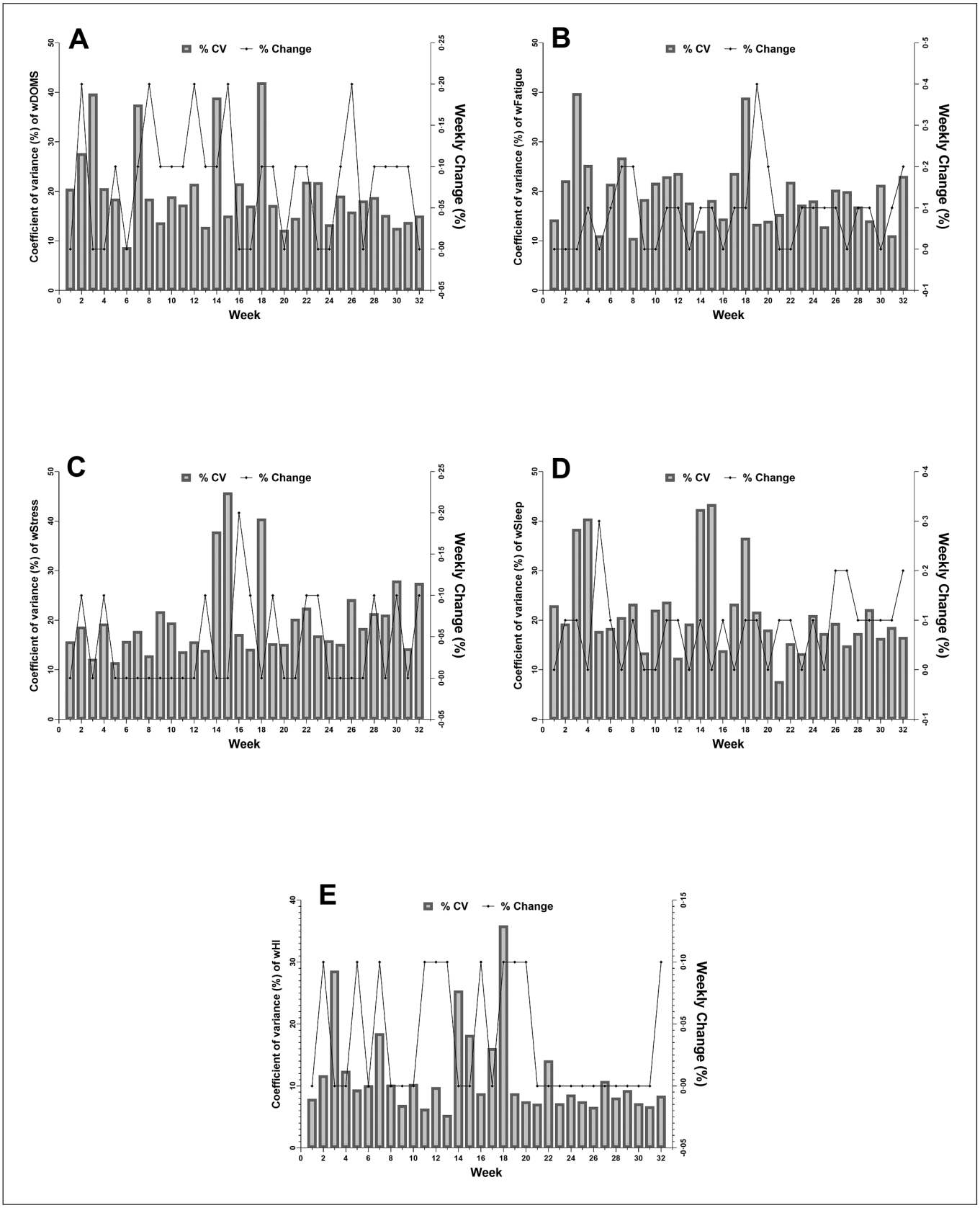


FIG. 4. Within-week coefficient of variations (CV) and between-week variations (%) for A) weekly delayed onset muscle soreness (wDOMS), B) weekly fatigue (wFatigue), C) weekly stress (wStress), D) weekly sleep quality (wSleep), and E) weekly Hooper indicator (wHI) across the season.

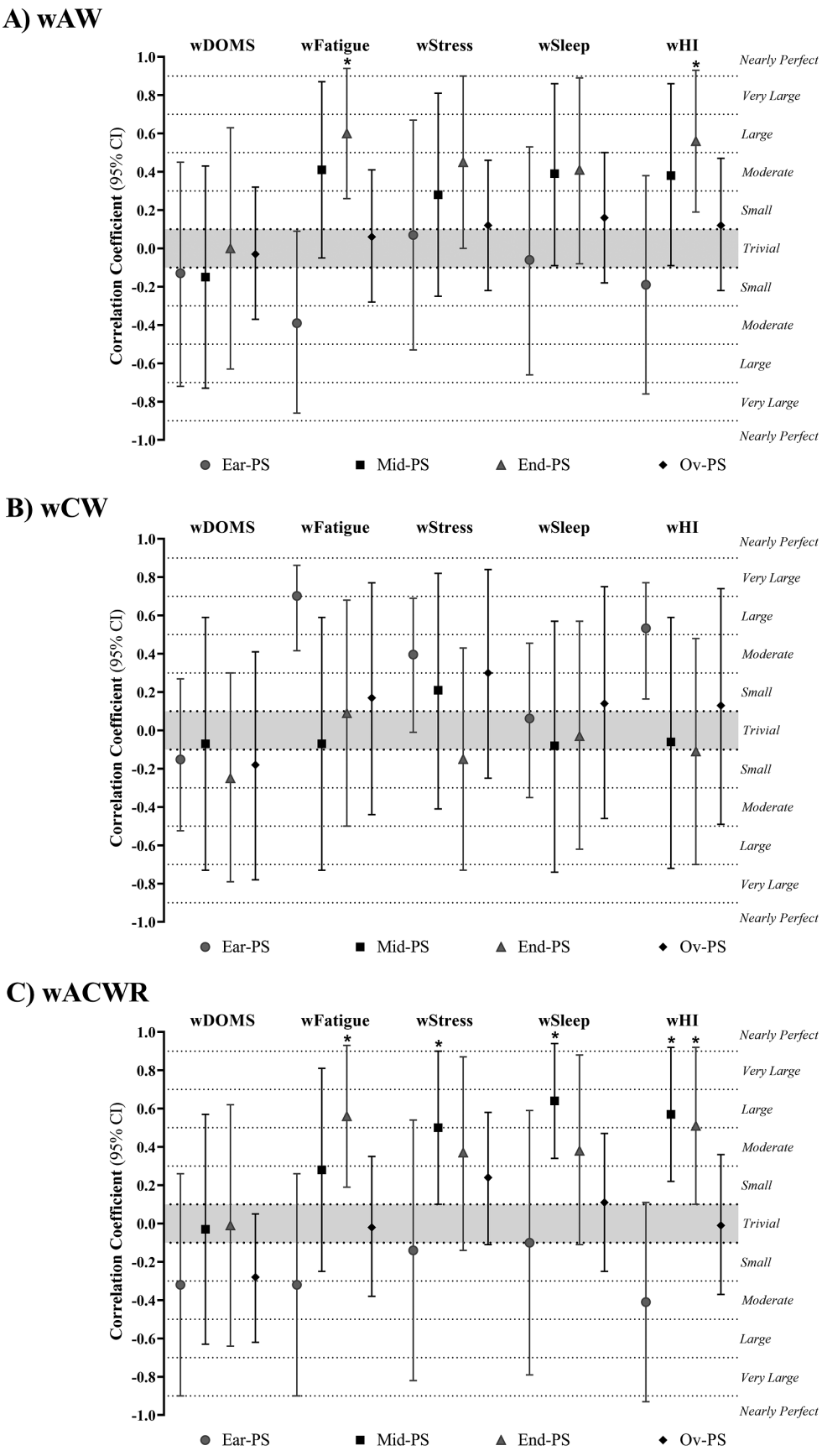


FIG. 5. Correlation coefficients (95% CI) of A) weekly acute workload (wAW), B) weekly chronic workload (wCW) and C) weekly acute/chronic workload ratio (wACWR) and wellbeing categories during early-preparation season (Ear-PS), mid-preparation season (Mid-PS), end-preparation season (End-PS) and Overall-preparation season (Ov-PS). wSleep, weekly sleep; wDOMS, weekly delayed onset muscle soreness; wFatigue, weekly fatigue; wStress, weekly stress; wHI, weekly Hooper indicator. * Correlation coefficient is significant at p-value ≤ 0.05.

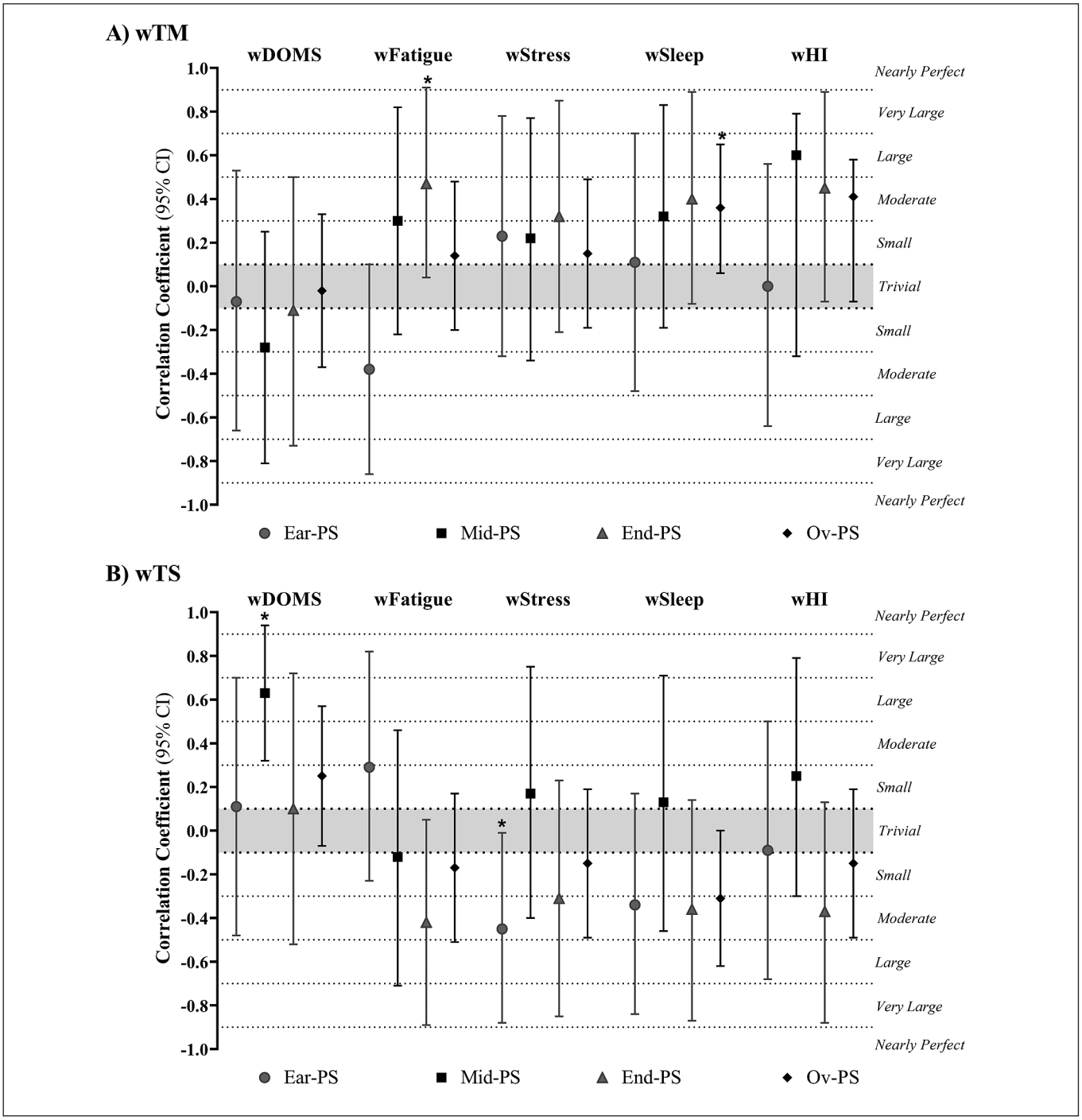


FIG. 6. Correlation coefficients (95% CI) of A) wTM (weekly training monotony) and B) wTS (weekly training strain) and wellbeing categories early-preparation season (Ear-PS), mid-preparation season (Mid-PS), end-preparation season (End-PS) and Overall-preparation season (Ov-PS). wSleep, weekly sleep; wDOMS, weekly delayed onset muscle soreness; wFatigue, weekly fatigue; wStress, weekly stress; wHI, weekly Hooper indicator. * Correlation coefficient is significant at p-value ≤ 0.05.

were observed in the mid season [13]. The discrepancies could be related to the difference between team and individual sport.

We found small differences in correlations between wTM, wTS and wellbeing. In line with this, Sawczuk et al. did not find a relationship between daily wellbeing and training loads in young athletes, but wellbeing was associated with low sleep duration while perceived recovery status did not show any association with sleep duration [34]. Hartwig et al. (2009) also did not find significant correlations between training load and well-being status in young rugby players [35]. It could be explained by two reasons. First, our research sample consists of young athletes. It is possible that this situation, which affects the results obtained, is caused by the difference in the relative stressor intensity of adult and young athletes. Young athletes have a unique environment for social, educational, and maturing conditions to navigate [36]. This environmental situation, which positively affects the well-being of young athletes, could be more important for them than their training. The second possible reason is that the participants in other studies are generally considered to be team athletes. Different physiological and kinematic needs of team sports athletes may have affected the results.

In our study the wTM was largely correlated with wFatigue during end PS and moderately correlated with wSleep in the overall PS. Our results agree with the study of Clemente et al. They found a similar correlation between wTM and wDOMS ($r = 0.80$), wSleep ($r = 0.72$), and wFatigue ($r = 0.82$) in volleyball players [37].

There was a correlation of wTS with wStress during early PS and with wDOMS during mid PS. Previous studies also found that stress was sensitive to training load [38]. Lathlean and colleagues [39] confirmed that larger variation in load with lowered monotony was associated with higher DOMS. Additionally, Bok et al. reported a stronger relation between training load and stress state [26]. In another study, Lupo et al. [12] found that a large variation of training load can be followed in the individual week-to-week fluctuations, whereby the single fluctuations can be significantly different from the overall mean of the group . In another study, Collette et al., Lupo et al. [12] found that a large variation of training load can be followed in the individual week-to-week fluctuations, whereby the single fluctuations can be significantly different from the overall mean of the group.

CONCLUSIONS

The results of this study provide new insights for coaches and practitioners, not only for those in Turkey, about the perceived load level and the variations of wellbeing over a season at elite youth level. Stronger associations between workload and wellbeing variables of young soccer players in the early season were also revealed. Thus, a greater consideration should be given to better control the training process and maximize the development of young players. Thereby, wellness variables may be considered as a useful tool to provide determinant psychological states of players' information to the coaches and thus possibly identify important variations in training responses. However, in future work, we intend to assess whether the results of our study are generalizable to all teams or whether the loading effort, during a season, is perceived differently depending on individual characteristics and training of elite youth. We also intend to increase the number of features recorded in each training session or match and to perceive as correctly as possible the level of load and the variations of well-being of the athletes.

Conflict of interest declaration

No conflict of interest for any of the authors.

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Factors affecting match running performance in elite soccer: Analysis of UEFA Champions League matches

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ABSTRACT: This study aimed to examine the independent effect of different match-related factors on match running performance (MRP) in elite soccer. Players' MRPs (n = 244) were collected during UEFA Champions League (UCL) group stage matches in the 2020–21 season. All MRP data were collected by the semi-automatic optical system InStat Fitness (InStat Limited, Limerick, Republic of Ireland). Match-related factors included match outcome, team quality, match location, opponent quality and difference in team quality, while MRP included cumulative and relative measures of total distance (TD and R-TD), low-intensity running (LIR and R-LIR) (≤ 4 m/s), moderate-intensity running (MIR and R-MIR) (4–5.5 m/s) and high-intensity running (HIR and R-HIR) (≥ 5.5 m/s). Linear mixed models were used to examine the collective effect of match-related factors on MRPs when controlling for between-player, between-playing position and between-team variation. The main findings were that match outcome was associated with reduced HIR (d = -0.38, p = 0.04), match location was associated with increased TD, R-TD, LIR and R-LIR (d = 0.54–0.87, all p < 0.01), while team quality, opponent quality and difference in team quality were not associated with MRP. These results show that (i) winning UCL matches was not strongly influenced by players' physical performance, (ii) away UCL matches were characterized by a slower match pace and greater match volume, and (iii) players' physical performance was similar irrespective of playing either in or against high- or low-quality teams. The findings from this study may help soccer coaches to ensure optimal physical preparation of players in elite soccer.

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INTRODUCTION

Soccer is a complex team sport characterized by high physical demands [1, 2]. To understand such demands, match running performance (MRP) is commonly analysed by quantification of the total distance covered, distances covered in various speed zones and acceleration rates [3–6]. Although MRP is highly variable due to the influence of different match-related factors [7, 8], there is a general consensus that soccer players during the match can cover between 9 and 14 km and can perform 0.7–3.9 km of high-speed distance, 0.2–0.6 km of sprint distance and approximately 600 accelerations [9, 10].

These findings undoubtedly have developed an understanding of the physical demands of soccer; however, a plethora of studies have analysed the effects of match-related factors on match running performance, and these metrics should not be analysed in isolation [11]. Indeed, empirical evidence suggests that factors such as match location (i.e., playing at home or away), team quality and opposition quality (i.e., defined by the final ranking at the end of the league or season coefficients) or match outcome (i.e., win, loss or draw) strongly affect MRP [12]. However, although the association between MRP and different match-related factors is well documented, previous studies have reported inconsistent findings [7].

In brief, older studies demonstrated that soccer players performed significantly fewer high-intensity activities when winning than when losing [12, 13], while more recent studies reported no differences in distance covered at higher speeds regardless of the match outcome [9, 14]. There was a similar inconsistency among studies that analysed the association between MRP and match location. For example, although both belong to a similar competition level, Spanish players accumulated significantly greater total distance during away matches [14], while Portuguese players covered significantly more total distance at home matches [9]. A lack of consistency also was observed when analysing MRP and team

quality. Specifically, while less successful teams (i.e., bottom ranked in competition) from the English Premier League covered a greater high-intensity distance (above 19.8 km/h and 25.2 km/h) than successful teams [15], both successful and unsuccessful teams from the Spanish La Liga presented the same RPs at higher velocities (above 14 km/h, 21 km/h and 24 km/h) [16]. Also, it is reported that MRP was higher when teams competed against higher-ranked opponents than against lower-ranked opponents [17]. Yet, some studies did not find significant differences in MRP between matches played against low-, medium- and high-ranked opponents [14], while other studies reported even greater MRP against lower-ranked competition [18].

Considering a very recent study which suggested that MRP may be influenced by multiple variables [19], it may be difficult to generalize associations between MRP and match-related factors. Furthermore, it should be emphasized that most of the previously conducted studies investigated such factors in isolation, and did not adequately control for the wide range of confounders. The application of an analysis that intends to assess the interaction effect, as well as the control of confounder variables, may bridge this research gap. Finally, although it was recently suggested that additional research should be conducted to develop an understanding of the influence of match-related factors on MRP across different leagues and countries [9], no study has analysed how match-related factors affect MRP in an elite soccer competition – the UEFA Champions League (UCL). Therefore, this study aimed to examine the independent effect of different match-related factors (match outcome, team quality, match location and opponent quality) on MRP in UCL matches.

MATERIALS AND METHODS

Participants

Match running performance (n = 224) of elite soccer players (n = 179) from teams (n = 24) that competed in the group stage of UCL during the 2020–21 season were included as cases in this study. Participants were classified as "elite" as the UCL consists of the best teams from European national competitions. Teams can qualify for the UCL directly (i.e., based on the final position in national competitions) or through qualification rounds.

All data were randomly obtained from 20 matches from groups A (n = 3), B (n = 3), C (n = 4), E (n = 4), F (n = 3) and G (n = 3). Players were classified by match playing position using official match reports provided by InStat Scout (InStat Limited, Limerick, Republic of Ireland) as: central defenders (CD), fullbacks (FB), central midfielders (CM), wide midfielders (WM) and forwards (FW) [20]. Goalkeepers were excluded from the cohort due to the uniqueness of the position. Only the MRPs of those players who played in whole matches were analysed [21]. As a result, the average number of observations for each participant was 1.36. The research was approved by the ethical board of the Faculty of Kinesiology, University of Split.

Procedures and data collection

MRP data were collected using a semi-automatic multiple-camera system, InStat Fitness (InStat Limited, Limerick, Republic of Ireland). This optical system has a sampling frequency of 25 Hz, and identifies players by their movement, shape, and colour information. The reliability of the system has been demonstrated by comparison of data to the Vicon system (Vicon Motion Systems, Oxford Metrics, UK) at five velocity bands (0–7 km/h, 7–15 km/h, 15–20 km/h, 20–25 km/h, and 25+ km/h). This procedure included analysis of mean velocity difference compared to Vicon (m/s) and mean position difference (m) compared to Vicon, and the system has passed the official Fédération Internationale de Soccer Association (FIFA) test protocol for Electronic and Performance Tracking Systems (EPTS) (authorization number: 1007382). A detailed report is available on the official FIFA webpage [22]. Finally, previous research showed that this system is very accurate with high levels of absolute and relative reliability [23].

Classification of MRP was similar to other studies which used the same thresholds [15, 17], although some exceptions should be noted. Specifically, since it is generally accepted that walking (0.2–2 m/s) and jogging (2–4 m/s) are not crucial for successful match performances [15], we considered it as one zone (i.e., low-intensity running). On the other hand, high-intensity running (i.e., high speed running (5.5–7 m/s) + sprinting (≥ 7 m/s) is typically considered as a vital element of success in soccer [15], and therefore we believed that it might be of greater interest to observe it as one zone. As result, MRP variables in our study included total distance covered (TD) (m), low-intensity running (LIR) (≤ 4 m/s) (m), moderate-intensity running (MIR) (4–5.5 m/s) (m) and high-intensity running (HIR) (≥ 5.5 m/s) (m), relative total distance covered (R-TD) (m/min), relative low-intensity running (R-LIR) (≤ 4 m/s) (m/min), relative moderate-intensity running (R-MIR) (4–5.5 m/s) (m/min) and relative high-intensity running (R-HIR) (≥ 5.5 m/s) (m/min).

Match-related factors in this study included match outcome, team quality, match location and opponent quality. Match outcome was assessed as won or not won (i.e., loss or draw) and match location as playing at home or away [24]. Team quality, opponent quality and differences between them were evaluated using UEFA season club coefficients [25]. The season club coefficients are based on the results of clubs competing in the current UEFA Champions League, UEFA Europa League and UEFA Europa Conference League season. Clubs' coefficients are determined either as the sum of all points won in the previous five years OR the association coefficient over the same period, whichever is higher. Points awarded each season are in accordance with the relevant competition regulations for that specific season [26].

Statistical analysis

Before running linear mixed effect models, assumptions of independence and collinearity were checked, and box plots and histograms were used to determine potential influential data points. Following

analysis, visual inspections of residual plots were used to determine obvious deviations from homoscedasticity or normality [27]. Afterward, a linear mixed model was used to examine the independent influence of the match-related factors on MRP. In this study, eight separate models were developed to examine the influence of fixed effects (match outcome, team quality, match location, opponent quality, difference in team quality) and random effects (team identity, playing position, player identity) on TD, R-TD, LIR, R-LIR, MIR, R-MIR, HIR, and R-HIR (dependent variables). Match outcome and match location were introduced as dummy variables, while team quality and opponent quality were continuous variables. Random factors were included in the model to allow random deviations for playing positions, teams and players from the overall fixed intercept and fixed coefficients (Table 1).

A 'step-up' model construction strategy was employed, similar to that used in the previous team sports mixed model studies [27, 28]. The modelling began with an 'unconditional' model using only a fixed intercept and random factors. The model was further developed by adding each single fixed effect. The order in which each fixed effect was added to the model was guided by a senior performance staff member based on extensive experience in the field [27]. The importance of each fixed effect was determined by whether its inclusion demonstrated statistically significant ($p < 0.05$, likelihood ratio test method [29]) improvements compared to the explanatory model. Also, the Akaike information criterion (AIC) and degrees of freedom (df) for each model were visually compared to the previous model, where a lower AIC represented a better model. The t statistics from the mixed models were converted into Cohen's d effect sizes and interpreted as < 0.2 trivial; 0.2–0.6 small; 0.7–1.2 moderate; 1.2–2.0 large; > 2.0 very large [27, 30]. All statistical analyses were conducted using SPSS software (IBM, SPSS, Version 25.0).

RESULTS

The effects of the different match-related factors on MRP are presented in Tables 2, 3, 4, 5. For all models, the best fit for the data was found by including random intercepts for each player, team and playing position. Introducing random slopes to the models in this study did not yield a better model fit (no additional lowering of AIC). The results showed that players covered greater TD ($t = 2.69$, $p < 0.01$, $d = 0.54$) and achieved greater R-TD ($t = 2.57$, $p = 0.012$, $d = 0.55$) in away matches. None of the other factors of interest contributed to a significantly different or better fit of Models 1 and 2 (all $p > 0.05$) (Table 2). LIR ($t = 3.50$, $p < 0.001$, $d = 0.67$) and R-LIR ($t = 4.10$, $p < 0.001$, $d = 0.87$) were also greater when playing away. Match outcome, team quality, opponent quality and difference in team quality had no effect on LIR and R-LIR (all $p > 0.05$) (Table 3). No associations between match-related factors, and MIR and R-MIR were found (all $p > 0.05$) (Table 4). Players covered lower HIR in winning matches ($t = -2.06$, $p = 0.04$, $d = -0.38$). Match location, team quality, opponent quality and difference in team quality did not contribute to a significantly different or better fit of Model 7 (all $p > 0.05$). In addition, no associations between match-related factors and R-HIR were found (all $p > 0.05$) (Model 8) (Table 5).

TABLE 1. Model specification.

Level of data		Factors	Type	Classification
Level 4	Cluster of clusters (random factor)	*Team*		
Level 3	Cluster of clusters (random factor)	*Position*		
Level 2	Cluster of units (random factor)	*Player*		
Level 1	Unit of analysis	*Individual match observations*		
	Dependent variables	Accumulative total distance (Model 1)	Continuous	meter (m)
		Accumulative low intensity running (Model 2)	Continuous	meter (m)
		Accumulative moderate intensity running (Model 3)	Continuous	meter (m)
		Accumulative high intensity running (Model 4)	Continuous	meter (m)
		Relative total distance (Model 5)	Continuous	meter per min (m/min)
		Relative low intensity running (Model 6)	Continuous	meter per min (m/min)
		Relative moderate intensity running (Model 7)	Continuous	meter per min (m/min)
		Relative high intensity running (Model 8)	Continuous	meter per min (m/min)
	Covariates	Match outcome	Dummy variable	0 = Loss/Draw 1 = Win
		Team quality	Continuous	UEFA club coefficient
		Location	Dummy variable	0 = Home 1 = Away
		Opponent quality	Continuous	UEFA club coefficient
		Difference in team quality	Continuous	UEFA club coefficient

TABLE 2. Influence of contextual factors on accumulative total distance (Model 1) and relative total distance (Model 2).

Fixed effects	Coefficients	95% CI	SE	df	t value	p	AIC difference	Likelihood ratio test	Effect size (95% CI)
Model 1									
(Intercept)	10833.2	10037.5; 11628.9	299.9	4.5	36.12	0.001			
Match outcome	NS								
Team quality	NS								
Match location	197.2	51.7; 342.8	73.3	100.4	2.69	0.008	17	< 0.001	0.54 (0.14; 0.93)
Opponent quality	NS								
Difference in team quality	NS								
Model 2									
(Intercept)	111.7	103.5; 119.9	3.30	5.61	33.82	0.001			
Match outcome	NS								
Team quality	NS								
Match location	1.74	0.4; 3.1	0.68	86.56	2.57	0.012	8	0.004	0.55 (0.12; 0.98)
Opponent quality	NS								
Difference in team quality	NS								

CI: confidence interval; SE: standard error; df: degrees of freedom; AIC: Akaike information criterion. Note: Likelihood ratio test based on comparison with previous model. Effect size is an approximation based on the t value obtained from each variable included in the model. NS: covariate not significant in final model.

TABLE 3. Influence of contextual factors on accumulative low-intensity running (Model 3) and relative low-intensity running (Model 4).

Fixed effects	Coefficients	95% CI	SE	df	t value	p	AIC difference	Likelihood ratio test	Effect size (95% CI)
Model 3									
(Intercept)	7996.1	7739.1; 8253.1	110.2	7.5	72.55	0.001			
Match outcome	NS								
Team quality	NS								
Match location	193.3	83.9; 302.8	55.2	110.3	3.50	0.001	20	< 0.001	0.67 (0.28; 1.05)
Opponent quality	NS								
Difference in team quality	NS								
Model 4									
(Intercept)	81.61	78.70; 84.53	1.35	14.41	59.95	0.001			
Match outcome	NS								
Team quality	NS								
Match location	2.00	1.03; 2.97	0.49	88.48	4.10	0.001	15	< 0.001	0.87 (0.43; 1.31)
Opponent quality	NS								
Difference in team quality	NS								

CI: confidence interval; SE: standard error; df: degrees of freedom; AIC: Akaike information criterion. Note: Likelihood ratio test based on comparison with previous model. Effect size is an approximation based on the t value obtained from each variable included in the model. NS: covariate not significant in final model.

TABLE 4. Influence of contextual factors on accumulative moderate-intensity running (Model 5) and relative moderate-intensity running (Model 6).

Fixed effects	Coefficients	95% CI	SE	df	t value	p	AIC difference	Likelihood ratio test	Effect size (95% CI)
Model 5									
(Intercept)	1920.1	1469.3; 2370.9	165	4.17	11.63	0.001			
Match outcome	NS								
Team quality	NS								
Match location	NS								
Opponent quality	NS								
Difference in team quality	NS								
Model 6									
(Intercept)	20.1	15.4; 24.8	1.73	4.20	11.60	0.001			
Match outcome	NS								
Team quality	NS								
Match location	NS								
Opponent quality	NS								
Difference in team quality	NS								

CI: confidence interval; SE: standard error; df: degrees of freedom; AIC: Akaike information criterion. Note: Likelihood ratio test based on comparison with previous model. Effect size is an approximation based on the t value obtained from each variable included in the model. NS: covariate not significant in final model.

TABLE 5. Influence of contextual factors on accumulative high-intensity running (Model 7) and relative high-intensity running (Model 8).

Fixed effects	Coefficients	95% CI	SE	df	t value	p	AIC difference	Likelihood ratio test	Effect size (95% CI)
Model 7									
(Intercept)	948.9	729.9; 1167.9	83.1	4.6	11.42	0.000			
Match outcome	-61.8	-121.3; -2.3	30.0	116	-2.06	0.042	13	< 0.001	-0.38 (-0.75; -0.01)
Team quality	NS								
Match location	NS								
Opponent quality	NS								
Difference in team quality	NS								
Model 8									
(Intercept)	9.70	7.4; 12.0	0.87	4.52	11.18	0.001			
Match outcome	NS								
Team quality	NS								
Match location	NS								
Opponent quality	NS								
Difference in team quality	NS								

CI: confidence interval; SE: standard error; df: degrees of freedom; AIC: Akaike information criterion. Note: Likelihood ratio test based on comparison with previous model. Effect size is an approximation based on the t value obtained from each variable included in the model. NS: covariate not significant in final model.

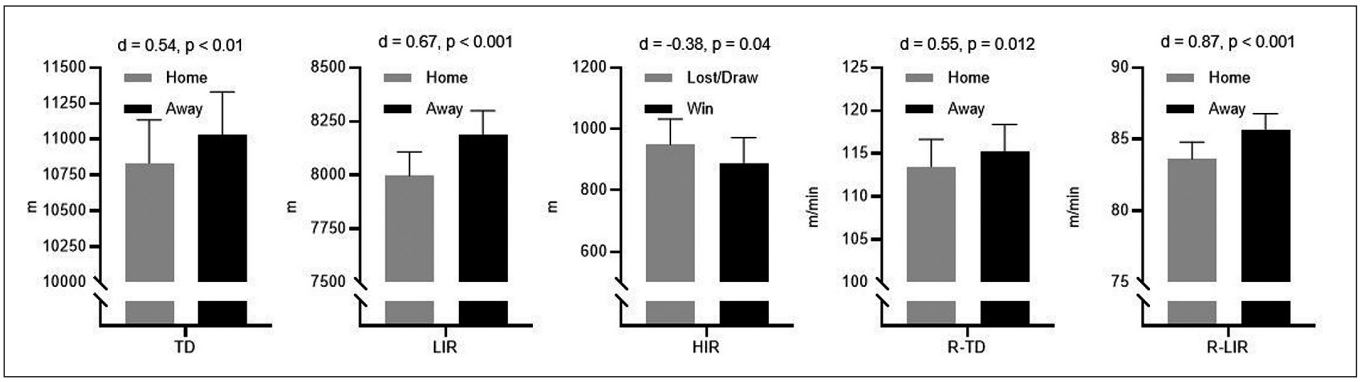


FIG. 1. The key descriptive data from this study (data are given as Mean ± SE).

The key descriptive data from this study are presented in Figure 1.

DISCUSSION

This study was the first to investigate the collective effect of different match-related factors on MRP when controlling for between-player, between-playing position and between-team variation in UCL. The main findings were that (i) match outcome was associated with reduced HIR; (ii) match location was associated with increased TD, R-TD, LIR, and R-LIR; (iii) team quality, opponent quality and difference in team quality were not associated with MRP.

Our results did not reveal an association between TD, R-TD, LIR, R-LIR, MIR or R-MIR and match outcome, suggesting that the final scores in UCL matches were not determined by overall distance or the distance covered at low or moderate speeds. On the other hand, there was a significant association (small effect size) between HIR (≥ 19.8 km/h) and match outcome. Specifically, in UCL match wins, players had a lower amount of HIR, indicating that successful UCL matches result in less cumulative total HIR. Conversely, when losing or drawing, elite soccer players had greater HIR, possibly to recover from an unfavourable match score [8, 31]. Nevertheless, it must be emphasized that no effect of match outcome on R-HIR was witnessed, confirming that successful match outcomes in the UCL were not associated with increased HIR. All these findings collectively demonstrate that winning UCL matches was not strongly influenced by players' physical performance. The high degree of technical and tactical capabilities of the players likely plays a crucial role in winning matches in elite soccer. Such a consideration supports the idea that, in modern soccer, overall technical and tactical effectiveness probably has a greater impact on results than MRP [16, 32].

Elite soccer players covered similar MIR and HIR distances, and achieved similar R-MIR and R-HIR irrespective of whether the matches were played at home or away. On the other hand, increased TD, R-TD, LIR and R-TD were associated with match location (all small to moderate effect sizes). Specifically, greater overall cumulative and relative distance and distance covered at lower speeds (e.g., walking and jogging) were observed at UCL matches that were played away. Although it is generally accepted that low-intensity activities, such as walking and jogging, are not crucial in elite soccer performance [15], such activities can provide a better understanding of the pace that players experience during the match. Thus, the greater LIR and R-LIR in our study suggest that away UCL matches were characterized by a slower match pace. Slower performances during away matches may have been a consequence of the tactical approaches and defensive strategies adopted to limit the opposition rather than using an attacking threat [9, 33]. The possible defensive strategies adopted during away matches most likely resulted in greater TD and R-TD as well. According to the findings of a contemporary study, teams that apply this approach (i.e., playing defensively without high ball possession) generally cover a greater overall distance, especially at low and medium speeds [20]. However, as we did not analyse playing strategies, these considerations should be confirmed in future studies by including technical and tactical factors in the analyses.

Results from our study did not indicate an effect of opponent quality on MRP in UCL matches. Specifically, MRPs were similar irrespective of playing against high- or low-quality teams. Such findings suggest that elite soccer players' physical performance was stable whether playing against "better" or "weaker" opponents. Taking into account the previous idea that professional soccer players regulate their physical efforts according to the specific demands of the individual matches [12, 17], these results may seem surprising. However, we believe that our findings are driven by the specific nature of the observed competition (i.e. UCL). Specifically, the UCL is an elite soccer club competition played by the world's best soccer players [21]. Such players are highly professional athletes whose match performance is most likely consistently at a high level, which almost certainly resulted in stable physical performance irrespective of their opponents. Possibly, for similar reasons (i.e., the high standard of the UCL players) no effects of team quality or difference in team

quality on MRP in UCL matches were found. Namely, our results indicated that MRP was not associated with these team-quality indicators, meaning that players' physical performance was similar (i.e., stable) irrespective of the quality of their teams and regardless of the differences in the quality of the opponent teams. Considering previous studies which investigated MRP in UCL [21, 34, 35], such findings are actually expected. The results from these studies imply that UCL is a highly physically demanding competition, and therefore to compete at elite soccer all UCL players must be able to handle high physical demands. This likely results in high (i.e., similar) MRP during the matches for all players and teams.

The present investigation has some limitations that should be considered. First, this study did not analyse all matches from the group stage of the UCL. Specifically, only 20 selected matches were observed. However, this is a very common obstacle in studies involving players who compete in elite soccer [36, 37]. For methodological reasons we included only players who played the whole match, which reduced the number of observations and may have affected MRP. In addition, we did not observe MRP in all speed zones. Future research should consider other match-related factors, such as weather conditions, team formations, match periods, current score, match importance, and number of players on the field, which have all been confirmed to influence MRP [19, 24]. Future research should analyse other MRP metrics such as accelerations/decelerations and metabolic power, considering peak running outputs. Finally, for a detailed understanding of the effect of match-related factors on running performance in UCL, external training load and its relationship with match loads should also be considered in future research [38].

CONCLUSIONS

Winning UCL matches was not strongly influenced by players' physical performance. Specifically, successful match performance (i.e., win) results in lower cumulative total HIR, possibly indicating that a high degree of technical and tactical capabilities of the players plays a crucial role in winning matches in elite soccer. However, it is more important to emphasize that unsuccessful match performance (i.e., loss and draw) in UCL results in greater HIR. As greater HIR is associated with greater blood lactate accumulation [39], different recovery strategies after UCL losses and draws should be applied than after wins.

Although playing away was associated with increased TD, R-TD, LIR and R-LIR, which clearly indicates that away matches were characterized by a slower match pace and greater match volume, the overall effect of match location on MRP is limited. Specifically, there is no effect of match location on HIR, which is considered as one of the vital elements of soccer [15]. However, as observed matches were played without an audience or with limited capacity in the stands due to the COVID-19 pandemic [40], the effect of match location should be further investigated.

Finally, there was also no effect of any of the team quality indicators on MRP. As UCL is a very physically demanding competition [21, 34, 35], this most likely indicates that players' physical performance was high irrespective of playing either in or against high- or low-quality teams. Aiming to handle such high physical demands, soccer coaches should ensure an adequate conditioning stimulus in preparation for every match in UCL. Ultimately, such an approach may help coaching staff in their efforts to ensure optimal physical preparation of players who participate in elite soccer and who are seeking UCL qualification.

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Conflicts of Interest

The authors declare no conflict of interest.

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Recovery time variation during sprint interval training impacts amateur soccer players adaptations – a pilot study

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ABSTRACT: The objective of the present study was to investigate the selected performance adaptations of amateur soccer players to 2 different running-based sprint interval training (SIT) protocols with different recovery intervals and work-rest ratios (1:5 & 1:1). Twenty-three subjects (age 21.4 ± 1.1 years; height 175.4 ± 4.7 cm; body mass 69 ± 6.4 kg) participated in the study. Before the 6-weeks training period, participants completed 3-weeks of low-intensity training preparation. Subsequently, the pre-tests (anthropometric measurements, repeated sprint test [12 × 20-m with 30-s recovery intervals], Yo-Yo$_{IRT1}$ & Yo-Yo$_{IRT2}$ and treadmill VO_{2max} test) were conducted. Thereafter, participants were randomly divided into 3 sub-groups (1 – SIT with 150 s recovery intervals [SIT150, n = 8]; 2 – SIT with 30 s recovery intervals [SIT30, n = 7]; and 3 – control group [CG, n = 8]). SIT150 and SIT30 training groups completed sprint interval training (2-days/week; 30-s all-out running, 6–10 repetition with 150 s recovery intervals for SIT150 and 30 s for SIT30 groups, respectively), a soccer match (1-day) and routine soccer training (3-days) per week. The CG attended only routine training sessions and the soccer-match (4-days). The study experiments and the trainings were conducted during off-season. Yo-Yo$_{IRT1}$, Yo-Yo$_{IRT2}$, and VO_{2max} were significantly improved both in SIT30 and SIT150 ($p < 0.05$) groups. Yo-Yo$_{IRT1}$ and VO_{2max} were also significantly improved in CG ($p < 0.05$). Both the SIT150 and SIT30 training were shown to improve Yo-Yo$_{IRT1}$, Yo-Yo$_{IRT2}$ and VO_{2max} performance compared to the control group, nevertheless, SIT150 was more efficient in improving the Yo-Yo$_{IRT1}$, Yo-Yo$_{IRT2}$ than SIT30. The authors of this study suggest using SIT150 to induce more effective performance outputs in amateur soccer players.

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INTRODUCTION

It is known that short-lasting maximal and near-maximal efforts with varying recovery intervals represent essential characteristics of the physical activity within soccer games [1, 2]. Soccer players perform between 10496 m (central defender) and 11779 m (axial midfielder) including 193.6 m – 278.2 m runs > 24.1 km·h^{-1} [3]. 243–364 changes of directions < 90° and 1000–1400 actions including 220 at high intensity (HI) [4]. Consequently, it is imperative to have sufficient physical capacity for soccer players to be able to cope with fatigue through the intense periods of the game where the anaerobic mechanisms prevail, especially very high intensity (VHI) activities [5, 6, 7, 8]. The need to produce HI and VHI activities all across soccer game encourages coaches and sports scientists to utilize different training methods based on HI efforts. To increase the capacity of the players to produce repeated HI and VHI activities, short-lasting high-intensity exercises such as sprint interval training (SIT) can be used in training.

SIT generally utilize three to seven 10–30 s all-out sprint bouts with various recovery periods in between [9, 10, 11]. Soccer players spend more time in HI exercise domain during SIT [9]. which is one of the most effective means to improve running performance. However, its effectiveness depends on recovery, positional roles and individual differences among soccer players. Lloyd Jones et al., [12] compared two SIT protocols with matched work-rest ratio and total sprint duration (the first group: 6 s all-out effort, 20 reps with

48 s rest; and the second group: 30 s all-out effort, 4 reps with 4 min rest; for two weeks) and investigated their adaptations on VO_{2max} performance. Authors reported that both 6 and 30 s all-out SIT training elicited similar changes in performance. Another study, comparing two 10 s (with 2 and 4 recovery intervals min) and a 30 s SIT exercises, showed that all three of the SIT protocols increased oxidative and anaerobic performance [13].

Thomassen et al. [14] compared two groups of SIT. They reported that group-1 (6–8 reps of 20-s all-out running, with 120-s of passive recovery in-between) and group-2 (same efforts, with 40-s of passive recovery intervals) training improved Yo-Yo_{IRT2} (intermittent recovery test) performance by 10% and 4% respectively. Similar studies also support that high-intensity interval training enhances aerobic and anaerobic performances [15, 16, 17, 18]. Considering various training options, this topic needs further investigations. Indeed, the changes in duration, intensity, number of sets and recovery intervals of training provide different metabolic, cardiovascular and neuromuscular improvements [16, 17, 18, 19]. Furthermore, there is a lack of information about how amateur soccer players adapt to widely used SIT protocols with different work-rest ratio. Therefore, the aim of the present study was to investigate the selected performance adaptations of amateur soccer players to 2 different running-based SIT protocols with different recovery intervals and work-rest ratios (1:5 & 1:1). We hypothesized that SIT150 protocol would improve Yo-Yo_{IRT1}, Yo-Yo_{IRT2} and VO_{2max} relatively better compared to SIT30.

MATERIALS AND METHODS

Subjects

A total sample size of 21 was required to detect an effect size of 0.4 with $\alpha = 0.05$ and 80% power. Initially, twenty-four male soccer players competing in an amateur soccer team with at least 5-year active soccer exercise background volunteered in this study. The participants were randomly subdivided into 3 sub-groups (1 – SIT150: n = 8, 30-s all-out running, 6–10 repetition with 150 s recovery intervals; 2 – SIT30: n = 7, 30-s all-out running, 6–10 repetition with 30 s recovery intervals; and 3 – CG: n = 8, control group). During the training 1 participant (from SIT30 group) was injured and consequently excluded from the study, leaving a total of 23 participants (SIT150: mean ± SD; age 21.1 ± 1.3 years, height 176.6 ± 4.7 cm, body mass 71 ± 5.9 kg; SIT30: age 21.4 ± 1.1 years, height 177 ± 5.4 cm, body mass 69.4 ± 7.3 kg; CG: age 21.4 ± 1.1 years, height 173 ± 3.5 cm, body mass 66.7 ± 6) (Table 1.). This study was approved by the Ankara University Faculty of Medicine Ethics Committee (ID: 01-13-17) before the data collection process and was conducted in accordance with the standards of ethics. Prior to signing informed consent form, all subjects were informed about the aim, methodology, possible risks, and benefits of the investigation.

Experimental Approach

Pre- and post-training tests including anthropometric evaluations, treadmill VO_{2max} test, Yo-Yo_{IRT1}, Yo-Yo_{IRT2} and repeated sprint ability (RSA) tests were performed to examine the performance adaptations

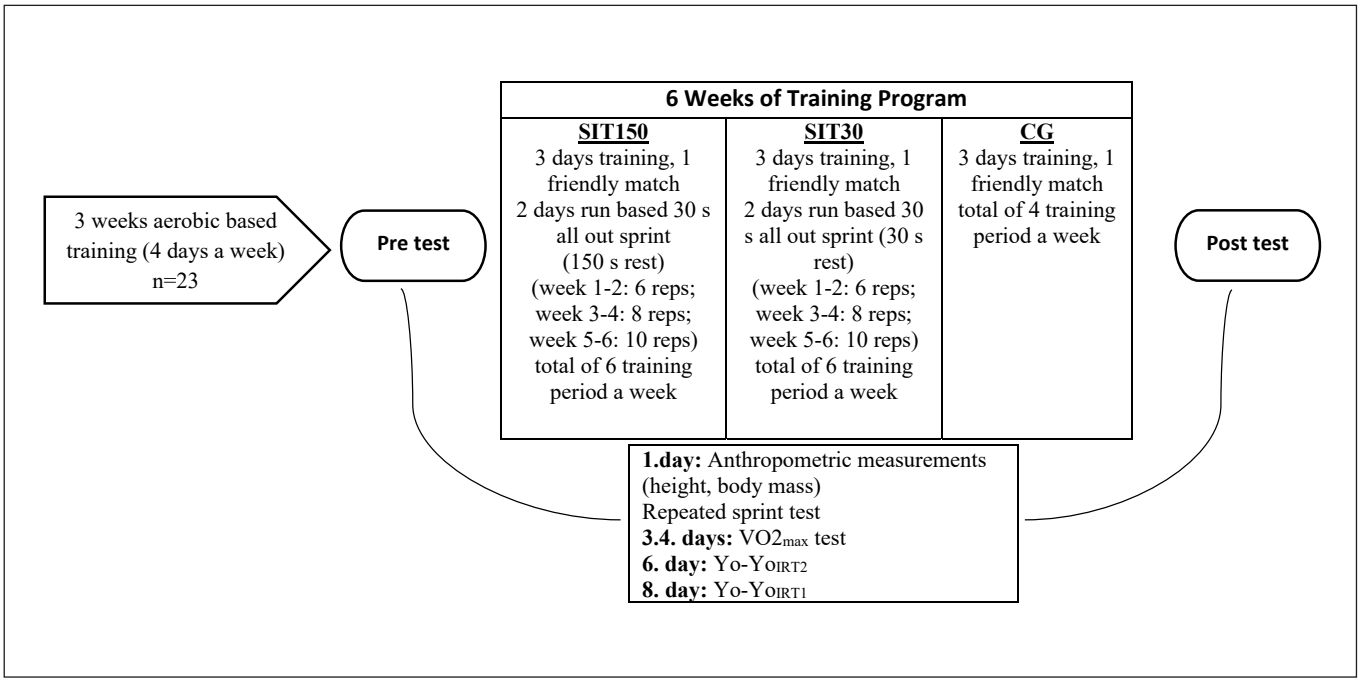


FIG. 1. Depiction of the study design.

induced by 2 different speed endurance training (Figure 1). Pre-training tests took place 3 weeks after the end of the amateur league finale (pre-season, from April to June 2017). The study orientation, training and testing sessions spanned 12 weeks. During the first 3 weeks (4 days a week), low-intensity exercises were completed for orientation. Before and after the 6 weeks of speed interval training, pre- and post-training tests were performed (in a total of 3 weeks). Temperature, humidity and the altitude of the testing and the training environment were ~18–21°C, % 45–60 and 1285 m respectively.

Training Protocols

In addition to their routine training (on Monday, Wednesday, Friday) participants from the SIT150 and SIT30 training groups performed running-based 30 s all-out sprints under supervision 2 times per week (on Tuesday and Thursday) (week 1–2: 6 reps; week 3–4: 8 reps; week 5–6: 10 reps). All participants also played a 90-min soccer match among themselves (on Saturday). Before every test and training session, a standard warm-up (5-min jogging, 3-min dynamic stretching [20] and 7-min specific drills) was instructed and supervised by the coach. The recovery intervals between the two bouts for SIT150 and SIT30 training groups were 150 and 30 s respectively. The CG attended solely routine soccer training sessions and 90-min soccer matches. Routine soccer training consisted of low to moderate intensity running based drills with and without a ball (on Monday), small sided games (3×3, 4×4, 5×5, 7×7) (on Wednesday), short-distance (5–10 m) maximal sprint, reaction and acceleration training (on Friday).

Yo-Yo$_{IRT1}$ and Yo-Yo$_{IRT2}$

All subjects were instructed to run between cones placed 20-m apart accordingly with the pre-recorded sound signal and the speed was increased as Bangsbo et al. [21] and Krustrup et al. (2006) stated. After every 40-m run, subjects had 10-s rest in 5-m-long area. The tests were completed when the subject missed two consecutive cones [22]. Although they have the same test settings, the initial running speeds for Yo-Yo$_{IRT1}$ and Yo-Yo$_{IRT2}$ were 10 and 13 km·h^{-1} respectively.

Graded Treadmill Test

The subjects were instructed to complete a continuous incremental run on treadmill to determine their VO_{2max}. The initial speed of the test was 9 km·h^{-1} and was increased 1 km·h^{-1} every minute until reaching the final speed the treadmill allows (16 km·h^{-1}). After that, the treadmill grade was increased by 1% every minute until volitional exhaustion. The protocols where treadmill grade was increased by 1% has been shown to provide a valid VO_{2max} measurement [23, 24]. Throughout the tests, expired gas was recorded using Masterscreen metabolic cart (Viasys Healthcare, Jaeger, Würzburg, Germany). The gas analyzers were calibrated as instructed by the manufacturer, with a certified gas mixture of known concentrations. It was considered VO_{2max} if at least two of the following criteria met: the presence of VO_2 plateau, a respiratory exchange ratio greater than 1.1, and a peak heart rate (HR) greater than 90% of age-predicted maximum (220-age) [25].

Repeated Sprint Test

Subjects completed twelve 20-m sprints with a 30-s recovery in-between on a grass field [26]. Newtest (Powertimer 300-series, Finland) telemetric system was used and photocells were placed at 0- and 20-m. Following each sprint, the subjects walked back to the starting line. After the test, the best sprint time (RST_{best}), total sprint time (RST_{total}; total sprinting time of 12 attempts) and percentage decrement of repeated sprinting times (RST_{dec}) were calculated as Glaister et al. [27] suggested.

$$Percentage\ of\ performance\ decrement = \left(\frac{s1 + s2 + \ldots + sn}{BST \times n} - 1\right) \times 100$$

where RST_{best} was the best sprint time; s was a given sprint performance (in second), n was the number of the final sprint (in this case 12).

Statistical Analysis

The study results and descriptive data were reported as mean ± SD. Normality of data was analyzed using Shapiro-Wilk test. Two-way repeated measures ANOVA was used with one within factor (time: pre vs. post) and one between factor (group: SIT150 vs. SIT30 vs. CG). The partial eta squared value (η_p^2) was calculated to indicate effect sizes, which can be interpreted as a proportion of variance. Comparing pre- and post-training test results, Paired samples t test (if data was normally distributed) and Wilcoxon test (if data was not normally distributed) were used. Cohen's d effect sizes were also calculated and the outputs were described as follows: < 0.20 (trivial), 0.20–0.59 (small), 0.6–1.19 (moderate), 1.2–1.99 (large); ≥ 2.0 (very large) [30]. Intraclass correlation coefficient (ICC) with 2-way random model [28] was used to test the consistency of pre & post measurements [29]. Based on 95% confidence interval of the ICC estimate, the values were classified as follows: < 0.5 (poor), 0.5–0.75 (moderate), 0.75–0.9 (good), > 0.90 (excellent). The significance level was set at 0.05 for all tests.

TABLE 1. Subject characteristics.

	SIT150	S30	CG
Age (years)	21.1 ± 1.3	21.2 ± 0.9	22.1 ± 1.2
Height (cm)	176.6 ± 4.7	177.0 ± 5.4	173.0 ± 3.5
Body Mass (kg)	71.0 ± 5.9	69.4 ± 7.3	66.7 ± 6.1

RESULTS

Inter- and intra- group performances are shown in Table 2 for RSA (RST_{best}, RST_{total} and RST_{dec}), Yo-Yo_{IRT1}, Yo-Yo_{IRT2} and VO_{2max}.

The two-way repeated measures ANOVA results revealed that there was a significant main effect of time (pre- post) for Yo-Yo_{IRT1} ($p = 0.001$, $\eta_p^2 = 0.88$), Yo-Yo_{IRT2} ($p = 0.01$, $\eta_p^2 = 0.70$) and VO_{2max} ($p = 0.001$, $\eta_p^2 = 0.84$); and no significant main effect of time or group (S150, SIT30, CG) for RST_{best}, RST_{total} and RST_{dec} ($p > 0.05$). There was no time*group interaction effect for any variable (Figure 2).

Intra-group comparisons indicated significant differences. A significant performance decrement in RST_{best} (3.5%, $p = 0.029$, Cohen's $d = 0.17$) and RST_{total} (2.5%, $p = 0.038$, Cohen's $d = 0.74$) was present in the SIT30 training group, whereas no significant difference in RST_{dec} was found ($p > 0.05$). In the SIT150 training group, RST_{best} did not significantly change ($p > 0.05$), similarly, no statistically significant change was present in RST_{total} (0.5%) and RST_{dec} (13.9%), nonetheless, there were relative improvements. Although there was no significant difference in RST_{best}, RST_{total} and RST_{dec}, performance improvement in CG was seen in RST_{dec} (24.3%, $p > 0.05$).

A greater improvement was seen in Yo-Yo_{IRT1} performance in SIT150 group (43%, $p = 0.001$, Cohen's $d = 1.48$) compared to SIT30 (23%, $p = 0.002$, Cohen's $d = 0.76$) and CG (20%, $p = 0.013$, Cohen's $d = 0.57$).

There was a significant improvement in Yo-Yo_{IRT2} performance in SIT30 (26.2%, $p = 0.018$, Cohen's $d = 1.28$) and even a greater improvement in SIT150 (32.8%, $p = 0.008$, Cohen's $d = 1.25$) training group.

VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$) significantly changed in all groups (SIT150 [18%, $p = 0.010$, Cohen's $d = 1.56$], SIT30 [19.1%, $p = 0.001$, Cohen's $d = 1.97$], and CG [13.4%, $p = 0.002$, Cohen's $d = 0.75$]).

ICC for pre- and post- tests was as follows: SIT30 VO_{2max} (.802, $p = 0.035$), Yo-Yo_{IRT1} (.958, $p = 0.001$), Yo-Yo_{IRT2} (.890, $p = 0.008$), RST_{best} (.857, $p = 0.016$), RST_{total} (.890, $p = 0.008$), and RST_{dec} (.403, $p = 0.273$); SIT150 VO_{2max} (.334, $p = 0.303$), Yo-Yo_{IRT1}

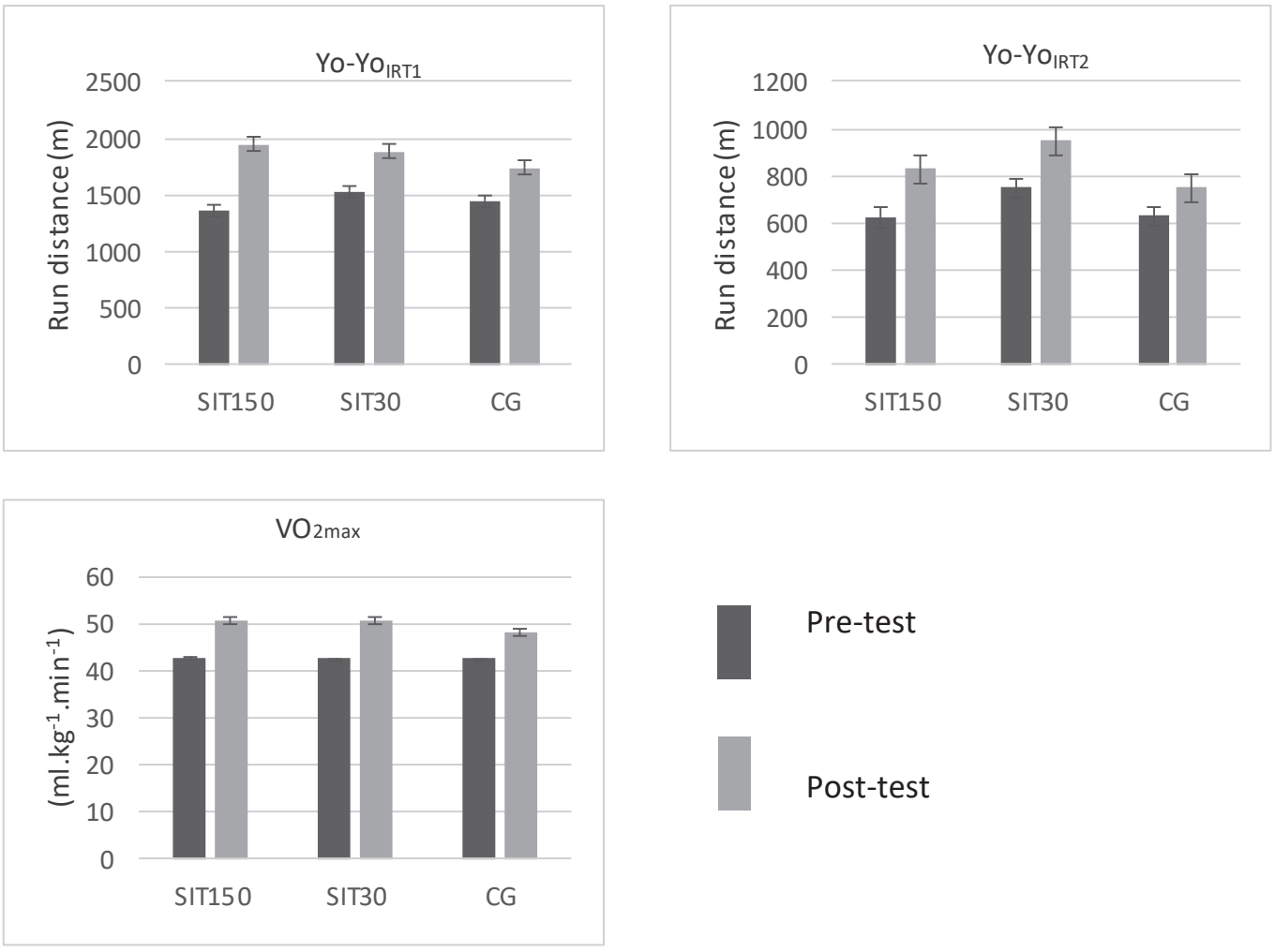


FIG. 2. Baseline and post training Yo-Yo_{IRT1}, Yo-Yo_{IRT2} and VO_{2max} performance level of SIT150, SIT30 and CG.

TABLE 2. Pre- and post-training performance, percentage change and effect size for the sub-groups

	SIT150 n = 8				SIT30 n = 7				CG n = 8			
	Pre	Post	d	%Ch	Pre	Post	d	%Ch	Pre	Post	d	%Ch
RST_{best} (s)	2.8 ± 0.1	2.8 ± 0.1	0	0	2.8 ± 0.1	2.9 ± 0.8*	0.17 trivial	↑3.5	2.9 ± 0.1	2.9 ± 0.1	0	0
RST_{total} (s)	35.8 ± 7.1	35.6 ± 11.9	0.02 trivial	↓0.5	35.5 ± 1.7	36.4 ± 1.1*	0.74 moderate	↑2.5	36.6 ± 1.6	36.4 ± 1.8	0.11 trivial	↓0.5
RST_{dec} (s)	4.3 ± 2.2	3.7 ± 1.9	0.29 small	↓13.9	3.6 ± 2.4	3.7 ± 1.2*	0.05 trivial	↑3.7	5.1 ± 2.3	4.1 ± 2.2	0.44 small	↓24.3
Yo-Yo_{IRT1} (m)	1360 ± 389.5	1945 ± 397*	1.48 large	↑43	1531 ± 411	1885 ± 512*	0.76 moderate	↑23.1	1445 ± 493	1735 ± 524*	0.57 small	↑20
Yo-Yo_{IRT2} (m)	625 ± 135.1	830 ± 187.3*	1.25 large	↑32.8	751 ± 165	948 ± 141*	1.28 large	↑26.2	630 ± 262	750 ± 247	0.47 Small	↑19
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	42.7 ± 5.3	50.4 ± 4.5*	1.56 large	↑18	42.4 ± 3.4	50.5 ± 4.7*	1.97 large	↑19.1	42.4 ± 8.3	48.1 ± 6.8*	0.75 moderate	↑13.4

Data presented as mean± SD. $RST_{best;}$ best sprint time; RST_{total}: total sprint time; RST_{dec}: the percentage of performance decrement; Yo-Yo_{IRT1}: Intermittent Recovery Test level 1; Yo-Yo_{IRT2}: Intermittent Recovery Test level 2; VO_{2max}: maximal oxygen uptake; (d): Cohen's d effect size; %Ch: percentage change. * Significant difference between pre- and post-training

(.822, p = 0.018), Yo-Yo_{IRT2} (.696, p = 0.070), RST_{best} (.0, p = 0.926), RST_{total} (.0, p = 0.648), and RST_{dec} (.131, p = 0.429); CG VO_{2max} (.948, p = 0.001), Yo-Yo_{IRT1} (.936, p = 0.001), Yo-Yo_{IRT2} (.522, p = 0.176), RST_{best} (.941, p = 0.001), RST_{total} (.796, p = 0.026), and RST_{dec} (.736, p = 0.05) (Table 3).

DISCUSSION

In this study, the performance adaptations of soccer players to 2 variations of 6 weeks running-based SIT protocols with different recovery intervals were investigated. The main findings of the study indicated that both SIT150 and SIT30 training methods improve Yo-Yo_{IRT1}, Yo-Yo_{IRT2} and VO_{2max} performance. However, SIT150 training appeared to ensure greater performance improvements.

TABLE 3. Pre and post test conditions Intraclass Correlation Coefficients for VO_{2max}, Yo-Yo_{IRT1}, Yo-Yo_{IRT2}, RST_{best}, RST_{total}, and RST_{dec}.

	SIT30		SIT150		CG	
	ICC	p	ICC	p	ICC	p
VO_{2max}	.802	.035	.334	.303	.948	.001
Yo-Yo_{IRT1}	.958	.001	.822	.018	.936	.001
Yo-Yo_{IRT2}	.890	.008	.696	.070	.522	.176
RST_{best}	.857	.016	.0	.926	.941	.001
RST_{total}	.890	.008	.0	.648	.796	.026
RST_{dec}	.403	.273	.131	.429	.736	.05

The structure of Yo-Yo_{IRT1} is known to fit the soccer game profile [31]. Previous research showed that HI training enhances Yo-Yo_{IRT1} performance [14, 32, 33, 34]. Nyberg et al., [32] investigated the effects of 9 weeks HIIT interval training (30 m all-out runs, 8–10 reps with 10 s rest in between; 3 sets with 3 minutes recovery intervals) in 13 semi-professional male soccer players during league season and reported that after the training period Yo-Yo_{IRT1} performance was improved by 11.6%. Hill-Hass et al. [33]. showed that 7 weeks of speed endurance training enhanced Yo-Yo_{IRT1} performance by 22.1% whereas Thomassen et al. [14] reported a 6.1% improvement in Yo-Yo_{IRT1} performance after 4 weeks of training (10–12 reps. × 30-s all-out running, 3 days a week). Our results were similar to the findings of previous investigations (Yo-Yo_{IRT1} improved by 43% in SIT150 and 23% in SIT30). The SIT30 training has shorter recovery intervals compared to the SIT150 training method, causing the SIT30 method to rely more on the anaerobic pathways for exercise metabolism. As supported by the previous research and the findings of this study, SIT150 training may be considered as a convenient method to enhance oxidative systems during a soccer match. High intensity interval training (HIIT) with relatively longer recovery bouts seemed to stimulate intra-muscle adaptations and produce a better quality training period compared to same training with shorter recovery intervals. Consequently, this method can be used in soccer players to enhance their capacity to perform high-intensity exercises.

In a study conducted by Mohr & Krustrup [15] on 18 sub-elite soccer players, 4 weeks of HIIT induced improvements in Yo-Yo_{IRT2} performance of training group-1 (W:R; 1:1) (26%), and even greater improvements training group-2 (W:R; 1:5) (50%). Authors also

emphasized that having longer recovery periods after a high-intensity exercise, SIT150 training may have improved the fatigue resistance by stimulating a wide range of muscular system adaptations. In a similar study by Iaia et al. [35] 13 soccer players were trained for 3 weeks with 3 sessions per week. The observed performance improvements of Yo-Yo$_{IRT2}$ were greater in group-1 (6–8 reps × 20 s with 120 s recovery intervals) (10%, $p < 0.001$) compared to group-2 (6–8 reps × 20 s with 40 s recovery intervals) (4%, $p < 0.049$). Also, it was highlighted that Yo-Yo$_{IRT2}$ performance improvements were more likely to associate with the ability of the muscle to produce forceful bouts rather than enhancing exercise tolerance [36]. While, no studies were investigating the effects of HI training at short and long recovery intervals that were utilized in this study (*i.e.* 150-s & 30), our results were in line with the observations reported in the literature. Moreover, the present study showed that the SIT150 improved the capacity to perform high-intensity exercises (improvements in Yo-Yo$_{IRT2}$ performance by 32%). It should be noted that considering the Yo-Yo$_{IRT2}$ and soccer have a similar nature (*i.e.* HI running bouts, change of direction & intermittent nature), SIT150 training may provide great performance gains in soccer.

Both the total distance covered and the distance covered at HI runs are particularly important in soccer. It was shown that Yo-Yo$_{IRT1}$ results correlated with the total distance covered in a soccer match [36] whereas Yo-Yo$_{IRT2}$ performance correlated with distance covered at HI [37]. Consequently, both these tests reflect various aspects of fitness level [38].

SIT protocols with different recovery periods elicited similar increase in VO_{2max} [11, 13]. Olek et al. [11] reported similar VO_{2max} improvements after 2 weeks SIT period (3 sessions a week, 6 sessions in total) in two different SIT training groups (W:R; 10:60 s; 10:240 s). Similarly, Hazel et al. [13] showed that 2-weeks SIT protocols with different recovery intervals (10 s all-out run with either 120 s or 240 s rest) induced similar increase in VO_{2max}. The results of the present study showed similar VO_{2max} improvements both in SIT150 and SIT30 training groups. As a result, to enhance VO_{2max} in amateur soccer players, either one of these methods may be utilized. Common finding of these studies indicate that the change in the duration of the recovery period may not be the key variable to get better VO_{2max} gains after VHI training sessions.

Mohr & Krustrup [15] reported that 4 weeks of HIIT improved the RST_{best} (1.7%), RST_{dec} (4.4%) and RST_{total} (2.1%) in SIT group (30 s all-out running, 8–10 repetitions with a passive rest period of 150 s in between). Iaia et al. [35], investigating the effects of HIIT on RSA, reported that group-1 (20 s all-out running with a rest period of 120 s; 6–8 repetitions) had improvements (%2.5), while there were no changes in group-1 (20 s all-out running with a rest period of 40 s; 6–8 repetitions). Furthermore, Ingebrigtsen et al. [39] showed that RSA was not improved significantly after 6 weeks of HIIT in young elite soccer players. In our study, the RST_{dec} (13.9%) and RST_{total} (0.5%) were improved in SIT150 and were impaired in SIT30 training group.

A limitation of this study is the control group which did not match with the total volume of the training groups. Most studies did not use a control group making it difficult to understand the amplitude of the change induced by speed endurance training. Given that these investigations tested the effects of additional training combined with routine training, it was not clear what caused the changes in performance. Another limitation of the present study was that the graded treadmill test protocol was not used in the literature. The maximum speed that the treadmill could reach was 16 $km \cdot h^{-1}$. To raise the intensity of the test we increased the treadmill grade by 1% every minute. Additionally, in this study design we did not control the workload, since the players were not used to any workload monitoring system; however, we have tried our best to ensure that both training interventions resulted in a consistent amount of sprints performed by the players of both groups. We are aware that the difference in recovery time in-between sprints would potentially result in a difference in overall sessions' training load, making this a weakness of the present study. Therefore, further studies with similar protocols should consider monitoring training load. Lastly, the population of the present study was limited to only 23 amateur soccer players.

CONCLUSIONS

This study was the first to investigate two SIT protocols with different work-rest ratios (1:5 & 1:1) in amateur soccer players. Both SIT protocols were effective in improving Yo-Yo$_{IRT1}$, Yo-Yo$_{IRT2}$ and VO_{2max} performance. However, SIT150 training (30 s all-out sprints with 150 s recovery intervals; 6 to 10 reps; for 6 weeks) induced greater improvements likely due to having longer recovery intervals between repetitions, and can be used as a training method to improve Yo-Yo$_{IRT1}$, Yo-Yo$_{IRT2}$ and VO_{2max} performance of amateur soccer players. Such a method may be particularly useful for amateur soccer players to improve a range of performance characteristics.

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The acute leukocyte and cytokine response of older adults to resistance exercise in normobaric hypoxia

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ABSTRACT: Ageing causes a decline in leukocyte function and blunted leukocyte responses to resistance exercise. Systemic hypoxia exposure augments the leukocyte response to resistance exercise in young adults, yet this response remains uncharacterised in older adults. This study characterised the effects of normobaric hypoxia on the acute leukocyte and inflammatory cytokine responses to resistance exercise in older adults. We recruited 20 adults aged 60–70 years to perform an acute bout of resistance exercise in normobaric hypoxia (FiO_2 14.4%; n = 10) or normoxia (FiO_2 20.93%; n = 10). Participants completed 4 × 10 repetitions of lower and upper body exercises at 70% of their predicted 1-repetition maximum. Venous blood was sampled before and up to 24 hours post-exercise to quantify neutrophils, lymphocytes, monocytes, eosinophils, basophils and cytokines (IL-1β, IL-4, IL-6, IL-8, IL-10, TNFα). Flow cytometry was used to classify lymphocytes as T ($CD4^+$ helper and $CD8^+$ cytotoxic), B and NK cells, in addition to the expression of the senescence marker CD45RA on T cells. The hypoxic group showed a larger lymphocyte response over the 24 hours post-exercise compared to the normoxic group (p = 0.035). Specifically, there were greater concentrations of $CD4^+$ T helper cells following hypoxic exercise compared to normoxia (p = 0.046). There was also a greater proportion of $CD45RA^+$ $CD4^+$ T helper cells, suggesting that the cells were more senescent (p = 0.044). Hypoxia did not impact any other leukocyte population or cytokine following exercise. Normobaric hypoxia increases the lymphocyte response to an acute bout of resistance exercise in older adults.

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INTRODUCTION

The American College of Sports Medicine (ACSM) recommends that older adults perform regular bouts of resistance exercise to maintain their muscle health and functional independence [1]. Each acute bout of resistance exercise causes a rapid increase in leukocyte (white blood cell) populations and inflammatory cytokines in the systemic circulation for up to 24 hours post-exercise [2]. These leukocyte and cytokine populations likely play a role in resistance to pathogens in the hours post-exercise, with some leukocytes migrating to peripheral tissues such as skeletal muscle to aid in repair [3]. Older adults likely have a blunted systemic leukocyte response to resistance exercise [4] that may impact innate and adaptive immunity.

Resistance exercise impacts the five leukocyte subpopulations in the hours post-exercise; neutrophils, lymphocytes, monocytes, eosinophils and basophils [2]. Circulating neutrophils typically peak between 90 and 120 minutes after resistance exercise [5, 6], with monocytes typically elevated beyond 120 minutes [7]. Although there are few studies on the leukocyte responses of older adults to resistance exercise, it appears that their neutrophil response to damaging exercise (downhill running) is blunted compared to young adults up to 8 hours post-exercise [8]. Hulmi et al (2010) did not show a blunted neutrophil response in older adults compared to younger adults following a heavy resistance exercise bout, however blood was sampled up to 30 minutes and 48 hours post-exercise, and therefore the peak in neutrophil concentration was likely not captured [9]. The exercise-induced neutrophilia likely plays several important roles, including the control oxidative stress [10], pathogen removal by degranulation [11] and interaction with other leukocytes such as monocytes [12]. The increase in monocytes following an acute bout of

resistance exercise is shorter in duration in older adults [4], possibly reducing their capacity to contribute to immune defence.

In healthy young adults, lymphocytes are typically elevated approximately 2-fold during and immediately post-resistance exercise (lymphocytosis), followed by a drop below resting levels by two hours post-exercise (lymphocytopenia) [2]. The lymphocytopenia in the hours following resistance exercise could be caused by the sequestering of lymphocytes back into tissues such as the lungs and lymphoid tissues, in addition to damaged muscle tissue [13]. The literature is divided on whether the lymphocytopenia signifies reduced resistance to infection (the 'open window') or rather enhanced immunosurveillance in the peripheral tissues where the lymphocytes redeploy [14, 15]. In older adults, the peak in lymphocyte concentration immediately following intense resistance exercise is potentially blunted compared to young adults [9, 16]. A coordinated lymphocyte response is vital to effectively respond to pathogens [17, 18], therefore this blunted lymphocyte response may signify an increased risk of infection and illness in older adults. It is currently unclear whether ageing causes a more pronounced lymphocytopenia in the hours post-exercise due to the scarcity of research and the lack of frequent blood sampling 2–3 hours post-exercise when lymphocytopenia is detectable.

The inflammatory cytokine response to resistance exercise is also dysregulated in older adults. For example, the systemic response of interleukin-6 (IL-6) following a bout of damaging eccentric exercise was less pronounced in older adults compared to younger adults [19]. The coordinated and proportionate signalling of inflammatory cytokines is vital for the effective coordination of the immune response [20].

The reasons for the dysregulation immune and cytokine responses to resistance exercise with ageing are not fully clear. In healthy young individuals, the acute increase in circulating leukocytes is likely caused by the exercise-induced increase in catecholamines and glucocorticoids that bind to receptors present on leukocytes [21–23]. Other factors contributing to the normal recruitment of leukocytes to the systemic circulation includes an increase in haemodynamic shear stress that reduces the adhesion of leukocytes to the endothelial lining of blood vessels [24]. With advancing age, contributors to leukocyte ageing (termed immunosenescence) may include the persistent exposure to pathogens across the lifespan and thymic involution that reduce the number of naïve T lymphocytes and their ability to respond to novel pathogens (see review; [25]). Ageing is also associated with altered concentrations of hormones such as cortisol, adrenaline and growth hormone [26, 27] that normally stimulate leukocyte populations during exercise [22, 28]. Given that the blunted immune response to resistance exercise in older adults may reduce their resistance to pathogens, interest is growing in strategies that reverse this blunted response.

Systemic hypoxia is a potent mobiliser of leukocyte populations, yet the combined effects of resistance exercise and systemic hypoxia have not been investigated in the context of ageing. In healthy young individuals, acute exposure to hypoxia for twenty minutes increases the number and function of circulating NK cells and increases monocyte concentrations [29]. These responses may confer increased resistance to infection. In combination with resistance exercise, systemic hypoxia is typically used with the aim of improving the training adaptations in young adults [30,31]. In older adults, three studies have investigated if hypoxia can improve muscular strength, muscle mass and aerobic capacity responses to resistance training [32, 33, 34]. One of those studies reported greater muscle mass and muscle function responses in hypoxia in obese older adults [34] whilst two studies showed equivalent training adaptations in healthy older adults between hypoxia and normoxia [32, 33]. We recently characterised the leukocyte response following moderate-intensity resistance exercise in systemic hypoxia (fraction of inspired oxygen (FiO_2) 14.4%) in young adults [35]. Participants in the hypoxic group showed a greater concentration of circulating neutrophils 120 and 180 minutes following the acute bout of resistance exercise, compared to normoxic controls. Although the mechanisms mediating this response are unknown, this result highlights the potential application of hypoxic training in older adults to reverse the blunted leukocyte response to exercise. Any improvements in the leukocyte response of older adults to exercise may confer increased resistance to pathogens in the hours post-exercise. Therefore, this study aimed to characterise and compare the acute leukocyte responses of older adults to a single bout of resistance exercise in normoxia and normobaric hypoxia. We hypothesised that hypoxia would augment the acute leukocyte and cytokine responses.

MATERIALS AND METHODS

Experimental Design

A single-blinded randomised trial was used to investigate the effects of resistance exercise in normobaric hypoxia on the acute leukocyte responses in older adults. The experimental methods used in this study are previously described, where we showed that performing hypoxic resistance exercise induces a safe but significant reduction in oxygen saturation to a minimum of 89.1 ± 1.2% (mean ± SD) [32]. Participants were closely monitored during their training session to ensure that their oxygen saturation did not drop below 80%. In brief, participants completed a single bout of supervised resistance exercise in either normobaric hypoxia or normoxia. Participants were randomly allocated to hypoxia or normoxia by a random number generator.

Subjects

Twenty healthy, recreationally active males (n = 12) and females (n = 8) aged 60–70 years were recruited into the study (Normoxia; mean ± SD: age 64.0 ± 2.6 years, body mass 71.9 ± 13.8 kg, BMI 23.9 ± 2.6 kg·$(m^2)^{-1}$, Hypoxia; mean ± SD: age 65.9 ± 3.5 years, body mass 70.7 ± 14.3 kg, BMI 24.9 ± 3.6 kg·$(m^2)^{-1}$, n = 6 males and 4 females per group).

Statistical power for the study was calculated as part of a larger study [32]. Here, a power analysis was performed to demonstrate

that the study was adequately powered to detect changes in our primary outcome measures (leukocyte). The analysis was performed using a priori in G*Power through repeated measures analysis of variance (ANOVA), within-between factors (the F test; Version 3.1.9.4; Universität Kiel, Germany) using our previous study that showed the immune response of young adults to a bout of resistance exercise in normobaric hypoxia [35]. Neutrophils were selected as the largest leukocyte population and 2 hours post-exercise was selected as the most important time point. Cohens d was calculated and transformed into effect size f. The parameters were; Alpha error probability (0.05), power (1-β error probability; 0.80), groups (two), number of measurements (two; pre-exercise and 2 hours post-exercise), standard correlation among repeated measures (0.5), non-sphericity correction (one). Therefore, to detect an effect size (f) of 0.721 using a two-way repeated measures ANOVA for mean neutrophil count, a minimum of eight participants were required per group.

Experimental procedures were approved by the Deakin University Human Research Ethics Committee (ID: 2016–308). The work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). After the nature, purpose, risks and benefits of the study were explained, participants gave written informed consent to participate in the study.

Procedures

Normobaric hypoxia was achieved in an environmental tent using a normobaric hypoxic generator (Pulford Systems, Australia), as previously described [32]. Briefly, the ambient air was enriched with nitrogen to reduce the FiO_2 to 14.4%, the equivalent altitude of approximately 3,300 m above sea level [36]. To blind participants from their group allocation, individuals in the normoxic group also completed their session in the environmental tent with the generator set to FiO_2 20.93%. We have previously shown that with this level of hypoxia and exercise intensity, older adults were unable to consistently identify their environmental conditions [32]. Environmental conditions in the exercise physiology laboratory were maintained at 19°C with small fluctuations in air pressure.

Training Session

After a 5-minute warm up on a stationary bicycle, participants performed four whole body exercises at 70% of their calculated 1RM, in the following order; leg extension, pectoral fly, standing row and squat. The method used to calculate 1RM was previously reported by our group [32]. Participants performed 4 sets of 10 repetitions for each exercise with a 1 minute rest between sets and a 2 minute rest between exercises. The session lasted approximately 50–60 minutes and participants exited the environmental tent after the last squat exercise, so that their recovery was completed in normoxia. Blood was sampled from an antecubital vein at the following time points; rest, 0, 15, 30, 60, 120, 180 minutes and 24 hours post-exercise. At each time point, 5 mL of venous blood was collected in an EDTA vacutainer (BD, USA). To ensure that the load performed by the normoxic and hypoxic groups was equivalent, the total work was calculated by summing the repetitions and weights lifted for each exercise and each participant. The total work was then averaged across the normoxic and hypoxic groups and analysed using an independent samples t-test.

Haematology

A full blood count was performed on the EDTA-treated whole blood samples using a haematology analyser (DhX500, Beckman Coulter, Australia) to quantify the concentration of total leukocytes, neutrophils, lymphocytes, monocytes, eosinophils basophils and platelets. Samples were run in duplicate on the same day as blood collection. The haematology analyser was regularly cleaned and a 3-point calibration was performed before testing each sample batch. The % coefficient of variation (%CV) for leukocyte, lymphocyte, monocyte, neutrophil, eosinophil, basophil and platelet measurements for the data collection period was 1.2, 3.7, 4.0, 1.8, 15.1, 10.5 and 8.2% respectively. Given that plasma can shift between the blood and extracellular space with exercise, plasma volume shift was accounted for using the Dill and Costill method [37].

Flow cytometry

Leukocyte subpopulations were characterised using flow cytometry with three colour analysis (FacsCanto II, BD Biosciences, Australia; FACSDIVA v9.0 software). All fluorescent dye-conjugated antibodies were sourced from BD Biosciences and underwent titration to determine the optimal volume of undiluted stock solution. Venous blood was analysed pre-exercise (rest) and 0, 180 minutes and 24 hours post-exercise using two panels. For each panel, 100 μL of EDTA treated whole blood was added to a 10 mL tube containing the relevant antibodies (Supplementary table 1). Samples were incubated at room temperature for 15 minutes in the dark. Two mL of 1 × lysing solution (buffered solution with < 15% formaldehyde and < 50% diethylene glycol; BD Biosciences, Australia) was added to each sample and incubated at room temperature for 10 minutes in the dark. Samples were centrifuged at 300 × g for five minutes and the supernatant was discarded. After washing, cells were resuspended in 2 mL of phosphate buffered saline (PBS), centrifuged at 300 × g for five minutes and the supernatant was discarded. Finally, cells were resuspended in 200 μL of PBS and stored at 4°C until analysis later that day using a FacsCanto II flow cytometer. Cytometer setup and tracking beads (CST; BD Biosciences, San Jose, CA, USA) were regularly run through the machine to confirm that the median fluorescent intensity of antigen positive high, intermediate, and low populations was comparable across the course of the study. The flow cytometer collected 10,000 lymphocytes from each sample, averaging approximately 60,000–90,000 events in total. Compensation was completed using single colour controls to minimise spectral overlap of the antibodies. FITC (CD45), APC-Cy7 (CD8), BV480 (CD14) and BV421 (CD45RA) were compensated using leukocytes and APC (CD3), PE (CD4) and PE-Cy7 (CD19) were compensated

using commercial compensation beads (Anti-Mouse Ig, κ / Negative Control (FBS) Compensation Particles Set; BD Biosciences, Australia). All samples were run in duplicate, with a %CV of 3.44% for panel 1 and 3.31% for panel 2.

The gating strategy firstly identified single cells (singlets) using forward light scattering (FSC) properties (Supplementary Figure 1a). Subsequently, the side scattering (SSC) of cells was plotted against CD45 to gate out any CD45 negative cells ($CD45^-$; Supplementary Figure 1b). After using a single gate for leukocytes (Supplementary Figure 1c), the leukocyte subpopulations (granulocytes, monocytes and lymphocytes) were then visually identified using their FSC and SSC properties (Supplementary Figure 1d). For panel one, lymphocytes were isolated (Supplementary Figure 1e), then B and T lymphocytes were subsequently identified using CD3 and CD19 (Supplementary Figure 1f). Two subsets of T lymphocytes were identified using CD4 and CD8; T helper cells ($CD4^+$) and T cytotoxic cells ($CD8^+$; Supplementary Figure 1g). The expression of CD45RA on $CD4^+$ and $CD8^+$ T cells was used as a basic indicator of cell senescence, where naïve T cells are typically $CD45RA^+$ and senescent T cells are $CD45RA^-$ (Supplementary Figure 1h, i) [38].

For panel two, monocyte populations were initially identified using CD3 and CD15 (Supplementary Figure 2e), then confirmed using CD45 (Supplementary Figure 2f). The subpopulations of monocytes were identified using CD14 and CD16 (Supplementary Figure 2g). Due to a low number of monocyte cells in each sample, it was not possible to definitively identify the three monocyte subpopulations; Classical ($CD14^{++}$ $CD16^-$), non-classical ($CD14^+$ $CD16^{++}$) and intermediate ($CD14^{++}$ $CD16^+$). For this reason, monocytes were identified either as classical ($CD14^+$ $CD16^-$) or non-classical ($CD14^+$ $CD16^+$), meaning that the small number of intermediate cells were likely included in the non-classical population. In panel two, NK cells were also identified using CD3 and CD56 antibodies ($CD3^-$ $CD56^+$).

Cytokine analysis

Venous plasma samples were analysed in duplicate at the following time points; pre-exercise (rest), 0, 180 minutes and 24 hours post-exercise. A high sensitivity human cytokine Milliplex T cell panel (MPHSTCMAG28SK06; Merck Millipore, Abacus Dx, Australia) was used to quantify the protein expression of cytokines. Kits were designed for the simultaneous measurement of IL-1β, IL-4, IL-6, IL-8, IL-10 and TNFα. The assay was conducted in accordance with the manufacturer's instructions, where standards were prepared for the high sensitivity range, equating to 0.49–2000 pg/mL for IL-1β, 1.83–7500 pg/mL for IL-4, 0.18–750 pg/mL for IL-6, 0.31–1250 pg/mL for IL-8, 1.46–6000 pg/mL for IL-10 and 0.43–1750 pg/mL for TNFα. The average intra-assay %CV for IL-1β, IL-4, IL-6, IL-8, IL-10 and TNFα was 5.6, 6.8, 5.9, 4.6, 6.1, 6.1%, and the average inter-assay %CV was 3.2, 5.5, 2.0, 4.4, 1.1, 2.3% respectively. The minimum detection limit for IL-1β, IL-4, IL-6, IL-8, IL-10, and TNFα was 0.14, 1.12, 0.11, 0.13, 0.56 and 0.16 pg/mL respectively. If values were below the minimum detectable limit they were assigned the minimum detectable limit. There were a small number of participants excluded from the analysis due to having > 50% of measurements below the minimum detectable limit; IL1β (n = 2), IL-4 (n = 0), IL-6 (n = 1), IL-8 (n = 2), IL-10 (n = 1) and TNFα (n = 1).

Statistical Analysis

Statistical analysis was completed using SPSS software (IBM SPSS 26, Chicago, IL) and graphed using GraphPad software (Prism 8.00, California USA). Data were assessed for normal distribution using a Shapiro Wilk test and an independent samples t-test was conducted to detect any between-group differences at pre-exercise (resting).

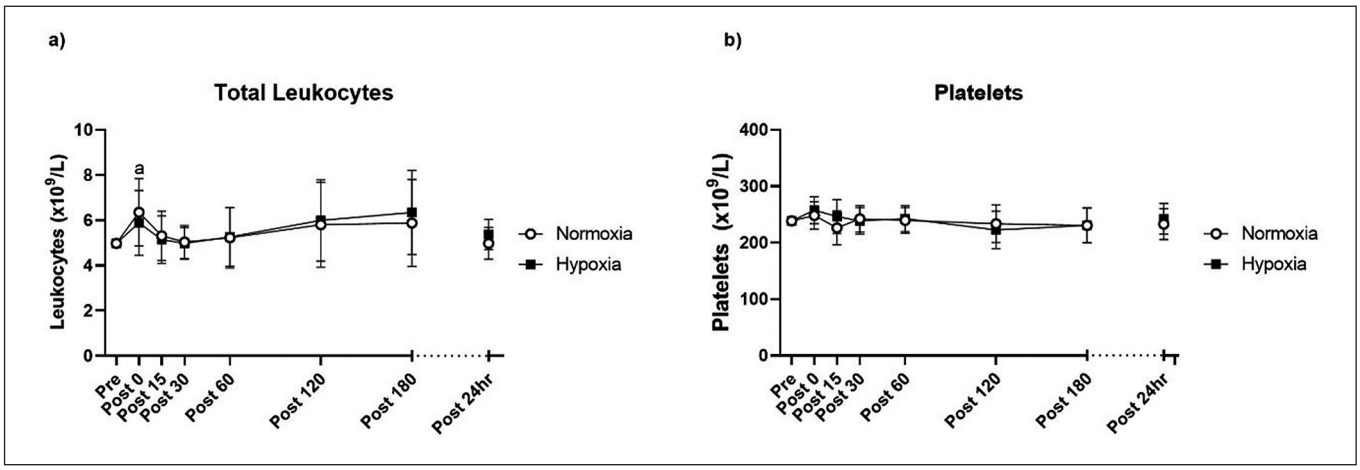


FIG. 1. Total leukocytes (a) and platelets (b) pre- and post-exercise. Values are adjusted means ± SD (n = 10). [a] Significantly different from pre-exercise ($p < 0.05$).

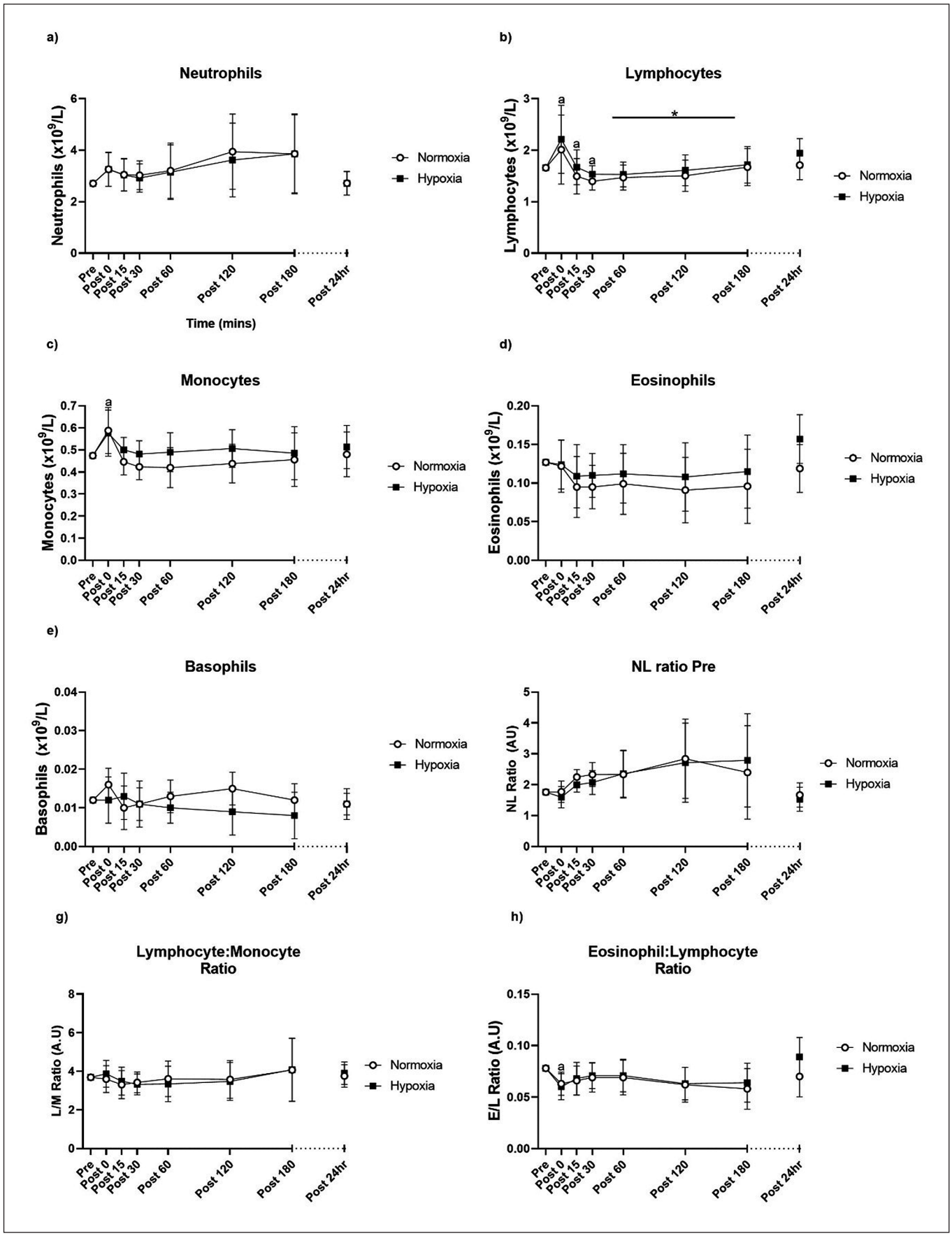


FIG. 2. Neutrophils (a), lymphocytes (b), monocytes (c), eosinophils (d) and basophils (e), neutrophil-lymphocyte ratio (f), lymphocyte-monocyte ratio (g) and eosinophil-lymphocyte ratio pre- and post-exercise. Values are adjusted means ± SD (n = 10). * Main GROUP effect ($p < 0.05$). [a] Significantly different from pre-exercise ($p < 0.05$).

Any variables that failed the Shapiro-Wilk test for normality underwent Log_{10} transformation prior to analysis. Analysis of the resting values revealed that leukocytes were different between groups at pre-exercise (rest). Therefore, the acute leukocyte responses to resistance exercise in hypoxia were analysed with an ANCOVA for the main effects of TIME (seven levels; 0, 15, 30, 60, 120 and 180 minutes, 24 hours post-exercise), GROUP (two levels; normoxia, hypoxia) using two covariates (sex, resting values). Sex was included as a covariate to account for known differences in leukocytes between males and females. For the leukocyte variables generated by flow cytometry (NK cells, B lymphocytes, T lymphocytes, $CD4^+$ cells, $CD8^+$ cells, CD45RA expression, $CD14^+$ $CD16^-$ monocytes and $CD14^+$ $CD16^+$ monocytes) there were four levels of TIME (pre-exercise and 0, 180 minutes and 24 hours post-exercise). If a TIME × GROUP interaction was present, a Bonferroni post-hoc test was used to evaluate the effect of hypoxia on individual time points. Data are presented as adjusted mean ± SD.

Given that the ANCOVA used the first resting value as a covariate (pre-exercise), it was not possible to determine the main effects of TIME across the normoxic and hypoxic groups. Therefore, a separate 'time course analysis' was performed using GROUP (two levels; normoxia, hypoxia), TIME (8 levels; pre-exercise, post 0, 15, 30, 60, 120 and 180 mins, 24 hrs) and COVARIATE (sex). The ANCOVA included pairwise comparisons on the pooled group data (estimated marginal means for TIME), where the resting (pre-exercise) value was compared to the post 0, 15, 30, 60, 120, 180 mins and 24 hrs values with Bonferroni confidence interval adjustment. This secondary analysis allowed comparison of the acute effects of exercise alone on the leukocyte responses, irrespective of group allocation.

Inflammatory cytokines showed no baseline (resting) or sex differences between hypoxia and normoxia, and were therefore analysed using an ANOVA for the main effects of TIME (four levels; pre-exercise and 0, 180 minutes and 24 hours post-exercise) and GROUP (two levels; normoxia, hypoxia). Significance was set at $p < 0.05$.

RESULTS

The total work performed during the resistance exercise bout was not statistically different between normoxic and hypoxic groups ($p = 0.388$; independent samples t-test). After accounting for plasma volume shifts, sex and baseline differences, there was no TIME × GROUP interaction for total leukocytes ($p = 0.853$) or

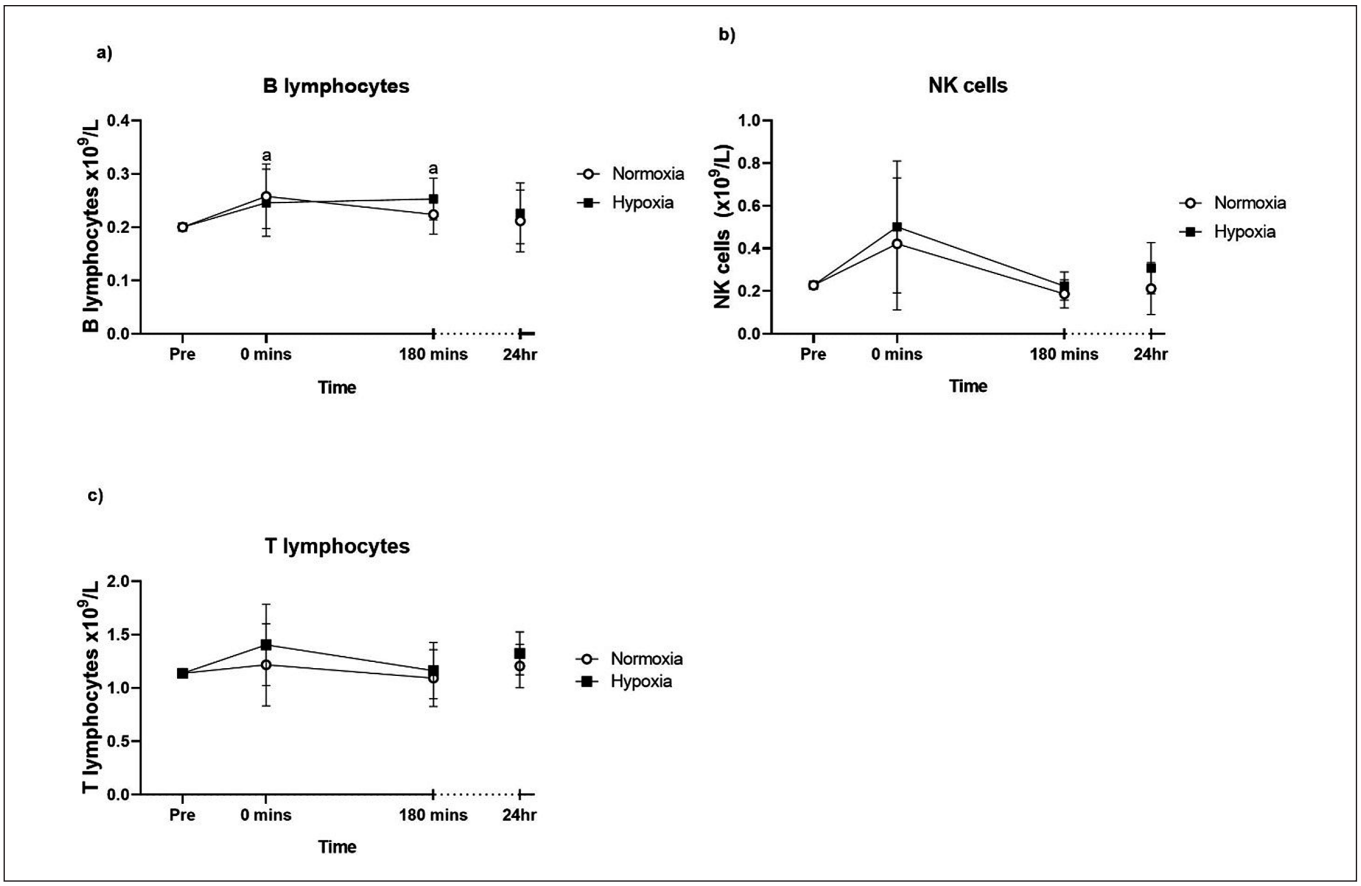


FIG. 3. B lymphocytes (a), NK cells (b) and T lymphocytes (c) pre- and post-exercise. Values are adjusted means ± SD ($n = 10$). [a] Significantly different from pre-exercise ($p < 0.05$).

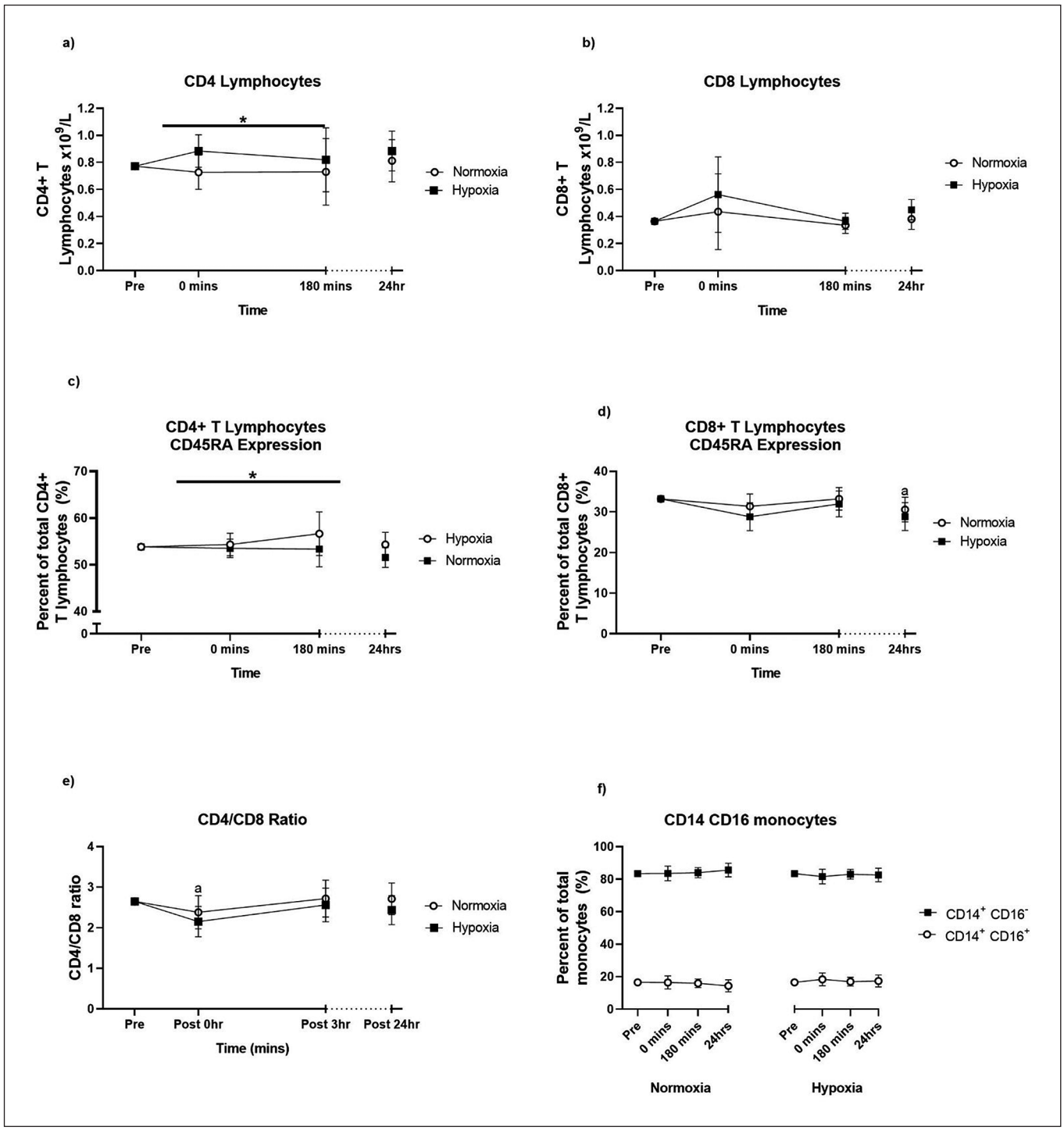


FIG. 4. $CD4^+$ T helper cells (a), $CD8^+$ T cytotoxic cells, the subsets of $CD45RA^+$ and $CD45RA^-$ T cells (c, d), the CD4/CD8 ratio and the subsets of $CD14^+$ $CD16^-$ (classical) and $CD14^+$ $CD16^+$ (non-classical/intermediate) monocytes (f) pre- and post-exercise. Values are adjusted means ± SD (n = 10). * Main GROUP effect ($p < 0.05$). [a] Significantly different from pre-exercise ($p < 0.05$).

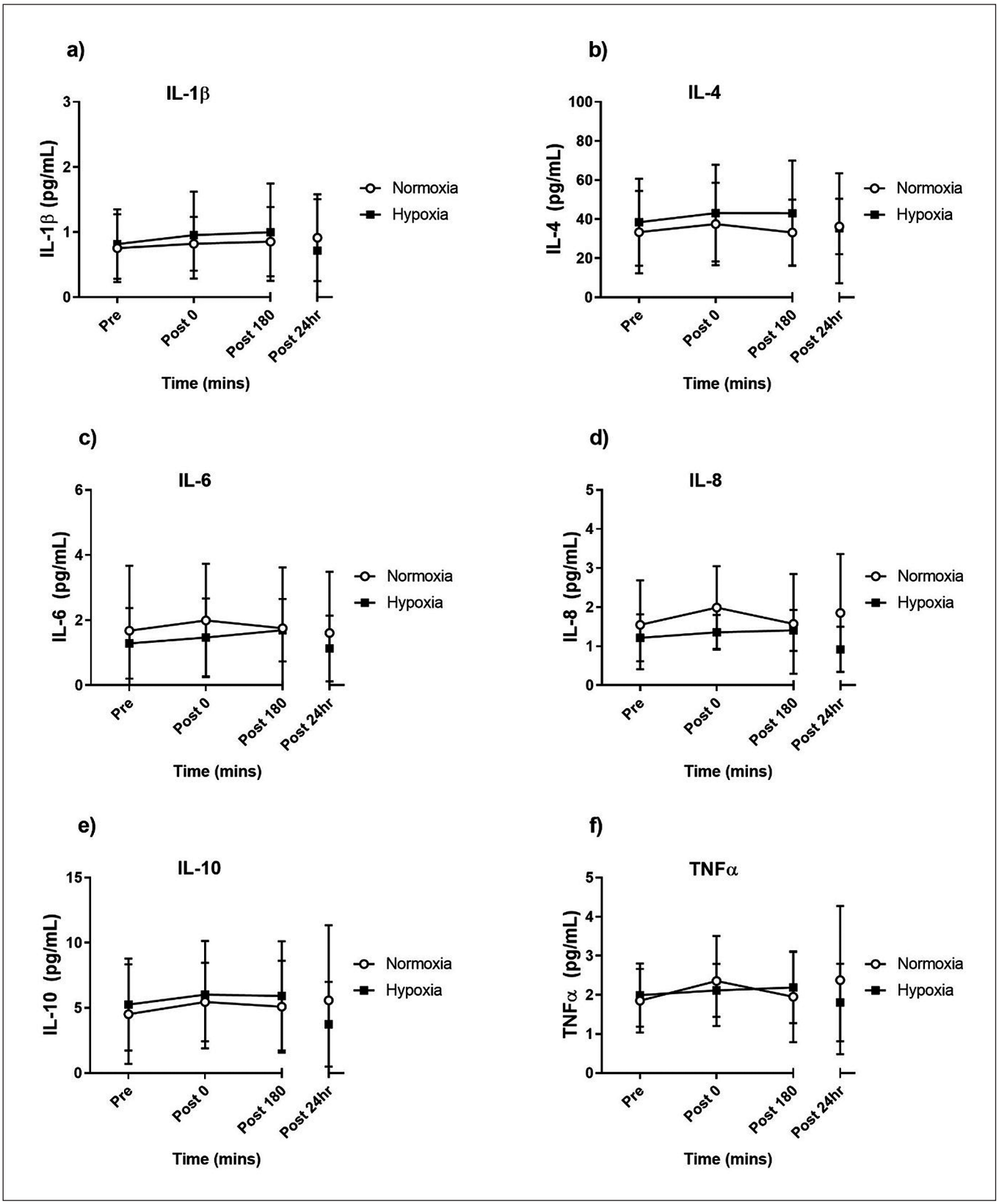


FIG. 5. Acute Interleukin-1 beta (IL-1β; a) Interleukin-4 (IL-4; b), Interleukin-6 (IL-6; c), Interleukin-8 (IL8; d), Interleukin-10 (IL-10; e) and tumor necrosis factor alpha (TNF-α; f) pre- and post-exercise. Values are mean ± SD (n = 10).

platelets in the 24 hours following the training session ($p = 0.674$; Figure 1a, b). The time course analysis showed that, irrespective of group allocation, total leukocytes increased immediately post-exercise ($p = 0.032$) compared to pre-exercise. Leukocytes then returned close to baseline and were not different to the pre-exercise values up to 24 hours post-exercise. Platelet counts did not change over the 24 hour measurement period ($p > 0.05$).

There were no TIME × GROUP interactions present for any of the five leukocyte subsets measured in the 24 hours following the training session; neutrophils ($p = 0.994$), lymphocytes ($p = 0.995$), monocytes ($p = 0.421$), eosinophils ($p = 0.747$) or basophils ($p = 0.408$), nor the ratio of neutrophils-lymphocytes ($p = 0.906$), lymphocytes-monocytes ($p = 0.971$) or eosinophils-lymphocytes ($p = 0.235$; Figure 2). However, there was a main GROUP effect for lymphocytes following the training session ($p = 0.035$), where lymphocyte concentrations were higher in hypoxia compared to normoxia. Monocytes, eosinophils and basophils showed no main GROUP effect. The time course analysis showed that, irrespective of group allocation, neutrophils showed a near-significant increase immediately post-exercise ($p = 0.055$), though were not different from pre-exercise at any other timepoint. There was an increase in lymphocytes immediately post-exercise ($p < 0.001$), followed by a decrease below pre-exercise levels at 15 ($p < 0.001$) and 30 minutes post-exercise ($p = 0.018$), returning close to pre-exercise values up to 24 hours post-exercise. Monocytes increased immediately post-exercise compared to pre-exercise ($p = 0.009$) and did not differ at any other timepoint. Eosinophils, basophils and the lymphocyte-monocyte ratio did not change over the 24 hours post-exercise. The neutrophil-lymphocyte ratio was increased above pre-exercise values at 15 and 30 minutes post-exercise ($p < 0.001$, $p = 0.008$, respectively). The eosinophil-lymphocyte ratio increased decreased post-exercise ($p < 0.01$) compared to pre-exercise, but was not different at any other timepoint.

There were no TIME × GROUP interactions for the lymphocyte subpopulations; B lymphocytes ($p = 0.549$), NK cells ($p = 0.795$) and T lymphocytes ($p = 0.885$; Figure 3a, b, c), nor were there any main effects of GROUP. However, the analysis of T cell subpopulations showed a main GROUP effect, where the $CD4^+$ T cell responses were higher in hypoxia compared to normoxia ($p = 0.046$; Figure 4a). $CD4^+$ T helper cells also showed a main GROUP effect on CD45RA expression ($p = 0.044$), where there was a higher proportion of $CD45RA^-$ $CD4^+$ T cells in hypoxia compared to normoxia (Figure 4c). For the acute $CD8^+$ T cytotoxic cell response and their expression of CD45RA, there was no main effect of GROUP or TIME following training session (Figure 4b, d). There was no main GROUP effect on the CD4:CD8 ratio in the 24 hours following the training session (Figure 4e). For the acute $CD14^+$ $CD16^-$ (classical) monocyte and the non-classical/intermediate ($CD14^+$ $CD16^+$) monocyte response there was no main GROUP effect following the training session (Figure 4f). The time course analysis showed that, irrespective of group allocation, B lymphocytes were increased at 0 minutes ($p = 0.033$) and 3 hours ($p = 0.010$) post-exercise compared to pre-exercise. NK cells were near-significantly increased at 0 minutes post-exercise compared to pre-exercise ($p = 0.063$). T lymphocytes ($CD4^+$ and $CD8^+$) and the expression of CD45RA on $CD4^+$ T lymphocytes did not change in the 24 hours post-exercise. The proportion of $CD45RA^+$ $CD8^+$ T cells was lower 24 hours after the exercise bout ($p = 0.041$).

The acute inflammatory cytokine responses to resistance exercise were measured at rest and 0, 180 minutes and 24 hours following the training session. The acute IL-1β, IL-4, IL-6, IL-8, IL-10 and TNFα responses did not show a TIME × GROUP interaction following the training session ($p = 0.894$, $p = 0.236$, $p = 0.174$, $p = 0.072$, $p = 0.062$, $p = 0.259$ respectively; Figure 5). The time course analysis showed that, irrespective of group allocation, there were no changes in cytokine concentrations in the 24 hours following the exercise bout ($p < 0.05$).

DISCUSSION

Older adults experience blunted physiological adaptations to exercise [39] and reduced resistance to pathogens [40], both of which contribute to the declining health of ageing individuals. Systemic hypoxia augments the leukocyte response to resistance exercise in young adults [35], yet this response remained uncharacterised in older adults. Therefore, this study characterised the acute leukocyte and cytokine responses of older adults to a single bout of resistance exercise in hypoxia.

Analysis of circulating neutrophils, monocytes, eosinophils and basophils showed no effect of hypoxia in the 24 hours following the resistance training protocol. An acute increase in monocytes following exercise is typical, possibly due to increased sheer stress in the vasculature and monocyte release from bone marrow [41, 42]. We expected hypoxia to further increase the systemic monocyte response as acute hypoxia can reduce monocyte migration from the systemic circulation into peripheral tissues [43]. We also expected a larger neutrophil response to the hypoxic training protocol, given that young adults show a greater neutrophil response 120 and 180 minutes after resistance training in FiO_2 14.4%, compared to normoxic controls [35]. Older adults are generally thought to have blunted neutrophil responses to acute exercise compared to young adults [8], and it appears that this is not reversed by exposure to systemic hypoxia.

We demonstrated that older adults have higher lymphocyte numbers following resistance exercise in hypoxia compared to normoxia, that persists for 24 hours post-exercise. Considering that ageing typically reduces lymphocyte concentrations following exercise, the older adults exposed to hypoxia in this study may have partially restored their lymphocyte response. Hypoxia (FiO_2 14.4%) does not elicit a greater lymphocyte response in young adults when performing a similar resistance exercise protocol to the current study [35]. However, young adults do show the classic lymphocytosis immediately post-exercise followed by a modest decrease below baseline for approximately 3 hours post-exercise [35]. In the present study,

the peak in lymphocytes immediately post-exercise in the older adults was approximately 2–2.5 $\times$ 10^9/L, whereas the younger adults in our previous study peaked at approximately 3.5–4.0 $\times$ 10^9/L. Although lymphocytes were not fully restored to that of young adults, it shows that hypoxia could benefit older adults and increase lymphocyte numbers following resistance exercise. It appears that the lymphocytopenia that typically occurs in the hours post-exercise was less pronounced in the hypoxic group compared to normoxia, suggesting if anything, that the older adults may have been less susceptible to pathogens in the systemic circulation. The exact mechanism causing the greater lymphocyte response in hypoxia is unknown. Although adrenaline [44], noradrenaline [45], growth hormone [46] and cortisol [47] are known recruiters of lymphocytes, we have previously shown that older adults do not show a greater concentration of these hormones in the 60 minutes following hypoxic resistance exercise, compared to normoxia [48]. Future studies would benefit from utilising both young and older participants to compare the lymphocyte responses to resistance exercise in hypoxia.

Analysis of the T lymphocyte subsets showed that exercising in hypoxia, compared to normoxia, elevated the proportion of circulating $CD4^+$ T helper cells over the 24 hours post-exercise. It is difficult to elucidate the cause of this response, given that the number of T cells in circulation can be influenced by many factors including the initial rate of T cell influx from the periphery into the bloodstream and the subsequent rate of T cell movement back into peripheral tissues [49]. The number of T cells in the circulation can also be influenced by stress-induced apoptosis of T cells and the entry of naïve T cells from the thymus [50, 51].

We also showed a higher proportion of $CD45RA^-$ $CD4^+$ T cells in hypoxia in the 24 hours following the training session, when compared to normoxia. Although CD45RA is only a crude marker for cell senescence, it is possible that hypoxia differentially regulates the movement of $CD4^+$ T cell phenotypes between peripheral tissues and the systemic circulation. It is possible that hypoxia caused greater recruitment of senescent $CD4^+$ T cells into the bloodstream or greater apoptosis of naïve $CD4^+$ T cells, given that a single bout of intense cycling in 12% O_2 increased $CD4^+$ T cell apoptosis through the caspase-9 pathway in young males [52]. These potential mechanisms require further investigation with a greater number of cell senescence markers. Despite the effects of hypoxia on the $CD4^+$ T cell response, hypoxia did not affect the acute CD4:CD8 T cell ratio, $CD8^+$ T cytotoxic response or the proportion of $CD45RA^+$ $CD8^+$ T cells. Resistance exercise alone elicited a decrease in the CD4:CD8 ratio immediately post-exercise that is consistent with moderate-intensity resistance exercise in older adults [53].

The inflammatory cytokines did not show any effects of hypoxia, nor did they change over the 24 hours post-exercise. This result is likely due to the variable nature of cytokine measurements [54] and a relatively small sample size in this study. Glycogen depletion is known to increase systemic IL-6 following exercise [55], therefore we had expected the increased reliance on carbohydrate metabolism with hypoxic resistance exercise to elevate IL-6 levels post-exercise. The exercise session may have been insufficient in both intensity and/or duration to induce a greater IL-6 response in hypoxia. Although the acute cytokine responses to resistance exercise in hypoxia were previously uncharacterised in older adults, systemic hypoxia exposure generally upregulates inflammatory pathways through transcription factors such as NF-κβ and hypoxia inducible factor 1 (HIF-1) [56, 57]. In young adults, resting exposure to normobaric hypoxia for 6.5 hours increases systemic levels of TNFα and IL-6 [58]. The only study to characterise the systemic inflammatory responses of young adults to acute resistance exercise in hypoxia found an increase in IL-6 four hours after exercise, but no changes to IL-4, IL-8, IL-10 or TNFα when compared to normoxia [59]. Future research with larger sample sizes is needed to determine the functional impact of these cytokine responses to resistance exercise in hypoxia, including the potential relationship between inflammatory cytokines and immune cell recruitment.

Strengths and Limitations

The inclusion of frequent blood samples between 0 minutes and 3 hours post-exercise enabled a thorough characterisation of the leukocyte responses of older adults to resistance exercise in hypoxia. Although the inclusion of males and females was important for the generalisation of results to the older adult population, the sample size could be expanded to more definitively determine the leukocyte and cytokine responses to hypoxic resistance exercise in both older males and females. The inclusion of more leukocyte senescence markers would have also strengthened the study.

CONCLUSIONS

Normobaric hypoxia amplifies the acute lymphocyte response to a single bout of resistance exercise in recreationally active, non-resistance trained older adults. Although these changes could confer enhanced immune function, more research is needed to clarify the causes and implications of these responses to resistance exercise in hypoxia. The potential implications of this response to lymphocyte function is of great interest in future research. Our findings show that hypoxia does not detrimentally affect the leukocyte response of older adults to resistance exercise and that it may enhance their lymphocyte responses to exercise. From a practical perspective, health professionals can prescribe hypoxic resistance exercise to older adults without any detriment to the acute leukocyte or cytokine response.

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Conflict of interest declaration

The authors declare no conflict of interest.

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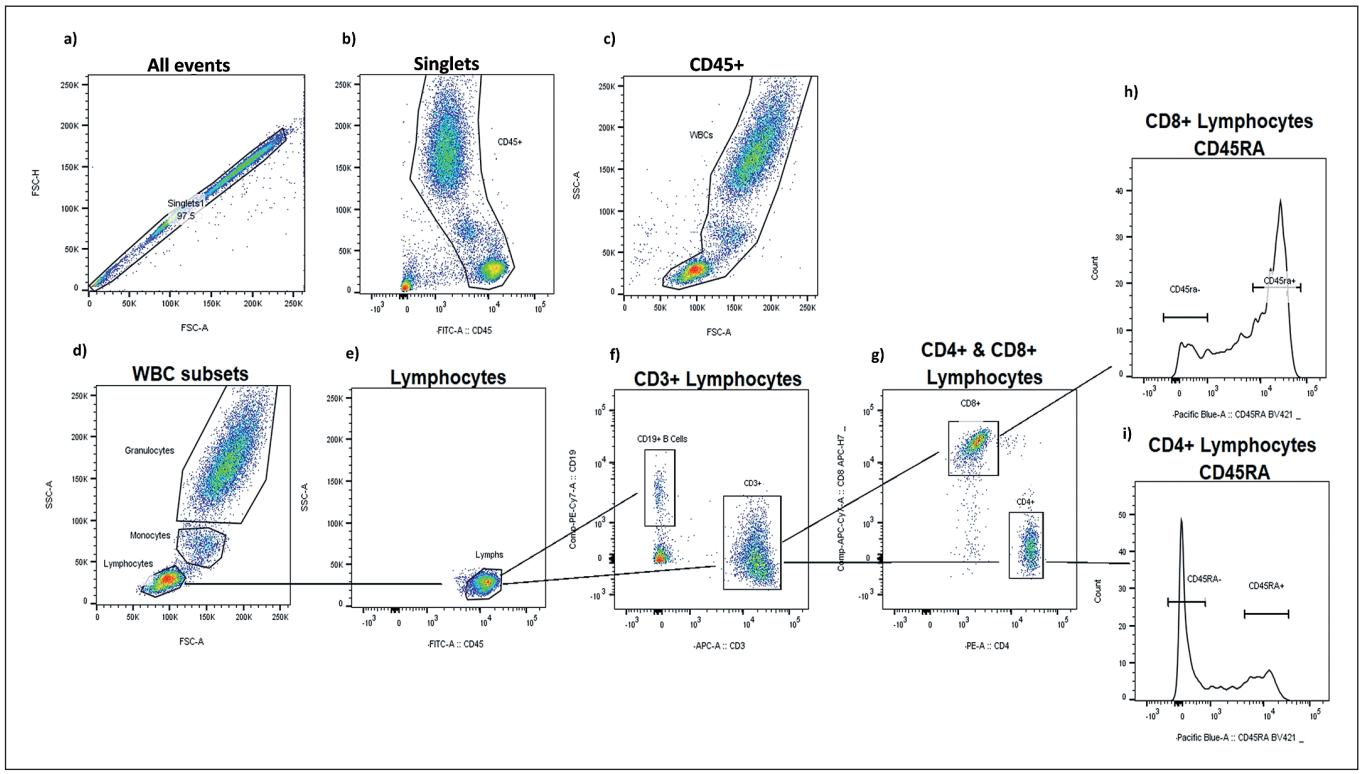
SUPPLEMENTARY TABLE I

Antibodies and flow cytometer settings for panel one and panel two. All antibody quantities listed were taken neat from the undiluted stock solution.

Panel one						
Laser	**Optical Filters**	**Markers**	**Fluorochrome**	**Amount (μL)**	**Cat No.**	**Clone**
Blue (488 nm)	530/30	CD45	FITC	10	555482	HI30
	585/42	CD4	PE	10	555335	RPA-T4
	780/60	CD19	PE-Cy7	2.5	557835	SJ25C1
Red (633 nm)	660/20	CD3	APC	10	555347	UCHT1
	780/60	CD8	APC-Cy7	2.5	560179	SK1
Violet (405 nm)	450/50	CD45RA	BV 421	2.5	562885	HI100
Panel two						
Laser	**Detector/PMT**	**Markers**	**Fluorochrome**	**Amount (μL)**	**Cat No.**	**Clone**
Blue (488 nm)	530/30	CD45	FITC	10	555482	HI30
	585/42	CD15	PE	10	555402	HI98
	780/60	CD16	PE-Cy7	2.5	557744	3G8
Red (633 nm)	660/20	CD3	APC	10	555347	UCHT1
Violet (405 nm)	525/40	CD14	BV480	2.5	566141	Mφp9
	450/50	CD56	BBV421	2.5	562752	NCAM16.2

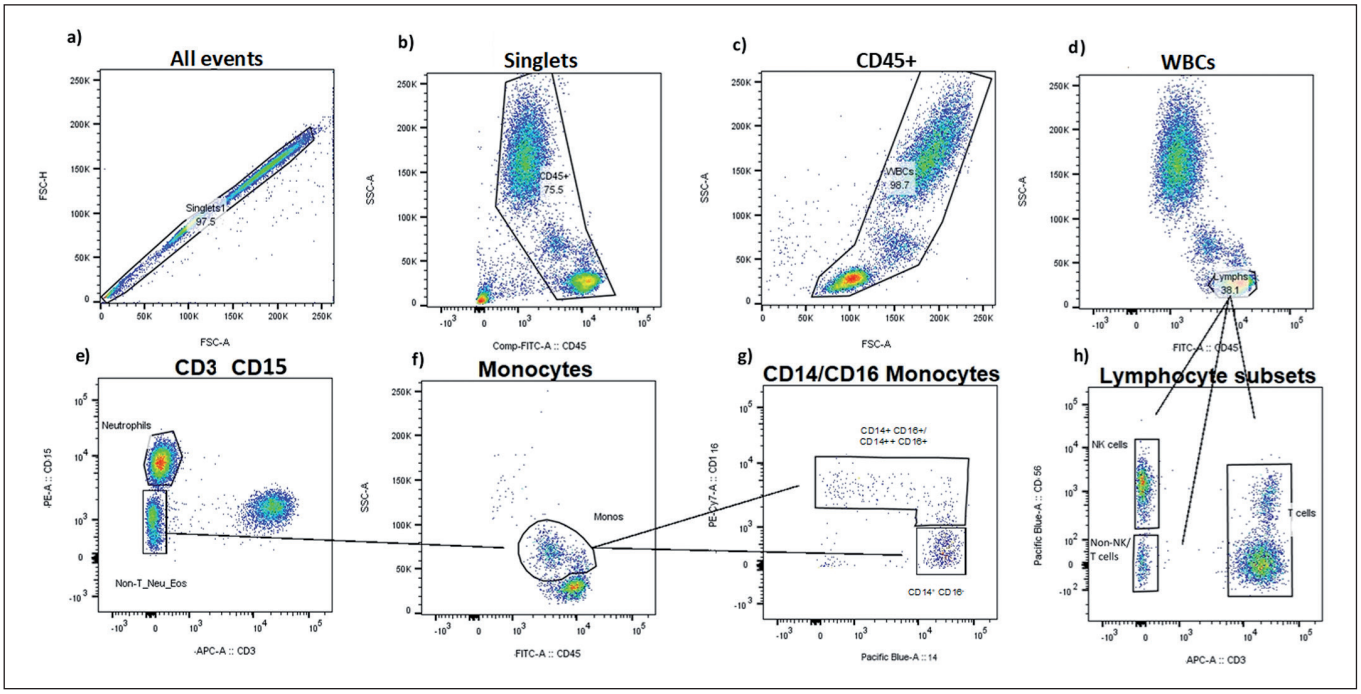
SUPPLEMENTARY FIGURE I

Panel one flow cytometry gating strategy, including all events (a), singlets (b), CD45$^+$ (c), white blood cell (WBC) subsets (d), lymphocytes (e), CD3$^+$ lymphocytes (f), CD4/CD8$^+$ Lymphocytes and their expression of CD45RA (h, j). Populations analysed include total lymphocytes, lymphocyte subpopulations (B lymphocytes and T lymphocytes) and the two subpopulations of T lymphocytes; CD4$^+$ T helper cells and CD8$^+$ T cytotoxic cells. CD4$^+$ and CD8$^+$ T cells were stained with CD45RA as a crude marker of cell senescence.



SUPPLEMENTARY FIGURE 2

Panel two flow cytometry gating strategy, including all events (a), singlets (b), $CD45^+$ (c), white blood cell (WBC) subsets (d), CD3/CD15 (e), monocytes (f), CD14/CD16 monocytes and lymphocyte subsets (h). Populations analysed include NK cells, total monocytes and the two monocyte subpopulations; $CD14^+$ $CD16^-$ monocytes (classical monocytes) and $CD14^{+/++}$ $CD16^+$ monocytes (grouped here as non-classical monocytes).



Training zones through muscle oxygen saturation during a graded exercise test in cyclists and triathletes

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ABSTRACT: Use of muscle oxygen saturation (SmO_2) has been validated as a performance factor during incremental exercise with portable near-infrared stereoscopy (NIRS) technology. However, there is little knowledge about the use of SmO_2 to identify training zones. The objective of this study was to evaluate the metabolic zones by SmO_2: maximum lipid oxidation zone (Fatmax), ventilatory thresholds (VT1 and VT2) and maximum aerobic power (MAP) during a graded exercise test (GXT). Forty trained cyclists and triathletes performed a GXT. Output power (W), heart rate (HR), oxygen consumption (VO_2), energy expenditure (kcal/min) and SmO_2 were measured. Data were analysed using the ANOVA test, ROC curves and multiple linear regressions. Significance was established at $p \leq 0.05$. SmO_2 decreases were observed from baseline (LB) to Fatmax (Δ = -16% $p < 0.05$), Fatmax to VT1 (Δ = -16% $p < 0.05$) and VT1 to VT2 (Δ = -45% $p < 0.01$). Furthermore, SmO_2 together with weight, HR and output power have the ability to predict VO_2 and energy expenditure by 89% and 90%, respectively. We conclude that VO_2 and energy expenditure values can be approximated using SmO_2 together with other physiological parameters and SmO_2 measurements can be a complementary parameter to discriminate aerobic workload and anaerobic workload in athletes.

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INTRODUCTION

Graded exercise tests (GXT) to exhaustion are traditionally used to evaluate the performance in cyclists through the evaluation of physiological parameters such as heart rate (HR), central venous oxygen saturation ($ScvO_2$), oxygen consumption (VO_2), ventilatory equivalent (VEQ) and power (W) [1, 2]. Generally, these parameters provide performance information from the athlete so as intensity increases, different training zones can be determined by the participation of metabolic pathways or energy [3]. Knowing this process is necessary to schedule individual workouts and can help optimize performance in endurance athletes. However, there are limitations to the detection of subtle changes in other physiological factors that affect performance and changes in metabolic pathways – for example, oxygenation changes in skeletal muscle, which cannot be determined with a cardiopulmonary gas analyser during GXT in endurance athletes [4, 5].

In studies of skeletal muscle physiology, near infrared stereoscopy (NIRS) technology is commonly used to detect changes in muscle oxygenation during exercise [6] and provides new knowledge about the muscle oxidative capacity [7]. Likewise, in the latest reviews on the use of NIRS as a research tool in sports settings, it has been shown that portable NIRS has good sensitivity to detect skeletal muscle oxygen supply and use during static and dynamic muscle work in response to interventions in exercise and training [8].

The Monitor portable NIRS device can evaluate the muscle oxygen saturation (SmO_2). For example, Moxy, which is affordable in price in the consumer market, it has been validated in comparison with other NIRS brands [9]. But, according to Crum [10], Moxy seems to have proven reliable to measure SmO_2 at low and moderate intensities during a GXT, but not at high intensities, where greater variation has been observed. However, Crum's study did not examine whether Moxy was able to discriminate between different training zones through the metabolic pathways used by skeletal muscle [11]. This would be interesting for future studies using other brands of portable NIRS.

By evaluating the training zones based on changes in muscle metabolism we can identify: the maximum lipid oxidation zone (Fatmax), ventilatory thresholds VT1 and VT2 and maximum aerobic power (MAP) [12, 13, 14]. With the information from these four zones, we can program workouts with different objectives. Currently heart rate (%) and VO_2 (l/m) are the most used internal load parameters in cycling [15] but including the measurement of SmO_2 is interesting because it allows the evaluation of muscle oxidative metabolisms and the relationship with factors that limit exercise tolerance in cyclists and triathletes [16]. As far as we know, no study has yet evaluated SmO_2 by training zones based on muscle metabolism in highly trained

athletes, so the objectives of this study are, first, to evaluate SmO_2 during a GXT and establish cut-off points for each training zone based on the scale (0%–100%), and second, to study the variables associated with $\dot{V}O_{2max}$ using an explanatory model that incorporates SmO_2 with other physiological parameters to identify the training zone.

MATERIALS AND METHODS

Subjects

The sample was composed of 40 trained cyclists and triathletes (age: 32 ± 8 years; height: 180 ± 005 cm; body mass: 74.6 ± 7.6 kg; $\dot{V}O_{2max}$: 64.6 ± 7.3 ml/kg/min; HR rest: 45.3 ± 6.3; % body fat: 9.6 ± 2.4; skinfold of the vastus lateralis: 13.4 ± 7.9 mm and experience in endurance training: 10.9 ± 4.9 years) who volunteered to participate in this study. The subjects were healthy individuals without any physical limitations or muscular-skeletal injuries that might affect the outcome of the exercise test. The study was carried out in accordance with the Helsinki Declaration and approved by the Bio-Ethical Committee of the University of Extremadura with the registration code: XXXX. Signed consent was obtained from each subject prior to their participation.

Trial design

The trial design was cross-sectional. Subjects carried out the test under similar environmental conditions (21–24ºC and 45–55% relative humidity) and were asked to abstain from doing intense exercise 48 hours prior to the test. Before the test, the anthropometric variables were determined: weight, percentage body fat [17] and vastus lateralis fold. The GXT was then carried out to obtain SmO_2.

Maximal graded exercise test (GXT)

First, a standardized warm-up of 10 min at 100 W was performed; the ramp protocol consisted of increments of 30 $W \cdot min^{-3}$ until volitional exhaustion [13]. The end of the test was considered when the participant was unable to maintain the power output of each final completed stage. During GXT participants were monitored through a gas exchange measurement system/device with breath-by-breath technology and calibrated before each test (Metalyzer 3b, CORTEX Biophysik GmbH, Leipzig, Germany). Each participant used their own bike mounted on a smart training device (Bkool, model Bkool one; Madrid, Spain). The protocol was completed with a PowerTap P1 (PP1), which produced reliable output power readings of 100–500 W, in a seated position (rho ≥ 0.987), and an absolute reliability index (150–500 W; COV = 2.3%; SEM < 1.0 W) [18]. The PowerTap during cardiopulmonary tests are more ecologically valid, allowing cyclists to use their own bicycles [18]. HR was collected via a HR monitor (HRM-Tri; Garmin Ltd., Olathe, KS, USA). The smart trainer assessed power with internal sensors that were paired to a smartwatch for future analysis (Forerunner 735xt, Garmin, Olathe, KS, USA).

Muscle oxygen saturation assessment

For the evaluation of local muscle oxygen saturation (SmO_2) a near-infrared spectroscopy device with a sampling frequency of 1 Hz (MOXY, Fortiori Design LLC, Minneapolis, Minnesota, USA), which is valid for measuring SmO_2 (ICC: r = 0.773–0.992), was used [10]. It was attached firmly to the belly of the right vastus lateralis (VL) muscle (12 cm above the patella border muscle) using a dark elastic strap to avoid light contamination and movement artefacts. The vastus lateralis was selected based on previous evidence and considering the role of this muscle in cycling [19]. The skinfold thickness at the NIRS measurement site VL was measured using a skinfold caliper (Harpenden Ltd.) to ensure that the skinfold thickness was < 1/2 of the distance between the emitter and the detector (25 mm). Furthermore, no participant presented values > 15 mm from the skinfold, as a reference point where SmO_2 measurements are usually excluded [20]. This technology allows the evaluation of saturation taking into consideration the relative change of total haemoglobin (tHb) and the interaction between O_2Hb and HHb with the following equation:

$$SmO_2 = ((O_2Hb)/(O_2Hb + HHb)) \times 100.$$

This is calculated by the quantification of variation in optical transmission by sequentially emitting light waves (630–850 nm) from light diodes into the tissue and recording the amount of light received. Using an algorithm, the system determines the amount of light absorbed at wavelengths relative to the oxygenated and deoxygenated Hb using the Beer-Lambert Law and tissue light propagation model processes. The raw muscle O_2 saturation (SmO_2) signal was treated with a soft spline filter to reduce noise created by movement [21] using Minitab 19 (Minitab, Inc, State College, PA; www.minitab.com, USA) (see Supplementary figure).

For the data analysis the following guidelines were followed: 1) the mean values of the last minute of each phase were used 2) exclude data of SmO_2 > 10% after the last recorded value and 3) data that gave a 0% reading were excluded due to the apparent lost signal. The data were viewable in real time to the NIRS technology expert researchers and muscle oxygenation measurement, using ANT + technology software (Golden Cheetah version 3.4, USA) and joint data processing software (Excel 2016, Microsoft Office 365, USA).

Gas exchange analysis of VT1 and VT2 by V-slope method and independent experts

The thresholds provided by MetaSoft Studio were adopted and confirmed according to the criteria of the expert researchers. VT1 and VT2 were determined with the equivalent ventilatory method (VEQ). VT1 was determined using the criteria of an increase in ventilatory equivalent of oxygen (VE/VO_2) with no concomitant increase in ventilatory equivalent of carbon dioxide (VE/VCO_2) [22]. VT2 was determined using the criteria of an increase in both the VE/VO_2 and VE/VCO_2 (Figure 1d) and analysing the behaviour of VCO_2 as a function of VO_2, during progressive exercise tests when exceeding the

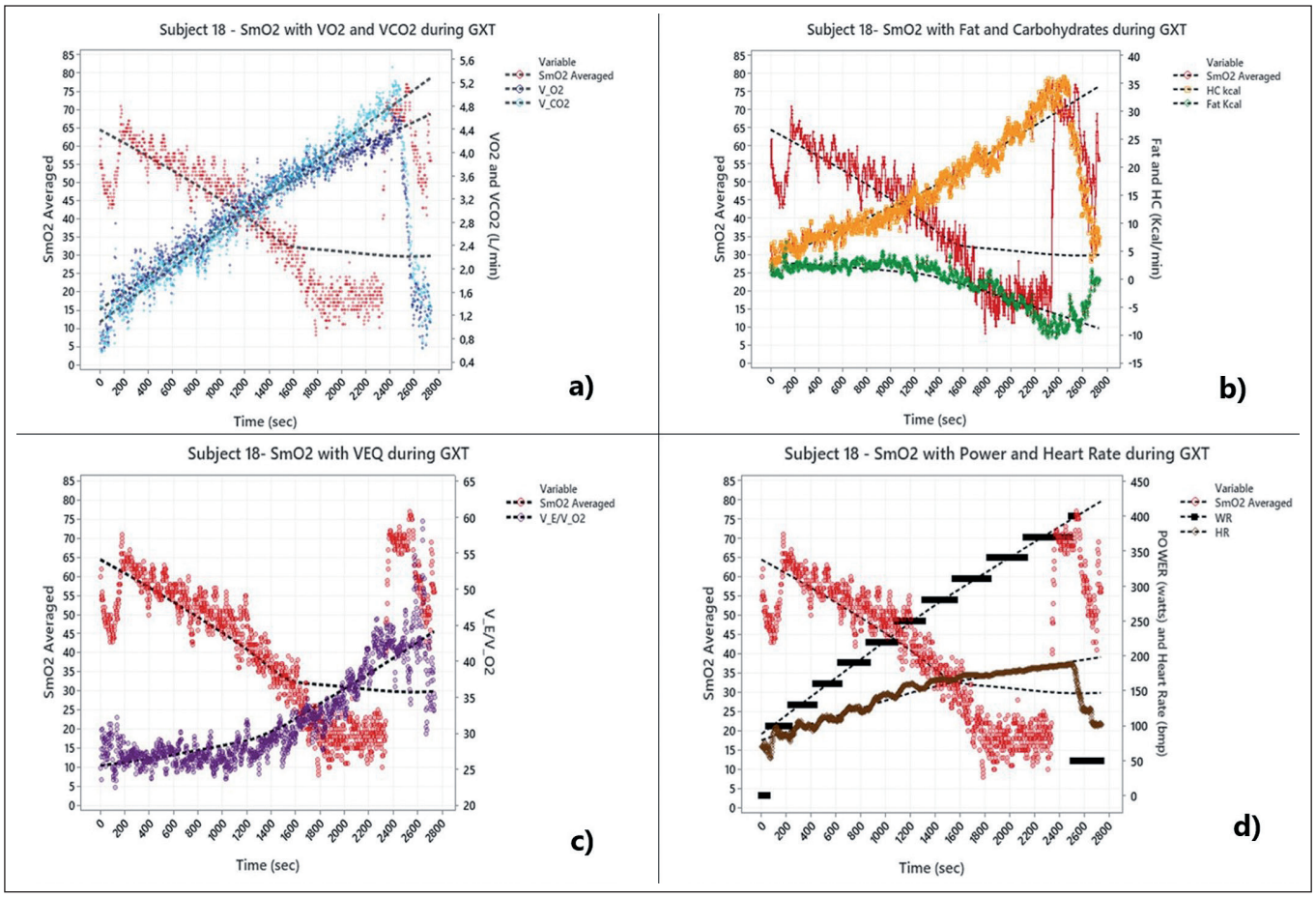


FIG. 1. Measurement of muscular oxygen saturation with other physiological parameters during maximal graded exercise test (example of a participant in this study).

lactate thresholds is accompanied by the buffering of lactic acid by [HCO_3] with a consequent VCO_2 increase. This results in a transition in the relationship between VCO_2 and VO_2, which is the underlying element in all anaerobic threshold methods of detection by gas exchange [23, 24]. V-Slope load was identified in that intensity of exercise which, in a plot of the minute production of CO_2 over the minute utilization of oxygen (VO_2), shows an increase in the slope above 1.0 [23, 25] (Figure 1a). The $\dot{V}O_{2max}$ was defined as the highest plateau (two successive maxima within 150 mL·min^{-1}, averaging the data every 5 s) reached [26].

Fatmax zone

The fat oxidation (FO) and carbohydrate oxidation (CHO) were calculated using appropriate stoichiometric equations [27] and energy equivalence, based on the

$$FAT\ (g/min) = [(1.67 \times VO_2) - (1.67 \times VCO_2)]$$

$$CHO\ (g/min) = [(4.55 \times VCO_2) - (3.21 \times VO_2)]$$

$$FAT\ (kcal/min) = [(1.67 \times VO_2) - (1.67 \times VCO_2)] \times 9$$

$$CHO\ (kcal/min) = [(4.55 \times VCO_2) - (3.21 \times VO_2)] \times 4$$

Data analysis to determine Fatmax involved the measured values approach in the stage with the highest recorded fat oxidation value and the corresponding $\dot{V}O_2$ [13] (Figure 1 b).

Statistical analysis

A descriptive analysis of the data extracted from the incremental test was applied and the Shapiro-Wilk normality test was applied for each variable. When normality was reached, the one-way repeated ANOVA test was performed for comparison of each step and training zone and then a Tukey's b post hoc test was applied to identify the internal differences between the steps. In addition, we observed the percentage change between each stage. Statistics based on the magnitude of the differences were applied to determine their clinical significance (standard deviation for individual response; SD_{IR}). SD_{IR} values were appraised against a minimum clinically important difference (MCID = SEM × 1.96 × √2) of each stage. Meaningful interindividual differences were observed in the ability to decrease SmO_2 considered present for a given variable when the SDIR exceeded the MCID (Yes) [28]. For results where the MCID exceeded the SD of the next

stage (w), we reverse the SD_{IR} formula and report these instances as negative SD_{IR} values (No). Using such an approach allows us to make comparisons between the different stages, where the data shifted from classifying individuals based on their measured change scores to classifying the change scores themselves in order to identify the inter-individual response [29]. Receiver operating characteristic (ROC) curves were then used to establish a cut-off for SmO_2 in each training zone, and the area under the curve (AUC) was used to evaluate the performance of the test, where the threshold cut-off values were defined by the points representing the highest concomitant sensitivity and specificity. The AUC was interpreted according to the following guidelines: not informative (AUC = 0.5), less accurate (0.5–0.7), moderately accurate (0.7–0.9), high precision (0.9–1) and perfect discriminatory test (AUC = 1.0). Finally, the Pearson correlation test was used to study the relationship of physiological parameters and a multiple linear regression analysis was performed among the variables associated with generating prediction equations of VO_2 and energy expenditure through SmO_2. The level of significance was established at $p < 0.05$ with 95% confidence intervals. The results were expressed as mean ± standard deviation. All analyses were performed with SPSS software (version 22).

RESULTS

Table 1 gives a description of the physiological parameters obtained from the GXT for each step. A progressive decrease in SmO_2 was observed, as expected, but without significant changes. The %HR reserve, VO_2 (ml/kg/min for l/min), carbohydrate oxidation/carbohydrate energy and the total energy expenditure (kcal/min) increased during the test. No inter-individual response was identified as positive.

Table 2 shows the differences by training zone during the exercise from baseline to the end of the test. Changes in SmO_2 were identified from BL to Fatmax (Δ = 9.0 p = 0.017 MCID = 8%), Fatmax to VT1 (Δ = 8.6, p = 0.024 MCID = 10%) and VT1 to VT2 (Δ = 19.5 p = 0.000 MCID = 9%). However, there is no significant

TABLE 1. Description of physiological parameters by step during the graded exercise test in cyclists and triathletes.

Steps / Variables	3´	6´	9´	12´	15´	18´	21´	24´	27´	30´	33´
Power (watts)	100 ± 4	130 ± 6	160 ± 7	190 ± 9	220 ± 13	250 ± 8	280 ± 9	310 ± 8	340 ± 7	370 ± 6	400 ± 34
Heart Rate (ppm)	110 ± 14	118 ± 15	127 ± 15	136 ± 16	148 ± 19	152 ± 13	161 ± 12	168 ± 12	174 ± 13	180 ± 15	181 ± 13
Heart Rate Reserve (%)	47 ± 7	53 ± 8	**60 ± 8***	**66 ± 9***	**74 ± 10***	78 ± 7	85 ± 6	89 ± 5	94 ± 4	96 ± 2	96 ± 3
Oxygen Consumption (ml/kg/min)	23.4 ± 3.3	26.9 ± 3.5	**31. 3 ± 4.2***	**35.8 ± 4.5***	**40.7 ± 5.5***	43.7 ± 4.1	48.0 ± 4.2	52.1 ± 4.7	56.1 ± 5.5	59.4 ± 6.7	63.4 ± 7.3
Oxygen Consumption (L/min)	1.73 ± 0.25	1.99 ± 0.22	**2.31 ± 0.23***	**2.64 ± 0.25***	**3.00 ± 0.32***	3.26 ± 0.32	**3.58 ± 0.37***	3.88 ± 0.36	4.17 ± 0.35	4.39 ± 0.43	4.70 ± 0.46
Muscle Oxygen Saturation (%)	60 ± 8	56 ± 10	51 ± 11	44 ± 13	35 ± 15	32 ± 13	26 ± 11	21 ± 10	20 ± 8	17 ± 6	16 ± 4
Fat Oxidation Rate (g/min)	0.33 ± 0.19	0.35 ± 0.19	0.41 ± 0.21	0.42 ± 0.24	0.38 ± 0.26	0.36 ± 0.28	0.34 ± 0.29	0.25 ± 0.20	0.20 ± 0.19	–	–
Carbohydrate Oxidation Rate (g/min)	1.4 ± 0.5	1.7 ± 0.6	**2.0 ± 0.6***	2.4 ± 0.7	2.9 ± 0.8	**3.4 ± 1.0***	3.8 ± 0.8	3.9 ± 0.5	**5.1 ± 0.7***	–	–
Fat energy (Kcal/min)	3.0 ± 1.7	3.2 ± 1.7	3.7 ± 1.9	3.8 ± 2.1	3.4 ± 2.4	3.2 ± 2.5	3.0 ± 2.6	2.3 ± 1.8	1.9 ± 1.7	–	–
Carbohydrate energy (Kcal/min)	5.6 ± 2	6.8 ± 2.2	**7.8 ± 2.2***	9.5 ± 2.7	11.7 ± 3.2	**13.7 ± 3.9***	15.1 ± 3.3	15.4 ± 1.9	**20.4 ± 2.8***	–	–
Total Energy (Kcal/min)	8.6 ± 1.3	**10 ± 1.2***	**11.5 ± 1.2***	**13.3 ± 1.3***	**15.1 ± 1.6***	16.9 ± 2.0	18.1 ± 1.9	19.7 ± 1.7	**22.7 ± 2.1***	–	–
Inter-individual response (SmO_2%)		**14%(7%)**	**16%(8)**	**16(9)**	**17(11)**	**19(11)**	**17(9)**	**15(8)**	**12(7)**	**9(5)**	**6(4)**
SD_{IR} > (MCID)		**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
Nº subjects	N = 40	N = 40	N = 40	N = 40	N = 40	N = 40	N = 40	N = 33	N = 27	N = 14	N = 6

Note: *p ≤ .0.05 compared to the previous stage. SD_{IR} = standard deviation of individual responses, MCID = minimum clinically important difference. Qualitative interpretations of SD_{IR} > SWC are provided for results with positive SD_{IR} values.

TABLE 2. Differences of physiological parameters by training zones during the graded exercise test in cyclists and triathletes.

Training Zones / Variables	Baseline	Δ (%)	Fatmax	Δ (%)	VT1	Δ (%)	VT2	Δ (%)	MAP ($\dot{V}O_{2max}$)
Power (W)	100 ± 0	62%*	162 ± 43	23%*	200 ± 41	45%**	290 ± 41	21%*	352 ± 49
Power (%)	27 ± 0	62%*	44 ± 10	23%*	55 ± 10	45%**	81 ± 8	21%*	98 ± 7
Heart Rate (ppm)	110 ± 14	14%*	126 ± 16	10%*	139 ± 13	20%*	167 ± 12	7%*	180 ± 12
Heart Rate Reserve (%)	47 ± 7	23%*	58 ± 8	15%*	67 ± 7	31%*	88 ± 3	10%*	97 ± 2
Oxygen Consumption (ml/kg/min)	23.4 ± 3.3	34%*	31 ± 6.2	19%*	37 ± 6.2	35%**	50 ± 7	16%*	58.4 ± 7.4
Oxygen Consumption (L/min)	37 ± 5	29%	48 ± 7	18%*	57 ± 6	38%**	79.0 ± 6	13%*	90 ± 5
Muscle Oxygen Saturation (%)	60 ± 9	-16%*	50 ± 12*	-16%*	42 ± 13	-45%**	23 ± 10	-26%	17 ± 7
Inter-individual response (SmO_2%) SD_{IR} > (MCID)			**12% (8) Yes**		**17% (10) Yes**		**18% (9) Yes**		**12% (7) NO**

Note: *p < 0.05 and **p < 0.01 compared to the previous stage. Subject numbers (n = 40). SD_{IR} = standard deviation of individual responses. MCID = minimum clinically important difference. Qualitative interpretations of SD_{IR} > SWC are provided for results with positive SD_{IR} values. Training Zones = Maximum lipid oxidation (Fatmax), Ventilatory thresholds (VT1 and VT2) and Maximal Aerobic Power (MAP).

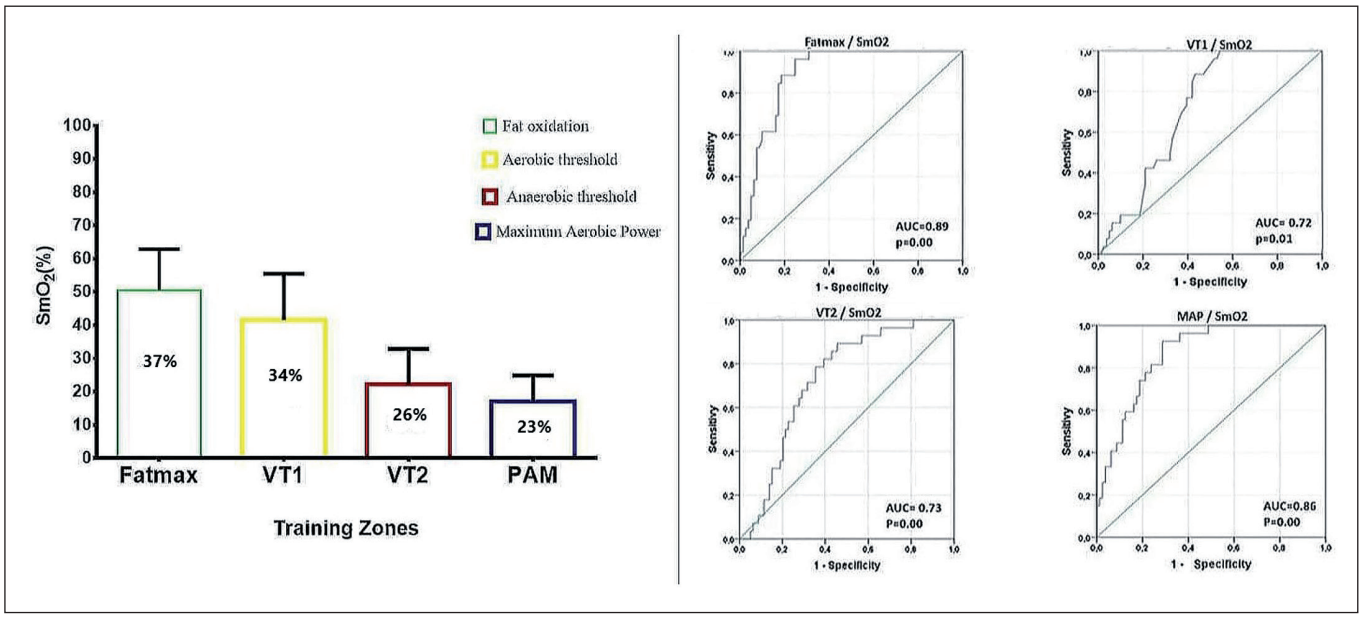


FIG. 2. Analysis of the receiver operating characteristics (ROC) curve to evaluate the cut-off for muscle oxygen saturation for each training zone.

TABLE 3. Prediction Equations between muscle oxygen saturation with oxygen consumption and energy expenditure.

		First order equation: Multiple linear regression						
Independent variable	**Dependent variable**	**Non-standardized coefficient B**	**Standardized coefficient B**	**Correlation (r)**	**Ajusted R-Square**	**SEE**	**F Value**	**Sig.**
VO_2 (L/min)	(k)	-0.579 ± 0.226						
	SmO_2 (%)	-0.007 ± 0.002	-0.146					
	Power (W)	0.008 ± 0.000	0.734	0.943	0.888	0.366	517.7	0.000
	Heart Rate (ppm)	0.003 ± 0.001	0.091					
	Weight (Kg)	0.022 ± 0.003	0.189					
VO_2 (ml/kg/min)	(k)	31.417 ± 3.766						
	SmO_2 (%)	-0.091 ± 0.025	-0.135					
	Power (W)	0.104 ± 0.007	0.716	0.939	0.880	5.087	479.2	0.000
	Heart Rate (ppm)	0.053 ± 0.018	0.114					
	Weight (Kg)	-0.247 ± 0.037	-0.153					
Energy Total (kcal/min)	(k)	-7.3 ± 1.392						
	SmO_2 (%)	-0.015 ± 0.010	-0.060					
	Power (W)	0.048 ± 0.003	0.772	0.949	0.900	1.341	383.8	0.000
	Heart Rate (ppm)	0.022 ± 0.007	0.122					
	Weight (Kg)	0.126 ± 0.014	0.226					

decrease after VT2, so SmO_2 did not detect changes in MAP (Δ = 5.6 p = 0.404). Similarly, there was no positive interindividual response from VT2 to PAM. Likewise, changes were identified in power (%), HR (ppm), heart rate reserve (%), VO_2 (ml/kg/min) and VO_2 (l/min) in all training zones.

Figure 2 represents the ROC curve for SmO_2-based training zones. The areas under the curve (AUC) were found in SmO_2: Fatmax: ≤ 37% (AUC); sensitivity = 0.891 and specificity = 0.247; SE = 0.30; IC = 0.831 to 0.950 (equivalent: 42%–36%); p = 0.000, VT1: ≤ 34% (AUC); sensitivity = 0.718 and specificity = 0.370; SE = 0.48; IC = 0.824 to 0.813 (equivalent: 35%–30%); p = 0.01, VT2: ≤ 26% (AUC); sensitivity = 0.786 and specificity = 0.354; SE = 0.50; IC = 0.175 to 0.371 (equivalent: 32%–23%); p = 0.000 and the MAP zone: ≤ 23% (AUC); sensitivity = 0.852 and specificity = 0.288; SE = 0.35; IC = 0.070 to 0.218 (equivalent: 28%–21%); p = 0.000.

Table 3 shows the most suitable variable equations for the multiple linear regression model that can be predicted by SmO_2 as an alternative to a VO_2 analyser. Our results indicated a high prediction in percentage 88% VO_2 (l/min) 89% VO_2 (ml/kg/min) and 90% total energy expenditure (kcal/min). The relevant equations are shown below.

VO_2 (l/min) = -0.58 – (0.007*SmO_2) + (0.008 + W) + (0.003* HR)+ (0.022*weight) (1)

VO_2 (ml/kg/min) = 31.42 – (0.09*SmO_2) + (0.10*W) + (0.05*H R) – (0.25*weight) (2)

Energy total (kcal/min) = -7.3 – (0.015*SmO_2) + (0.05*W) + (0. 02*HR) + (0.13*weight) (3)

DISCUSSION

To the best of our knowledge, this is the first study to evaluate SmO_2 based on training zones established by cut-off points and also to present equations that can be used by trained cyclists. During GXT, SmO_2 progressively decreased as exercise intensity increased. However, no differences were observed in the change for each step (Table 1), which means that using a Fatmax protocol [13] where the steps go from 3 min to changes of 30 W no differences can be identified. This is similar to Crum's study [10], where SmO_2 changes were observed in each step increase (5 and 50 W), until the final stages of the test. Therefore, changes in SmO_2 are only observable with large step differences in watts and by training zone (Table 2), except after passing VT2, where oxygen becomes independent for power production, and there was a change of metabolic pathway due to high intensity work. Furthermore, the Crum study indicates that at high intensities, SmO_2 measured with a portable Moxy is not sensitive to changes. This can be observed in many studies that use Moxy [10, 30], but adequate treatment of the data is needed, such as the application of the soft spline filter (Figure 1 supplementary) [21], the Moxy calibration scale (0%–100%) [20] and the measurement standards as they were used in this study. Through such treatment, we were able to narrow down the problem. Similarly, studies have not reported measurement problems using this methodology [31, 32]. The contribution of our study is that it presents the difference of work in VT1 and VT2 with SmO_2.

Another explanation for the lack of changes of SmO_2 passing the VT2 is the data interpretation, because the behaviour of SmO_2 at high intensity is non-linear, contrary to the moderate intensity zones,

where it does retain linear behaviour [33]. This occurs due to changes in the metabolic pathway in the muscle where the regeneration of PCr in the last stages is limited by time and maximum power. There are also increases in blood flow due to the accumulation of vasoactive metabolites, such as H + , K + and lactate. That interrupts the use of energy to withstand fatigue in the high intensity zone [34, 35] Likewise, in our study, muscle oxygenation in cyclists and triathletes seemed to be affected at high intensities (VO_2 = > 50 ml/kg/min). According to Oueslati et al. [36], when $\dot{V}O_{2max}$ values are higher than this, anaerobic metabolism and lactate accumulation acquire greater relevance, causing an imbalance between oxygen supply and demand. Along the same lines, another factor to highlight in this study is that the greatest observable changes in SmO_2 occur in the transition from VT1 to VT2, in line with two previous studies [37, 38] showing that the greatest differences in muscle oxygenation could be found when the VO_2 values are between VT1 and VT2 (VO_2 values > 40 ml/min/kg) [39]. This suggests the potential of SmO_2 to observe an aerobic workload vs an anaerobic workload.

Likewise, although it is commonly believed that it is difficult to identify training zones with SmO_2, in our study it was possible to establish cut-off points for each training zone. It was observed that in the VT2 and MAP zones the sensitivity and specificity were higher (Figure 2). This means that for values below < 26% it is more likely that the anaerobic energy system is being used. Compared with zones such as Fatmax and VT1, the specificity is lower; however, the change from higher to lower sensitivity and specificity is due to the physiological behaviour of oxygen-dependent and oxygen-independent exercise [40], that is, the change in energy pathway from VT1 to VT2. So far, this study proposes that new ways of assessing performance in high-intensity zones should be explored through non-linear changes, for example analysis of results with exponential and quadratic regressions; this is the next challenge for researchers in this line of work. Likewise, it is well known that Fatmax zone and muscle deoxygenation kinetics are associated [41], SmO_2 remains stable in the presence of fat oxidation and at the SmO_2 breakpoint where VT2 is entered one no longer consumes fat and is totally dependent on carbohydrate energy (Figure 1b). This is also a result of the subjects with better performance in endurance tests maintaining higher SmO_2 values during exercise than sprinting athletes [42].

Regarding the interpretation of the predictive capacity in studies that use muscle oxygen, There is still none with the SmO_2 variable, but we found the study by Montero et al. [43] which related the Hb mass in the muscle as an independent predictor of the VO_2 peak when factoring in the regression analysis model (adjusted $r^2 = 0.73$, $P < 0.0001$). Also, to predict VO_2 and energy expenditure in our study, we used an equation and percentage prediction ($r^2 = 0.89$ $p < 0.000$) using the SmO_2 for HR, power and weight. Contrary to the ACSM predictive metabolic equations that only use the individual's power and weight [44], however, our equations require SmO_2 as a predictive metabolic marker of fats and carbohydrates (Figure 1b) and HR as a necessary cardiovascular parameter in the explanation of muscle oxygen extraction [45]. This makes it more specific to find the VO_2 and energy expenditure. Additionally, with the cut-off points we can approximate the SmO_2 values to VT1; this is observable when the VEQ has an increase in the VE/VO_2 ratio without an increase in the VE/VCO_2 ratio and an abrupt decrease in SmO_2 occurs. VT2 corresponds to an increment of the VE/VCO_2 ratio and a fractional decrease in the concentration of CO_2 ($PetCO_2$), and VT2 can be identified as a plateau of SmO_2 (Figure 1 and 2). However, care must be taken, because this is the first time that SmO_2 has been used.

Likewise, Paquette et al. [46] highlighted the importance of using peripheral adaptations during short and long events, since they were able to predict performance through muscle oxygenation by multiple regression analysis. That is, muscle oxygen extraction with NIRS was a predictor of metabolic performance that approximated VO_2 and energy expenditure [46, 47]. Furthermore, using the set of SmO_2 with HR provides information on the internal load of each athlete, because although there is an inverse correlation between HR and SmO_2 (-0.71) [10], at high intensities, HR (> 90%) stabilizes and shows small changes. SmO_2 continues to decrease slowly and then increases again at this precise moment due to the increase in the oxidative phosphorylation and the increase in blood flow caused by the hyperaemia response [48, 49]. This phenomenon is also known as critical oxygenation and was recently disregarded by Feldmann [50]. Also, power decreases, and then performance does as well. Finally, our equation is justified by the SmO_2 values as an indicator of the internal load of metabolic demands [10], HR as an indicator of cardiovascular stress of the autonomic nervous system [51], as well as power as an indicator of the external load and weight as an indicator of the health factor of each athlete. All of these data are more accessible for athletes to obtain in each training session, if they wish to know the changes in the metabolic pathways at work without fatigue as VT1 vs working with more fatigue at VT2, using a portable NIRS (SmO_2). We thus demonstrate the dependence of a better VO_2 and a higher energy expenditure with these variables. These equations can be entered into software or a smartphone application, thus providing an alternative for coaches and athletes who do not have access to a cardiopulmonary test.

LIMITATIONS

One of the limitations of this study is that the zones and performance points such as critical power, respiratory compensation point, and functional thresholds power were not defined, as these depend on muscle bioenergetics, although they approximate to VT2 by 21% [52]. Likewise, it would be interesting to observe the verification of VT1 and VT2 in submaximal efforts with intensity according to the determined threshold value of SmO_2 (34 and 26%) with simultaneous measurements of blood lactate concentration. Furthermore, we have shown scientific advances for SmO_2 measured with Moxy that were not studied in the Crum validation study. Moxy is

an instrument that is not the most suitable for measuring SmO_2 but is accessible to the athletic population.

CONCLUSIONS

In conclusion, SmO_2 measured with a portable NIRS can be a complementary physiological parameter to identify the transition from a more aerobic workload to a more anaerobic workload, because it is similar to indicating threshold changes from VT1 to VT2 during exercise. In addition, SmO_2 at moderate intensity before entering VT1 can be interpreted as work of maximal fat oxidation (Fatmax). Finally, SmO_2 together with power, heart rate and weight can predict performance by approximating VO_2 and energy expenditure.

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Conflicts of interest

The authors did not received any funding for this work and have no conflicts of interests to declare.

Author Contributions

G.O. and A.G contributed to the conception of the study. A.V., A.C., R.T. and G.O. designed and reviewed the protocol of the study. A.V.,A., A.C and M.C. performed the data collection. A.V. organised the database. A.V. and A.G. performed the statistical analysis. A.V. and R.T. wrote the first draft of the manuscript. A.V., R.T. and G.O wrote sections of the manuscript. R.T. and G.O. supervised the project. All authors contributed to manuscript revision, read, and approved the submitted version.

Ethics approval

The study design was approved by the Bioethical and Biosecurity Commission of the University of Extremadura (document 138/2018).

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The effect of α-lactalbumin consumption on sleep quality and quantity in female rugby union athletes: a field-based study

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ABSTRACT: This double-blind randomised placebo-controlled trial aimed to investigate the effects of α-lactalbumin consumption on sleep quality and quantity in female rugby union athletes during a competition season. Eighteen semi-professional female rugby union players (age 23.8 ± 5.2 y; mean ± SD) wore wrist actigraphy watches for four seven-day blocks corresponding to the pre-season, a home game, a bye week (i.e. no competition game scheduled) and an away game. Participants consumed either an α-lactalbumin (α-LAC), or placebo drink (PLA) every night two hours before bed for the duration of the season. Generalised linear mixed models were used to investigate the effects of the nutritional intervention on sleep variables (total sleep time, sleep efficiency (SE), sleep onset latency (SOL) and wake after sleep onset) over the duration of the season. There was a significant condition by period interaction effect on SOL ($p = 0.01$). While similar at baseline (23.3 ± 16.3 and 23.2 ± 18.9 min α-LAC and placebo respectively) and for the home game (22.4 ± 17.6 and 19.3 ± 14.9 min α-LAC and placebo respectively), SOL was reduced in the α-LAC group for the bye (11.6 ± 13.4 min) and away game (17.0 ± 11.5 min; $p = 0.045$). In comparison, SOL remained unchanged in the PLA group (bye 21.2 ± 17.3 and away 22.5 ± 18.5 min). Pre-sleep α-lactalbumin consumption improved SOL in a semi-professional female team-sport cohort. Thus, α-lactalbumin could be utilised by athletes to support sleep during a competitive season.

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INTRODUCTION

Sleep is widely recognised as being critical to athlete recovery and optimal performance. However, athletes appear to experience more sleep disturbances than the general population [1, 2] relating to training, travel, and competition commitments [3, 4]. Despite clear evidence supporting the importance of restorative sleep [5], the efficacy of interventions to negate disturbances and improve sleep and related recovery outcomes in athletes is somewhat equivocal. While research suggests both sleep hygiene education and sleep extension interventions are effective short-term, the sustainability of their effects is questionable without ongoing follow up and further education sessions [6]. Furthermore, a recent survey study by Miles et al. [7] indicated female athletes may be resistant or less likely to implement sleep hygiene interventions. As such, additional, easily implemented techniques to improve sleep in the female athlete population are required.

One candidate for an easily implemented intervention is nutrient supplementation, with emerging evidence suggesting that nutritional supplements may be able to improve sleep [8–11]. Candidate supplements from studies in general population cohorts include tart cherry juice and kiwifruit, both of which show modest beneficial effects on sleep parameters due to their natural level of both melatonin and seratonin [12–14]. Importantly, many athletes may already have a supplement regimen with research suggesting 40–70% of athletes use protein supplements [15, 16]. As such, altering existing protein supplement protocols may offer a more feasible and easily implemented nutritional intervention to improve sleep. Recent studies suggest pre-sleep protein ingestion can improve physical recovery processes (e.g. muscle repair and immune function) and there is evidence that certain proteins may improve sleep outcomes [17, 18].

A protein which has recently been investigated as a nutritional pre-sleep intervention is α-lactalbumin, which is the dominant protein in human milk and constitutes approximately 17% of whey proteins in bovine milk [19, 20]. α-lactalbumin is reported to have the highest natural level of tryptophan [20], which is an essential amino acid and serves as a precursor to the synthesis of the sleep promoting hormones of serotonin and melatonin [21]. Ong et al. [22] reported improvements in sleep quantity and quality for healthy adult participants following 20 g of α-lactalbumin supplementation. Additionally, findings from Miles et al. [23] indicate acute pre-sleep supplementation of α-lactalbumin in a trained female cohort may improve parameters of sleep following simulated evening competition.

However, while some evidence suggests α-lactalbumin may be a useful intervention to improve sleep, this is yet to be evaluated in free living conditions in a competitive athlete population.

Thus, we aimed to investigate the effects of α-lactalbumin consumption on sleep quality and quantity in semi-professional female rugby union players during a competition season. We hypothesised that the ingestion of the α-lactalbumin supplement would improve markers of sleep quality and quantity.

MATERIALS AND METHODS

Participants

A priori power analysis using female sleep data collected from wrist activity monitors and the Harvard sample size calculator determined that 14 participants would be sufficient to detect a significant medium to large change of $f^2 = 0.25$ in sleep outcome variable total sleep time (TST) at an alpha = 0.05 and power = 0.80 [24]. Twenty semi-professional female rugby union athletes (23.8 ± 5.2 years) provided written informed consent to participate in this study. The participants were part of a Super Women's rugby team and were well-trained, and free of any injuries, diagnosed sleep conditions, illnesses or intolerances (i.e. lactose and gluten) that would exclude them from participating. Training structure during the study period was the same for all participants and consisted of three field sessions, two gym sessions and one recovery session in the pool per week. The study was approved by the Human Research Ethics Committee of the University of Canberra (HREC 2297).

Experimental overview

We used a double blinded placebo-controlled trial whereby participants were stratified based on age and playing position (forward or back), then randomly allocated to receive either the α-lactalbumin supplement (α-LAC) or a placebo supplement (PLA, whey protein drink) while their sleep was monitored during a Women's Super Rugby competition season. The data collection period encompassed four, seven-day blocks corresponding to the pre-season (week prior to competition), a home game (week 1 of competition), a bye week (i.e. no competition game scheduled, week 2 of competition) and an away game (week 3 of competition (Figure 1). The competition then ceased, as did our data collection due to COVID-19.

Measurement of sleep

Participants wore an activity monitor (Actiwatch 2, Philips Respironics, Pennsylvania, USA) on the wrist of their non-dominant hand which was utilised to assess sleep. Data for each separate week (pre-season, a home game, a bye week and an away game) was collated and averaged for each individual participant for each 7-day period. Validation studies comparing wrist activity monitors with the gold standard polysomnography (PSG) report high correlations for sleep duration (0.84–0.89) and moderate to high correlations for wake time (0.65–0.76) [25]. According to previously described methods from Sargent and colleagues [26], data from the sleep diaries (detailed below) and activity monitors were used to determine when participants were awake and asleep. Time records were scored as awake unless: the sleep diary indicated the participant was lying down attempting to sleep; and monitors activity counts were sufficiently low to indicate that the participant was immobile. Time was scored as sleep when these two conditions were satisfied. This scoring process was conducted using Philips Respironics' Actiwatch Algorithm with sensitivity set at 'medium' to generate measures of total sleep time (TST, sleep duration), sleep efficiency (SE, the percentage of time spent in bed actually spent asleep), sleep onset latency (SOL, time taken to fall asleep)

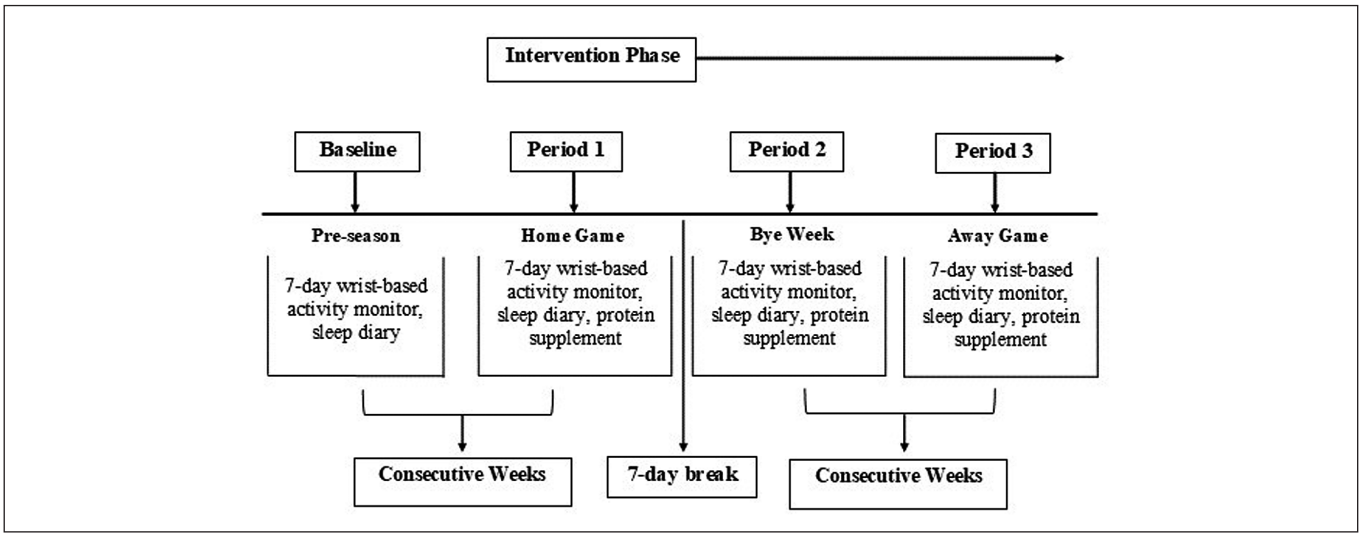


FIG. 1. Overview of the study experimental design.

and wake after sleep onset (WASO, time spent awake after falling asleep).

Simultaneously to wearing the activity monitor, participants completed a sleep diary. This sleep diary included before and after sleep sections, where bedtime and wake time are recorded. This data was used in conjunction with the actigraphy data to determine sleep and wake periods.

Nutritional intervention

The first seven-day block corresponding with the pre-season served as a baseline period and was completed a week prior to the first competition game to assess habitual sleep without the consumption of a protein drink. Following the baseline week (i.e. week of the first competition game), each participant was provided with a seven-day supply of either the α-LAC or PLA in individual containers, with instructions to add 300 mL of water and consume approximately two hours prior to going to bed. At seven-day intervals throughout the trial, the participants were provided with their next supply of the α-LAC or PLA supplement. Any containers not utilised were recorded as an assessment of compliance. This protocol continued for five consecutive weeks from the commencement of the competition season up to the premature end of the season ahead of the grand final due to COVID-19.

Participants randomly assigned to the α-LAC group consumed an α-lactalbumin drink which contained 40 g of α-lactalbumin protein powder (4.8 tryptophan/100 g amino acids) (Davisco Foods International, Eden Prairie, MN, USA) mixed with 10 g of a sugar free drinking chocolate powder (Avalanche, Auckland, New Zealand), 7 g of stevia and 300 mL of water. Those in the PLA consumed a whey protein drink which contained 40 g of chocolate flavoured protein powder (1.05 g tryptophan/100 g) (Body Science Whey Ultra, Burleigh, Australia) and 300 mL of water. A 40 g dose of α-lactalbumin protein powder was chosen based on the two previous studies utilising α-LAC in athletic populations [27, 28]. Both products were batch tested for banned substances by Human and Supplement Testing Australia (HASTA) and were closely matched for colour, texture and flavour. A comparative nutritional analysis can be seen in Table 1.

TABLE 1. Nutritional analysis comparing interventions: α-LAC and PLA.

	α-LAC (50 g)	PLA (40 g)
Ingredients (g)	**A-LAC protein (40)**	**Whey protein (40)**
	Powdered chocolate (6)	
	Stevia (4)	
Energy (kcal)	153	151
	Amino acids (g)	
Isoleucine	2.4	1.7
Leucine	4.3	3.2
Phenylalanine	1.6	0.9
Tyrosine	1.8	0.9
Valine	1.7	1.7
Tryptophan	1.9	0.4

TABLE 2. Bed and wake times across the season for both conditions (mean ± SD).

	A-LAC	PLACEBO
	Bedtime	
Baseline	23:13 ± 01:13	23:29 ± 01:13
Home game	23:17 ± 01:38	24:17 ± 01:46
Bye week	23:14 ± 01:14	23:27 ± 01:11
Away game	23:34 ± 01:38	23:35 ± 01:22
	Wake time	
Baseline	06:22 ± 01:07	06:26 ± 01:46
Home game	06:37 ± 01:18	07:04 ± 01:24
Bye week	06:51 ± 01:36	06:48 ± 01:40
Away game	06:59 ± 01:42	06:51 ± 01:35

Statistical analysis

Sleep data from the activity monitors were included in the data analysis if the participant had worn the monitor for a minimum of 4 days out of the assessable 7 day period, and was scorable using the diaries and watches when cross referenced. All statistical analysis was conducted in *R* Studio statistical software (V 4.0.2, R Studio Inc, Boston, USA). Generalised linear mixed models were used to determine the effect of the nutritional intervention and period of the season on outcome sleep variables. The nutritional intervention (i.e. α-LAC or PLA) and period (i.e. baseline, home game, bye week or away game), and their interaction, were fitted as fixed effects (with some models fitting participant as a random effect with condition and period as random slopes) to determine whether there was a difference in the effect of dietary intervention over period on the dependent sleep variables (e.g. TST, SE, SOL and WASO). All variables are reported a mean ± SD and the significance level at $p < 0.05$.

RESULTS

Sixteen participants provided adequate sleep data during the baseline week (8 in each group), 15 for the week preceding the home game (α-LAC = 7, PLA = 8), 12 for the week preceding bye week (α-LAC = 5, PLA 7) and 12 for the week ahead of the away game (α-LAC = 5, PLA = 7). During the first week of the nutritional intervention, two nights worth of protein (2 individual serves) were returned within the individual containers provided to each athlete from participants randomised to the α-LAC group. From that point onwards, all α-LAC or PLA containers were returned empty, implying compliance with the nutritional intervention. Bed and wake times for each condition over the season is shown in Table 2. While bed and wake times were similar across the two conditions, participants in the

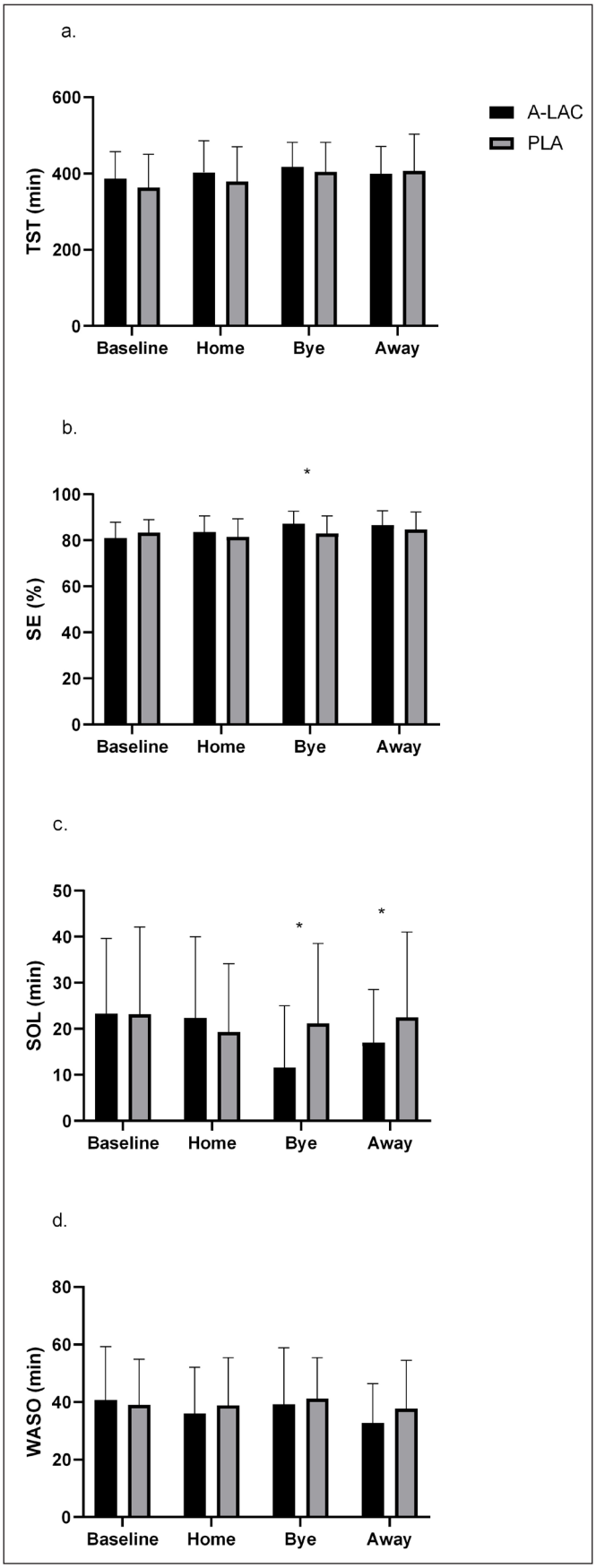


FIG. 2. The effects of the nutritional interventions on indices of sleep quantity and quality across the competitive season. *significantly different compared to baseline and placebo. SE = sleep efficiency; TST = total sleep time; SOL = sleep onset latency; WASO = wake after sleep onset.

α-LAC group on average went to bed earlier (23:20) compared to PLA (23:52), and woke earlier (α-LAC, 06:42; PLA, 06:57).

There was no effect of nutritional supplement on TST or WASO across the intervention period ($p > 0.05$, Figure 2). However, there was a significant condition by period interaction effect on SOL ($p = 0.01$). While similar at baseline and for the home game, SOL was significantly shorter in the α-LAC group for the bye week and away game (difference bye week, 9 min; difference away game 5 min, ES = 0.62 and ES = 0.37, $p = 0.045$) but remained stable in the PLA group. No other significant differences were identified between groups for any other parameter.

DISCUSSION

The primary purpose of this study was to evaluate the efficacy of α-lactalbumin supplementation to improve sleep quality and quantity in female rugby union players. While we observed no effect of α-lactalbumin supplementation on sleep quantity, in line with our hypothesis α-lactalbumin supplementation led to improvements in SOL with a trend towards improved SE relative to the placebo supplement.

To our knowledge, we are the first to examine the efficacy of α-lactalbumin supplementation as a home-based sleep intervention designed to improve sleep quality and quantity for team-sport athletes. The main finding of our study was that α-lactalbumin supplementation significantly improved SOL and showed a trend towards a significant increase in SE, consistent with reports on the effects of pre-sleep α-lactalbumin ingestion (20 g, an hour prior to bed) in healthy males [22]. Results regarding the efficacy of α-lactalbumin supplementation, however, vary between studies depending on dosage and intervention length. Recently, MacInnis et al. [27] investigated α-lactalbumin supplementation to improve sleep in six elite male cyclists, finding no significant differences between their two conditions (α-lactalbumin and collagen peptides) for any actigraphy recorded sleep variables. However, MacInnis et al. only administered the α-lactalbumin supplement for three days, potentially not long enough to see an effect on sleep outcomes in free living conditions. Indeed, in our study the effects of α-lactalbumin on sleep quality only became evident after several weeks of supplementation, which may indicate there is a cumulative effect of chronic α-LAC consumption. Importantly, given our finding it's unlikely that α-lactalbumin will negatively affect athlete sleep. Furthermore, given that α-lactalbumin is a source of whey protein which supports muscle remodelling and immune function [18], it appears that α-lactalbumin offers an intervention that supports athlete sleep, and subsequently wellbeing and performance. Future research should investigate the most effective dosage and loading protocol that may positively influence sleep.

When compared to the reported impacts of sleep hygiene strategies on sleep in female athletes, our results suggest α-lactalbumin may have a greater impact on sleep quality. O'Donnell et al. [29] found a sleep hygiene education session resulted in no significant improvements in both SOL and SE. While other studies suggest sleep

hygiene may be beneficial in male athlete groups [6, 30], it is yet to be proven whether these protocols can be beneficial in female populations who appear to be more resistant to these interventions than their male counterparts [7]. Thus, α-lactalbumin may be a good addition to other sleep interventions that may not be beneficial alone. α-lactalbumin may also serve as an alternative to pharmaceutical aids such as temazepam, melatonin, zaleplon, and zopiclobe [31, 32], which are known to improve sleep, but are associated with other negative outcomes such as performance decrements, dependency, possible increased cancer risk, accidental overdose, and dangerous drug interactions [33]. Future research should investigate α-lactalbumin supplementation in conjunction with interventions like sleep hygiene/extension to substantially improve sleep more so than either intervention could alone.

As our study was conducted in free living conditions, there were no restrictions placed on participant bedtime habits or daytime naps, and as such, TST was limited by the time our participants had available in bed around late and early training sessions, and did not include daytime naps. While we saw a significant difference in SOL, the limited time in bed perhaps wasn't enough to see an increase in TST. In a population where TST may be limited, the ability of a nutritional intervention to enhance SOL and SE would be valuable, particularly female athletes who often train around full-time work and family commitments. A study investigating the sleep behaviours of elite swimmers found TST and SE were substantially poorer on training days compared to a rest day [34]. Similar findings were reported in a mixed cohort of elite and sub-elite Irish athletes, with both elite and sub-elite athletes reporting poor sleep quality, which improved on rest days [35]. Female team-sport athletes also often face undesirable training schedules (i.e. morning or late evening sessions) which can compromise an optimal recovery regime by reducing sleep quantity due to limited time in bed [36]. Thus, the efficacy of α-lactalbumin supplementation to improve sleep quality regardless of time available in bed could be highly beneficial for team-sport athletes.

Although our study did not investigate the mechanisms by which α-lactalbumin supplementation may influence sleep outcomes, earlier work in general populations suggest beneficial effects on sleep may be due to the loading of tryptophan, an essential amino acid that serves as a precursor to the sleep promoting hormones melatonin and serotonin [21]. Tryptophan is reported to have beneficial effects on sleep indices, increasing the total sleep time and reducing waking time encountered by individuals [19]. Pre-sleep administration of tryptophan increases the plasma tryptophan to large neural amino acid ratio (TRP:LNAA) [21, 37, 38], leading to an increase in brain tryptophan availability [38]. This is thought to lead to a downstream increase in synthesis of melatonin and serotonin, both which display sedative effects [39, 40]. Although not directly investigating sleep parameters, the research by Markus et al. [37] indicates sleep quality may have improved with a significant reduction in sleepiness, and improved attention processes the morning following the intervention [37]. Markus et al. [38] also reported decreases in depressive feelings following α-lactalbumin consumption in their participants. Research suggests there are strong links between poor sleep and feelings of anxiety and depression, with women experiencing more insomnia complaints than males [41]. As such, an intervention like α-lactalbumin that can increase sleep quality and decrease depressive feelings may be beneficial during high-stress team-sport seasons, particularly for female athletes.

We acknowledge there were several limitations associated with our study, many due to the applied nature of the project that should be taken into consideration when assessing the results. These limitations include: inability to accurately capture training loads due to non-compliance with recording gym sessions and wearing global positioning systems, inability to control for hormonal related factors and menstrual cycle, inability to control nutritional intake, specifically prior to bed which may influence the quality and quantity of the individuals sleep [11], external situational factors, and the number of athletes who participated for the entire duration of the project. The power analysis conducted for this study indicated 14 participants were required to determine significant changes in TST. Although this number was met, we recognise the small sample size of our study may have hindered the statistical power and minimised optimal stratification of participants by playing position. Due to the length of our study and the associated uncontrollable external factors associated with being a semi-professional female athlete, we recommend future studies assessing the efficacy of α-lactalbumin utilise a more intensive or controlled environment like a training camp (whilst acknowledging these settings may see increases in training load and potential implications associated with changes to sleep environments).

CONCLUSIONS

In conclusion, this study provides initial field-based evidence on the benefits of α-lactalbumin consumption across a competitive season. This study highlights the efficacy of pre-sleep α-lactalbumin consumption as a nutritional intervention to improve SOL in a semi-professional female team-sport cohort. Thus, α-lactalbumin could be utilised by athletes to support sleep during a competitive season and be taken easily in the home-environment regardless of training or lifestyle requirements.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Intra-unit reliability and movement variability of submission grappling external load as measured by torso mounted accelerometery

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ABSTRACT: Submission grappling consists of skills and movements used in combat sports to physically control opponents whilst trying to apply choke holds and joint locks. There is currently no accepted method of monitoring external load in grappling-based sports due to the absence of key variables such as distance, velocity or time. The primary aim of this study was to determine whether PlayerLoad is a reliable variable for measuring external load of submission grappling movements, with a secondary aim of determining the between repetition variance of submission grappling movements. 7 experienced submission grapplers were recruited. Each wore a torso mounted Catapult® Optimeye S5 microelectromechanical systems (MEMS) device and completed 5 repetitions of each of the following: 4 submission techniques; 5 transition techniques; 2 guard pass techniques; 2 takedown techniques. Accumulated PlayerLoad (PLd_{ACC}) was recorded as a marker of absolute load, with accumulated PlayerLoad per minute ($PLd_{ACC}{\cdot}min^{-1}$) representing relative load. Reliability of each was assessed using intraclass correlation coefficient ($ICC_{(3,1)}$) (≥ 0.70). Between repetition movement variation was assessed via coefficient of variation with 95% confidence intervals (CV, 95%CI) (acceptable ≤ 15%, good ≤ 10%). PLd_{ACC} $ICC_{(3,1)}$ range = 0.78–0.98, with CV range = 9–22%. $PLd_{ACC}{\cdot}min^{-1}$ $ICC_{(3,1)}$ range = 0.83–0.98, with CV range = 11–19%. Though several variables displayed CV > 15%, all had 95%CI lower boundaries ≤ 15%. Whilst PlayerLoad was found to be a reliable measure for submission grappling, relatively high CVs across most techniques examined suggest PlayerLoad may not be appropriate for measuring changes in external load for individual movements in submission grappling. However, it may prove a useful tool for monitoring the external load of full, grappling-based, training sessions within an individual.

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INTRODUCTION

Submission grappling refers to a series of skills, techniques and movements used in a range of combat sports including: Brazilian jiu jitsu (BJJ), mixed martial arts (MMA), sambo, wrestling and judo [1]. The aim is for participants to attain and maintain a dominant position over an opponent in order to apply joint manipulations or choke holds to make them admit defeat by 'submitting' [2]. While submission grappling techniques are a secondary skill in wrestling, judo and sambo [3–5], they are a key skill component in both MMA and BJJ respectively [6, 7]. As with most sports, understanding and quantifying the physiological load imposed during grappling based training, sparring and competition is important in order to manipulate and manage training loads effectively [8].

As previous work has described, the outcome of a training process is dependent on the external and internal training load an individual is exposed to. External load refers to the physical actions completed in a training session, whereas internal load refers to the physiological response of the individual to the imposed external load [8]. Due to the combative nature of submission grappling, there are inherent difficulties in directly measuring internal and external loads of participation [9]. Proxy measures of external load such as time motion analysis (TMA) suggest that submission grappling is an intermittent activity with effort:pause ratios between 6:1 and 13:1, comprised of effort periods of 85–290 s and pauses of 5–44 s [10, 11]. More recently, however, internal load measured directly by heart rate (HR) during simulated competition revealed physiological responses to submission grappling may be relatively stable [6, 12]. Therefore, whilst specific physical actions in submission grappling may be interrmittant and acyclic, the physiological responses to these actions may not be. As such, methodological limitations inherent within TMA may limit its ability to fully elucidate the contribution of discrete movements or

isometric contractions to the overall load of training or competition. This restricts the capacity of TMA to measure the external load of submission grappling. The absence of an accurate external load measurement may cause difficulties in understanding the relationship of external to internal load in this population, leading to suboptimal training prescription and implementation [8].

The use of microelectromechanical systems (MEMS) devices for monitoring external load of athletes is now commonplace across sport [13]. Such devices typically contain both a satellite navigation chip which connects to global navigation satellite systems (GNSS), and also inertial sensors such as accelerometers, gyroscopes and magnetometers [14]. The most common variables to quantify external load using such devices include total distance, high speed distance and metabolic power-based derivatives [15]. Given the minimal influence of distance or ambulatory speed on performance in combat sports, however, the use of positional-based data is limited, with potentially more relevant data provided by the inertial sensors [13]. The most common variable used by practitioners with inertial sensors is the use of accelerometry-based variables such as PlayerLoad [15]. PlayerLoad is an arbitrary unit that is derived from 3-dimensional measures of the instantaneous rate of change of acceleration [16]. Previous research has revealed PlayerLoad demonstrates excellent levels of inter and intra reliability using both a mechanical shaker [17] and human locomotion during treadmill running [16]. Hurst et al. [18] revealed that PlayerLoad demonstrated acceptable levels of reliability for MMA-based movements, including wrestling-based takedowns and ground strikes (CV = 2.4–7.8%, ICC = 0.79–0.98). Body worn accelerometery has since been used for measuring external load in MMA [19, 20], taekwondo [21] and boxing [22, 23]. Recent research has also shown accelerometery to be capable of measuring pacing changes in combat sports inclusive of submission grappling movements [24]. However, there is currently no research supporting the reliability of accelerometry specifically for standing and ground-based transitions and submission manoeuvres common in grappling-based sports [25, 26].

For accelerometery to be used as an acceptable method of external load monitoring in submission grappling inclusive sports, the reliability of this equipment in measuring submission grappling techniques must be determined. Therefore, our primary aim in this study was to determine the intra-unit reliability of PlayerLoad for measuring external load in a series of representative submission grappling movements. In addition, knowledge of between repetition variation in technique and movement as recorded by PlayerLoad would also be required to enable appropriate use of this technology in an applied setting. To this end, a secondary aim was to quantify the variability of PlayerLoad between repetitions of grappling-based movements.

MATERIALS AND METHODS

Participants

Inclusion criteria for participants was at least 18 months experience (mean = 6 ± 2 years, range = 2–10 years) of submission grappling, BJJ or MMA training, or holding at least a blue belt in BJJ (male n = 5, female n = 2, age = 31 ± 6 years, stature = 177 ± 13 cm, body mass = 84 ± 18 kg). Participants were recruited following informed consent and institutional ethical approval (Ref: S05-03-21GF059) in keeping with the Declaration of Helsinki.

Equipment

Participants were requested to wear either a t-shirt or rashguard with shorts or BJJ gi trousers; the wearing of gi jackets or belts was not permitted. Participants were then fitted with a GPS device incorporating a triaxial 100 Hz accelerometer (Optimeye S5, Catapult®, Melbourne, Australia), which has previously been shown to have excellent intra-unit reliability [27]. The units were worn in the manufacturers garment, sized so as to ensure a tight fit on the participant, with the unit positioned on the T3-4 vertebrae [28]. Each unit was calibrated on the morning of data collection in keeping with manufacturer instructions. Data collection was filmed and 'time stamped' using a tripod-based camcorder with a sampling rate of 60 Hz (HC-V250, Panasonic, Japan) to allow accurate determination of movements on the resultant accelerometery data traces. Data collection using the GPS unit adhered to previously established guidelines for their use in sport [14].

Protocols

Participants were paired with each other based on body mass and stature. Following a group-based warm up, participants were requested to complete three small jumps on the spot to provide a clear, distinct acceleration marker on the collected data to allow synchronisation with the video recording. The participants were then led through 5 repetitions of each of the submission grappling movements listed in Table 1, with each repetition commencing on the count of one of the authors. Minimum sample size in terms of participants and technique trials was estimated a priori using the guidance provided by Bujang and Baharum [29], in which 3 participants performing 5 trials of a technique would provide $\beta = .9$. Following data collection of 7 participants performing 5 trials each, providing a total sample of 35, post hoc power was estimated using 'ICC.Sample. Size 1.0' R package in RStudio 1.3.1073 stating a required $\alpha < .05$ in a two tailed test. Each technique was analysed in turn with $\beta = .98–.99$ demonstrating high power. The analysed techniques were selected to represent some of the most fundamental movements from the three main categories of techniques within submission grappling; Passess/Transitions, Sweeps, and Submissions. Technique order was randomised, but all 5 repetitions of each technique were completed before moving onto the next technique. To ensure consistency of technique, participants were shown a video clip of the required technique three times prior to each being completed. Techniques on the video clips were performed by two experienced submission grapplers (both holders of purple belts in BJJ) and can be viewed here: https://osf.io/t6x7q/?view_only = 97ecf7d086ce 4c40bbbf7c966619fb5f. The techniques of

TABLE 1. Submission grappling techniques included in analyses

Submissions	Transitions	Guard passes	Takedowns
Arm bar from full guard bottom	Butterfly sweep from bottom	Knee slice from full guard top to side control top	Single leg
Arm bar from full mount top	Half guard sweep from bottom	Standing pass from full guard top to side control top	Double leg
Kimura from full guard bottom	Hip bump sweep from full guard bottom		
Guillotine choke from north-south top	Side control top to full mount top		
	North-south top to back (opponent in turtle)		

participants were reviewed both during the testing sessions and during data analysis to ensure the correct technique was followed. If an error was spotted during the session, participants were asked to repeat it and if errors were observed during data analysis the action was removed.

Data Treatment and Statistical Analysis

Data were downloaded from the accelerometers and analysed using the manufacturers software (Openfield™, Catapult®, Melbourne, Australia). Each participant's data was individually synchronised with the recorded video of the data collection session. Each movement was determined as the first deviation of the PlayerLoad trace from zero in conjunction with the commencement of movement on the synced video, to the end of the movement according to the video. Data recorded for each movement was accumulated PlayerLoad (PLd_{ACC}), calculated from the sum of the magnitude of changes in accelerations in the three cardinal planes (Bredt et al. 2020) designed to measure overall external load (AU). PLd_{ACC} is automatically calculated by the Optimeye units using equation (1) where a_y = anterior-posterior changes in acceleration, a_x = medial-lateral changes in acceleration, a_z = vertical changes in acceleration and t = time [27]:

$$\text{PlayerLoad} = \sqrt{\frac{\left(a_{y(t)} - a_{y(t-1)}\right)^2 + \left(a_{x(t)} - a_{x(t-1)}\right)^2 + \left(a_{z(t)} - a_{z(t-1)}\right)^2}{100}} \quad (1)$$

Also recorded was PlayerLoad per minute ($PLd_{ACC}{\cdot}min^{-1}$), which indicates relative external load (AU). The intra-unit reliability of the units in recording external load of submission grappling movements was determined using two way mixed effect intraclass correlation coefficient ($ICC_{(3,1)}$) using an minimum acceptance threshold ≥ 0.70 [30, 31], ≥ 0.75 classified as 'good' and ≥ 0.90 being 'excellent' [31] and is presented as point estimate and 95% confidence intervals. Significance was accepted at $\alpha < .05$. The mean within participant, between repetition variation in PLd_{ACC} and $PLd_{ACC}{\cdot}min^{-1}$ was calculated using coefficient of variation (CV) with 95% confidence intervals (95%CI). Owing to the highly open skill nature of grappling movements and techniques, a high variability of movement was predicted. In such cases there is likely to be high dispersion of SD around the mean, with a relatively high CV as a result. As such it is recommended to analyse CV within the context of the variable being measured and the action being performed [32]. Therefore, whilst CV ≤ 10% was determined as being good, CV ≤ 15% was deemed acceptable [33]. All statistical analyses were completed using SPSS 26 (IBM, USA).

RESULTS

The results for PLd_{ACC} reliability can be viewed in Table 2, whilst the reliability for $PLd_{ACC}{\cdot}min^{-1}$ are in Table 3. All techniques were found to have high $ICC_{(3,1)}$.

Unit Reliability

Submissions

PLd_{ACC} $ICC_{(3,1)}$ for all submission movements were high (> 0.89). However, the lower bound for arm bar bottom fell marginally below the minimum threshold. Similarly, $ICC_{(3,1)}$ for $PLd_{ACC}{\cdot}min^{-1}$ were all high (> 0.84) and were statistically significant, with only the lower bound for the north-south guillotine falling below the a priori threshold (0.55).

Transitions

PLd_{ACC} for all transitions had statistically significant $ICC_{(3,1)} > 0.70$, with only north-south turtle to back demonstrating a lower bound < 0.70. In addition, the $PLd_{ACC}{\cdot}min^{-1}$ all had very high $ICC_{(3,1)}$ (> 0.83). All movements had $PL_{ACC}{\cdot}min^{-1}$ $ICC_{(3,1)}$ lower bounds above the minimum threshold except for the transition from side control to the mount position (0.52).

Guard Passes

The standing and knee-slice passes had very high reliability for PLd_{ACC} (≥ 0.95) with lower bounds also above the minimum threshold.

TABLE 2. Accumulated PlayerLoad (PLd_{ACC}) reliability results for all movements.

Technique	$ICC_{(3,1)}$	Upper Bound	Lower Bound
Submissions			
Arm bar bottom	0.89	0.98	0.65
Arm bar top	0.95	0.99	0.84
Kimura	0.94	0.99	0.80
North-south guillotine	0.90	0.98	0.71
Transitions			
Butterfly sweep	0.93	0.99	0.80
Half guard sweep	0.90	0.98	0.68
Hip bump sweep	0.98	0.99	0.93
Mount from side control	0.94	0.99	0.81
North-south turtle to back	0.78	0.96	0.37
Guard Passes			
Knee-slice pass	0.95	0.99	0.83
Standing pass	0.96	0.99	0.88
Takedowns			
Single leg	0.92	0.99	0.79
Double leg	0.91	0.98	0.72

Nb. All ICC $\alpha < .05$; TD = takedown; ICC = intraclass correlation coefficient

TABLE 3. Accumulated PlayerLoad per minute ($PLd_{ACC} \cdot min^{-1}$) reliability results for all movements.

Technique	$ICC_{(3,1)}$	Upper Bound	Lower Bound
Submissions			
Arm bar bottom	0.91	0.98	0.73
Arm bar top	0.98	0.99	0.92
Kimura	0.94	0.99	0.83
North-south guillotine	0.84	0.97	0.55
Transitions			
Butterfly sweep	0.97	0.99	0.92
Half guard sweep	0.92	0.99	0.73
Hip bump sweep	0.97	0.99	0.93
Mount from side control	0.83	0.97	0.52
North-south turtle to back	0.93	0.99	0.81
Guard Passes			
Knee-slice pass	0.96	0.99	0.85
Standing pass	0.96	0.99	0.90
Takedowns			
Single leg	0.93	0.99	0.80
Double leg	0.94	0.99	0.82

Nb. All ICC $\alpha < .05$; TD = takedown; ICC = intraclass correlation coefficient

TABLE 4. Between repetition variation in accumulated PlayerLoad™ (PLd_{ACC}) for each participant and the cohort overall

	Submissions				Transitions					Guard Passes		Takedowns	
Participant	Arm bar bottom	Arm bar top	Kimura	North-south guillotine	Butterfly sweep	Half guard sweep	Hip bump sweep	Mount from side control	North-south turtle to back	Knee slice pass	Standing pass	Single leg	Double leg
1	8%	13%	12%	15%	16%	16%	11%	18%	23%	13%	7%	22%	38%
2	8%	9%	11%	15%	24%	8%	10%	14%	10%	12%	9%	16%	10%
3	27%	7%	20%	14%	15%	12%	8%	20%	16%	16%	12%	23%	12%
4	14%	8%	9%	22%	18%	15%	13%	15%	7%	13%	22%	13%	22%
5	20%	11%	25%	11%	11%	29%	16%	16%	11%	9%	15%	15%	21%
6	37%	12%	10%	25%	7%	12%	18%	16%	15%	14%	17%	8%	26%
7	25%	10%	25%	24%	10%	**	15%	19%	17%	31%	22%	28%	25%
Cohort (95% CI)	17 (13–21)%	11 (7–16)%	16 (10–22)%	19 (14–24)%	13 (9–17)%	14 (7–23)%	13 (10–17)%	14 (8–20)%	17 (11–22)%	14 (12–17)%	14 (10–18)%	14 (11–17)%	17 (10–24)%

*Nb. CV = coefficient of variation; 95%CI = 95% confidence interval; ** = unit error resulted in no data*

TABLE 5. Between repetition variation in PlayerLoad™ per minute (PLd_{ACC}·min^{-1}) for each participant and the cohort overall

	Submissions					Transitions				Guard Passes		Takedowns	
Participant	Arm bar bottom	Arm bar top	Kimura	North-south guillotine	Butterfly sweep	Half guard sweep	Hip bump sweep	Mount from side control	North-south turtle to back	Knee slice pass	Standing pass	Single leg	Double leg
1	17%	16%	11%	10%	16%	5%	6%	10%	20%	15%	10%	14%	35%
2	7%	11%	8%	23%	16%	11%	15%	15%	7%	13%	9%	13%	18%
3	17%	6%	16%	20%	19%	14%	10%	3%	16%	18%	14%	19%	12%
4	15%	9%	17%	29%	10%	11%	19%	8%	6%	17%	17%	6%	12%
5	19%	7%	24%	11%	11%	35%	17%	24%	13%	8%	17%	15%	20%
6	26%	8%	8%	26%	13%	15%	17%	12%	21%	18%	8%	15%	13%
7	19%	23%	29%	15%	3%	**	10%	24%	11%	15%	23%	16%	9%
Cohort (95% CI)	20 (12–28)%	9 (8–11)%	16 (11–22)%	18 (14–22)%	15 (10–19)%	16 (10–21)%	13 (10–16)%	17 (15–18)%	22 (12–31)%	15 (10–21)%	15 (11–19)%	18 (13–23)%	22 (15–29)%

*Nb. CV = coefficient of variation; 95%CI = 95% confidence interval; ** = unit error resulted in no data*

Further, the same pattern of reliability was seen for both actions for PLd_{ACC}·min^{-1} (≥ 0.96).

Takedowns

Both single and double leg takedowns also demonstrated high reliability for PLd_{ACC} and had lower bounds above the minimum threshold of 0.70. $ICC_{(3,1)}$ for PLd_{ACC}·min^{-1} for both actions were also very high with lower bounds > 0.70.

Between Repetition Movement Variation

Mean between repetition CV was above the good a priori threshold of 10% for PLd_{ACC} and PLd_{ACC}·min^{-1} for all submissions, except for PLd_{ACC} during arm bar top (9[8–11]%), which was the only technique to fall under the acceptable threshold. All transition movements also demonstrated CV > 10%. Three transition techniques had acceptable CV for PLd_{ACC} (13–15%), while all but one was acceptable for PLd_{ACC}·min^{-1} (13–14%). Both guard passes exhibited very similar acceptable CV's for PLd_{ACC} (15%) and PLd_{ACC}·min^{-1} (14%). The PLd_{ACC}·min^{-1} single leg takedown was the only takedown that had an acceptable CV (14[11–18]%). The lower boundary of CV 95%CI for all techniques fell within the acceptable threshold. Individual participants displayed a wide range of CVs for both PLd_{ACC} and PLd_{ACC}·min^{-1} in each technique measured, as shown in Tables 4 and 5.

DISCUSSION

Our aim in this study was to investigate the reliability of the Catapult® PlayerLoad metric in measuring the external load of submission grappling techniques. Our results show that the PLd_{ACC} and PLd_{ACC}·min^{-1} metrics display excellent intra-unit reliability across most techniques, but demonstrate high between repetition variability in measuring individual participant movement. This suggests that whilst PLd may not be capable of differentiating changes in external load of individual techniques between repetitions, it may be effective at quantifying the overall external load of full training sessions within an individual athlete. These results are similar to reliability data from MMA movements which also found high intra-unit reliability but lower inter-unit reliability [18]. Where these studies differ is that in MMA movements the CV = 2.4–7.8%, whilst all techniques in our current study were found to exceed this range (CV = 9–22%).

In viewing our data, there is little difference in $ICC_{(3,1)}$ of PLd_{ACC} or PLd_{ACC}·min^{-1} between the different categories of techniques observed with all techniques demonstrating high to excellent reliability. This indicates that PlayerLoad may be a reliable tool to quantify the external load of grappling-based training sessions. In order to support this proposition, further studies should be completed comparing PlayerLoad across multiple sessions of differing planned intensities to determine this variable's capability of distinguishing between sessions of higher and lower loads. In addition, within session PlayerLoad should be compared to internal load measurements such as HR or rating of perceived exertion (RPE) to determine a potential dose-response relationship to enable coaches to monitor the load-fatigue-recovery process [8].

Our data do, however, demonstrate high between repetition movement variance as measured by PlayerLoad. A potential explanation for the differences seen in the present study compared to data from the MMA study, may be the nature of the movements being performed. Hurst et al. [18] mostly performed strikes onto a stationary heavy bag. This would allow the participants to move without having to make changes in movement or technique in response to external influence. In addition, the performance of single strikes has

fewer stages to each technique [34], and therefore a consistent movement pattern is more likely within individuals. In the current study, and in submission grappling in general, this is not always the case. Participants sometimes complete their movements in response to the movement of their opponent, or attempt to initiate a movement by their opponent to facilitate their own technique. Though participants were instructed not to resist any of the techniques being performed, any slight changes in their balance, mass distribution or subconscious movement would in turn influence the movement of the participant being measured. Moreover, the combination of multiple stages within each grappling technique provides greater chance of measurement variation due to a culmination of small changes within each stage of a technique. The high CVs for each technique is evidence of such small changes within the individuals technique leading to high variation in the measured load of that movement. This was also seen in the takedowns in the aforementioned MMA study [18] having lower bound values < 0.70, which were the only movements where the participants in that instance interacted with another person physically.

Similarly, many movements in submission grappling do not involve changes in acceleration of the torso. For example, isometric gripping or holding actions may not be registered by the device at all. The same may be said for movements in which a participant in a prone position pushes or applies force onto their opponent with their legs only. Neither of these movements would necessarily result in movement of the torso but would still add to the actual load experienced. Previous work has highlighted that microsensors may not be able to capture certain sport specific actions, such as tackling or the scrum in rugby, the latter of which shares some of the high-force low movement actions present in grappling sports [35]. In each of these scenarios, it may be the case that accelerometery would record high, but not low, impulse movements. Given the inherent variation in discrete aspects of a repeated gross skill [36], it is possible that participants were making subconscious alterations to the impulse of the movement being performed on each repetition. If accelerometery is sensitive to changes in movement or technique along this spectrum this may be revealed in a relatively high CV. Therefore, when considering the use of PlayerLoad in a live training or competition setting, increased movement and resistance from the opponent is likely to cause greater between repetition variation in accelerometer measured external load.

A second potential cause of a high variance between repetitions may be the regular changing of the torso angle and position during grappling movements and the unavoidable occurrence of the accelerometer coming into contact with the ground or the opponent. These movement artefacts have been highlighted as a potential reason for inaccurate measurements from accelerometers in field settings [37, 38]. This is a limitation of the use of this technology in grappling sports that cannot be overcome without a change in the structure and design of the units, or the harness used to attach the unit to the participant. Despite these issues, the lower bound 95%CI of all techniques for both variables still fell under the acceptable CV threshold, with 12 falling under the good threshold. This may indicate that PLd_{ACC} and $PLd_{ACC}{\cdot}min^{-1}$ may have greater consistency when measured with participants capable of more consistent technique performance. It also reinforces the requirement of establishing individual minimal detectable changes for monitoring changes in performance or load. This might entail individual monitoring across a number of sessions of matched and differing intensities to determine each participant's smallest worthwhile change (SWC) or Z scores for PLd_{ACC} and $PLd_{ACC}{\cdot}min^{-1}$ [39]. Equally, these data indicate that fixed, prescriptive external load thresholds via accelerometery would not be recommended for submission grappling.

PlayerLoad may be used in research to help determine the external load and pacing of simulated and competitive bouts across a range of grappling-based sports, mirroring its use in MMA research [19, 24]. The contribution of isometric contractions or opponent mass to external load, however, cannot be measured by PlayerLoad. Both of these aspects are likely to be important determinants of load [40]. Equally, there are currently no studies validating PlayerLoad against internal load or gold-standard motion analysis for submission grappling [41]. Due to the continuous physical contact nature of submission grappling, there are inherent difficulties in the collection of internal markers such as HR. Recent studies though have demonstrated that whilst difficult, using HR monitors in simulated BJJ bouts is possible with minor adaptations [12]. Research application of HR telemetry integrated into the GPS harness may make collection of HR data in the field easier and provide a valuable combination of internal and external load measures [42]. Further, the future development of sport-specific algorithms, which have the capacity to detect specific movements [43, 44], would aid in understanding the relationship of internal and external load in grappling-based athletes.

CONCLUSIONS

In conclusion, high ICCs suggests PlayerLoad may be capable of quantifying the overall external load of grappling-based training sessions. Whilst comparison between individuals may be limited due to high variation between individuals and repetitions, it may play a role for monitoring session-to-session changes for an individual athlete. Coaches may use PlayerLoad to measure the external load of their athletes during submission grappling training and set targets or thresholds for monitoring purposes. Researchers may also use PlayerLoad in simulated or actual competition to determine the external loads that participants should be preparing for. However, the incorporation of physiological measurements and individual thresholds may enhance the validity and usefulness of this measurement for quantifying overall training load. Future work should investigate the use of PlayerLoad in measuring the external load of grappling-based training sessions of differing intensities and planned loads.

Declarations of Interest

There are no conflicts of interest for any of the authors.

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High fat diet improves metabolic flexibility during progressive exercise to exhaustion (VO_2max testing) and during 5 km running time trials

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ABSTRACT: Recently we reported similar performances in both progressive tests to exhaustion (VO_2max) and 5km running time trials (5KTT) after consuming low-carbohydrate, high-fat (LCHF) or high-carbohydrate, low-fat (HCLF) diets. Accordingly, we tested the null hypothesis that the metabolic responses during both tests would be similar across diets. In a randomized, counterbalanced, cross-over design, seven male athletes (VO_2max: 61.9 ± 6.1 mL/kg/min; age: 35.6 ± 8.4 years; height: 178.7 ± 4.1 cm; mass: 68.6 ± 1.6 kg; body fat: 5.0 ± 1.3%) completed six weeks of LCHF (6/69/25% energy carbohydrate/fat/protein) and HCLF (57/28/15% energy carbohydrate/fat/protein) diets, separated by a two-week washout. Substrate utilization and energy expenditure were measured during VO_2max tests and 5KTTs. The LCHF diet markedly increased fat oxidation and reduced carbohydrate oxidation, with no associated impairment in either the VO_2max tests or the 5KTTs. Following the LCHF diet, athletes generated 50% or more of their energy requirements from fat at exercise intensities up to 90% VO_2max and reached the crossover point for substrate utilization at ~85% VO_2max. In contrast, following the HCLF diet, carbohydrate provided more than 50% of the total energy consumption at all exercise intensities. During the 5KTT, ~56% of energy was derived from fat following the LCHF diet whereas more than 93% of the energy came from carbohydrate following the HCLF diet. This study provides evidence of greater metabolic flexibility following LCHF eating and challenges the popular doctrines of "carbohydrate dependence" for high intensity exercise and the role dietary macronutrients play in human performance.

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INTRODUCTION

It is generally taught that the oxidation of fat by skeletal muscle is unable to provide ATP sufficiently rapidly to sustain exercise of either high or moderate intensity [1] . It has been suggested that the exclusive use of fat cannot sustain metabolic rates during exercise above 50% of the maximum oxygen consumption [2]. Indeed, a popular book [3] by one of the present authors includes the statement that: "At exercise intensities greater than 95% VO_2max only carbohydrate is burned" so that "The practical point is that at high exercise intensities, carbohydrate, especially muscle glycogen, is used at very high rates and is probably the principal energy fuel" (3, p. 120). This belief originates, at least in part, in a series of iconic Scandinavian studies undertaken in the late 1960s. Adopting the novel percutaneous needle muscle biopsy technique [4], these studies measured the disappearance of glycogen from muscle during both prolonged [5–12] and high intensity [13] exercise. The most frequently cited study [10] reported a linear associational relationship between the pre-exercise muscle glycogen content and the duration of exercise that could be sustained during exercise at high intensity (75% VO_2max). Many of these studies also reported that the termination of prolonged exercise was associated with near-total muscle glycogen depletion [5, 7, 11, 13].

Two principal conclusions were drawn from these studies: First, that limited glycogen stores is a limiting factor for high intensity exercise [14]. Second, that at low exercise intensities, energy is primarily derived from lipids. However, the fraction of carbohydrate used as an energy source increases with increasing workload, with the result that at 85% to 90% VO_2max, all energy is derived from carbohydrates [14]. As a result, endurance athletes were advised to eat carbohydrate-rich diets for at least 3 days before competitive events [15].

In 1974, Gollnick [2] provided a theoretical explanation for an essential role for carbohydrate use during exercise at higher intensities: "Part of this may be related to the fact that carbohydrates produce about 5% more energy per liter of oxygen consumed than fats.

The ready availability of carbohydrates in muscle may also be a factor. This can be contrasted to the need to transport fats from the blood into the muscle cell and then into the mitochondria. This may well limit the total energy production that can be sustained from the exclusive use of fat. It may also be related to the fact that carbohydrates are necessary to maintain citric acid cycle intermediates at a level needed to support the oxidative capacity of muscle. The most important of these anaplerotic processes is probably the production of oxaloacetate from pyruvate via the pyruvate carboxylase reaction. When the concentration of oxaloacetate in mitochondria is low, entry of acetyl groups to form citrate is reduced. This can retard fatty acid oxidation". This explanation is known as the "anaplerotic theory" [16] to rationalize why fat oxidation cannot substitute for carbohydrate, especially muscle glycogenolysis, during high intensity exercise. Others propose that glycogen is essential for the optimum calcium release from the sarcoplasmic reticulum so that glycogen depletion may cause fatigue by interfering with skeletal muscle excitation-contraction coupling [17, 18].

Thus, has arisen the belief that exercise of high intensity is "carbohydrate dependent" [3, 19–21] and that "fat-derived ATP production is designed to provide a 'helper fuel' during exercise, with a maximum amount of energy at power outputs of ~60–65% VO_2max [22]" [23]. As a result, "For most events at the Olympics, carbohydrate is the primary fuel for anaerobic and aerobic metabolism" [23] so that "when elite athletes train for and compete in most sporting events, carbohydrate fuels are the predominant and critical substrate for the working muscles, and the availability of carbohydrate [19, 24] rather than fat, wins gold medals" [25].

Perhaps the strongest body of evidence supporting this hypothesis is the well-described metabolic response to progressive maximal exercise testing for measurement of maximal oxygen consumption (VO_2max). Countless studies beginning more than 100 years ago [26] have repeatedly established that the percentage contribution of fat oxidation to energy metabolism falls progressively with increasing exercise intensity. Thus, Achten and Jeukendrup [22] have shown that maximal rates of fat oxidation (0.5 g/min) occur at about 63% VO_2max with a rapid reduction to 0% at 85% VO_2max (Figure 1). According to this evidence, carbohydrate becomes the sole energy source during exercise at greater than ~85% VO_2max. This observation has become known as the "crossover concept" [27–29].

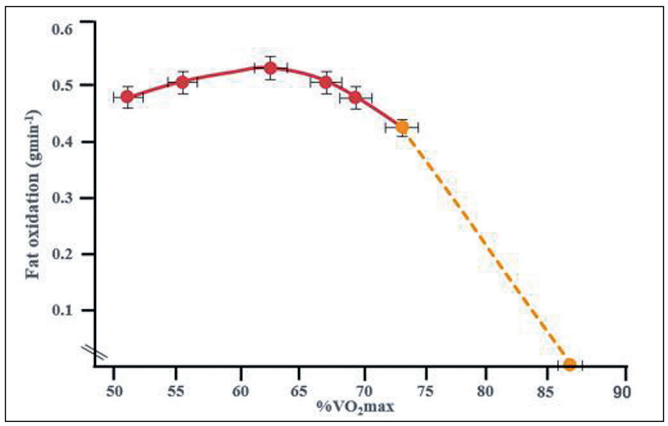


FIG. 1. The study of Achten and Jeukendrup [22] found that rates of fat oxidation increase during exercise, reaching a maximum at an exercise intensity of ~65%VO2max before falling to zero at ~85% VO2max in carbohydrate-adapted athletes.

Other studies [30, 31] measuring rates of carbohydrate and fat oxidation during more prolonged exercise confirm that carbohydrate becomes the predominant fuel source used during prolonged exercise at higher exercise intensities of, for example, 65 and 85% VO_2max [32]; 55 and 75% VO_2max [33]; 70% VO_2max [34–37]; and 65% VO_2max [38]. Even during three hours of lower intensity exercise (55% VO_2max), carbohydrate provided more than 50% of energy use at the termination of exercise even when no carbohydrate was ingested during exercise [39].

Importantly all these studies were of athletes chronically adapted to high carbohydrate diet so that this "carbohydrate-dependence" could potentially be the result [30, 31] of beginning exercise with high muscle and liver glycogen contents [40, 41]. Indeed, Achten and Jeukendrup [22] reported that the metabolic response during VO_2max testing showed wide individual variability so that some athletes could cycle up until intensities higher than 85% VO_2max before any decrease in fat oxidation occurred. They acknowledged that differences in habitual diet might partially explain these different responses. Indeed, many publications now suggest that this "carbohydrate-dependence" may, at least in part, reflect a state of chronic adaptation to a high-carbohydrate low-fat (HCLF) diet that alters quite rapidly on exposure to a low-carbohydrate high-fat (LCHF) diet [24, 42–46].

Recently we reported the results of a dietary randomized controlled trial in which the same subjects performed 5 km time trials following exposure to LCHF or HCLF diets [47]. As the subjects also completed progressive VO_2max exercise tests to exhaustion when eating either the HCLF or LCHF diets, we realized that a complete data set was available to determine the effects of these two different diets on carbohydrate and fat metabolism during progressive maximal exercise to exhaustion. Since our data showed that performances during both the VO_2max test and the 5 km time trials were identical on both dietary interventions, we wished to determine whether the metabolic response especially during the VO_2max test had been influenced by the pre-testing diet. According to the conventional belief that fat oxidation cannot sustain exercise of high intensity, the null hypothesis we evaluated was that the metabolic responses during the VO_2max tests following either diet must have been identical since the different diets produced identical athletic performances.

MATERIALS AND METHODS

Experimental Design

The data presented in this manuscript was collected as part of a larger project [47] examining the effects of LCHF and HCLF diets on running performance, physiological, perceptual, and metabolic

adaptations, and change in body composition. Detailed description of general methods and other results can be found in Prins et al. [47].

In brief, participants participated in two 42-day experimental conditions (HCLF or LCHF) in a randomized (www.randomizer.org), counterbalanced, crossover design. The main goal of this study was to determine the effects of the two different diets on carbohydrate and fat metabolism during progressive exercise to exhaustion in the VO_2max test in highly trained, recreational endurance athletes who underwent 12 weeks of experimental and dietary intervention phases. Participants were instructed to maintain their usual training frequency and log (mode, duration, and intensity of each workout) throughout the study intervention. Additionally, a sequence of tests was performed on day 1, 4, 14, 28, 39, and 42 during each dietary phase. A VO_2max test was performed at baseline (Day 1) and 6 weeks (Day 39) following the dietary intervention. A 5-km running time trial (5KTT) was performed four times during each dietary intervention (Day 4, 14, 28, and 42). Participants reported to the testing laboratory (Grove City College Exercise Science Human Performance Laboratory) between 6:00 and 9:00 am after an overnight fast (8–12 h).

Participants

Seven male, competitive recreational runners (age: 35.6 ± 8.4 years; body height: 178.7 ± 4.1 cm; body mass: 68.6 ± 1.6 kg; body fat: 5.0 ± 1.3%; lean body mass: 65.1 ± 1.5 kg; VO_2max: 61.9 ± 6.1 ml/kg/min; running distance per week: 63.0 ± 27.1 km; running experience: 15.1 ± 7.1 years) volunteered to participate in this study. Inclusion criteria were divided into three objective categories: running performance (< 21'00" 5-km within 3 months of study enrolment; > 32 km of running per week; > 2 years of running experience); age (18–45 years); habitual dietary intake (> 50% total energy intake from carbohydrates). Exclusion criteria included habitually consuming a ketogenic or low-carbohydrate diet (< 20% total energy needs from carbohydrates) or being prescribed lipid- or glucose-lowering medications. Participants were prohibited from using any ergogenic aids for one month preceding the study and were asked to refrain from taking any performance enhancing supplement(s) during the course of the study.

Before enrolling in the study, participants were fully informed of any associated risks and discomforts prior to giving their written informed consent to participate. The experimental protocol was approved by the Institutional Review Board of the College prior to implementation. Participants who met the criteria were invited to an in-person consent visit where the protocol and study responsibilities were described in greater detail. After randomization, each participant was assigned to an *ad libitum*, low-carbohydrate/high-fat diet (LCHF**)** or a high-carbohydrate/low-fat diet (HCLF**)** for six-weeks. A two-week, also *ad libitum,* mixed diet (i.e., CHO > 50 g/day and > 20% fat) washout stage separated the two experimental dietary phases.

Nutrition and Exercise Guidelines

Using direct counselling and prepared educational handouts, a registered dietitian taught and guided each athlete prior to the experimental phase on how to implement the LCHF and HCLF diets at-home. The primary macronutrient targets for LCHF and HCLF

TABLE 1. Dietary composition in the low-fat and low-carbohydrate diet groups over the course of the study.

	Overall Six Week Mean		
Variable	**LCHF**	**HCLF**	**P Value**
Energy (Kcal/day)	2947 ± 284	2837 ± 251	0.686
Carbohydrate (g)	43 ± 6.0	402 ± 32	0.001
Protein (g)	184 ± 28	106 ± 9.0	0.001
Fat (g)	226 ± 21	89 ± 14	0.001
Carbohydrate (%)	6.0 ± 1.3	56.4 ± 2.6	0.001
Protein (%)	25.1 ± 1.5	15.3 ± 1.1	0.001
Fat (%)	68.6 ± 2.1	27.8 ± 2.3	0.001
Cholesterol (mg)	1199.3 ± 172.1	264.1 ± 29.5	0.001
Saturated fat (g)	89.1 ± 13.2	28.7 ± 5.2	0.001
Monounsaturated fat (g)	72.8 ± 6.3	25.5 ± 4.5	0.001
Polyunsaturated fat (g)	23.4 ± 2.5	14.7 ± 1.9	0.023
EPA (g)	0.08 ± 0.04	0.02 ± 0.02	0.019
DHA (g)	0.22 ± 0.09	0.04 ± 0.04	0.012
Fiber (g)	9.7 ± 1.5	29.6 ± 0.8	0.001
Sugar (g)	18.1 ± 2.4	132.4 ± 4.7	0.001

Note: Values are mean ± SD (n = 7). LCHF, low carbohydrate high fat; HCLF, high carbohydrate low fat. Determined from 3 day 24-hour weighed dietary food records including 1 weekend day.

were expressed as both a percentage of total daily energy intake and daily gram intake: LCHF: < 50 g/day carbohydrate, 75–80% fat, 15–20% protein; HCLF: 60–65% carbohydrate, 20% fat, 15–20% protein (Table 1).

Participants were explicitly instructed to consume the diets until they reached satiety. Consumption of a wide range of foods was encouraged to minimize micronutrient deficiencies. To ensure that mineral status was met, we recommended including an additional 1–2 g/day of iodized table salt to offset the additional loss of sodium associated with a reduction in total carbohydrate intake on the LCHF diet [48]. Weekly energy intake and relative macronutrient distribution was monitored and estimated via 3-day weighed food records, capturing two consecutive weekdays and a weekend day. A digital scale (Ozeri ZK14-S Pronto, San Diego, CA) calibrated to the nearest ± 0.1 g was provided to each athlete prior to experimental phases to improve food tracking accuracy (intended for both dry and cooked items). Dietary macro- and micronutrients were calculated by the same registered dietitian using advanced nutrient software (Nutritionist Pro, Axxya Systems, Redmond, WA). In addition to food records, compliance to the LCHF dietary regimen was monitored by daily, morning capillary blood measurement of beta-hydroxybutyrate (BHB) concentrations (β-hydroxy-butyrate; Precision Xtra, Abbott Diabetes Care Inc., Almeda, CA).

To minimize confounding exercise effects, participants were instructed to select and maintain a constant training intensity and volume that they could adhere to for 14 weeks. Subjects were instructed to record their training habits (mode/duration/intensity) one week prior to commencing the experimental dietary phases. Post-hoc training load analysis revealed no differences in free-living exercise habits throughout the study.

Testing procedures

Progressive Exercise Test to Exhaustion (VO_2max)

Subjects performed an incremental test to exhaustion on motorized treadmill (Trackmaster TMX425C treadmill, Newton, KS, United States) utilizing the modified Astrand treadmill protocol. Participants began running at a speed between 5–8 mph for 3 min (0% grade). After 3 min of running at 0% grade, the speed was kept constant, and the grade was increased 2.5% every 2 minutes until volitional exhaustion. Heart rate was measured throughout (Polar Electro, Kempele, Finland). The following criteria were used to ensure a physiologically valid VO_{2Max} was attained: (1) a plateau in VO_2 with increasing exercise intensity (< 150 ml/min or < 2.1 ml/kg/min), (2) a respiratory exchange ratio (RER) of ≥ 1.1, and (3) volitional termination due to exhaustion.

5-km running time trial (5KTT)

Participants performed a 5KTT on a motorized treadmill (TMX425C treadmill; Trackmaster, Newton, KS, USA). Before the start of the run, participants completed a 5-min self-paced warm-up run. Participants were instructed to finish the run as fast as possible. The gradient was set at 0.0% grade. Participants were provided with feedback on the distance (at regular 500-m intervals) covered during each TT but were not informed of the overall performance time until completion of the study. During the 5KTT, participants were permitted to adjust their speed whenever they saw fit with the use of control buttons located on the treadmill. The speed indicator and timing devices were concealed from the participant's view throughout the TT. Therefore, participants regulated their treadmill pace according to their perceived exertion associated with the intensity of the exercise and their subjective feelings of their running capabilities [49].

Respiratory Gas Analysis

Respiratory gas exchange was recorded using an automated metabolic analyzer system (TrueOne 2400, ParvoMedics, Sandy, UT, United States). Prior to each experimental session, the device was calibrated using procedures according to manufacturer instructions. The breath-by-breath measurements were performed for oxygen uptake (VO_2), carbon dioxide production (VCO_2), and respiratory exchange ratio (RER) and was measured continuously throughout trials (VO_2max and 5-km TT).

The average values for VO_2 (L/min) and VCO_2 (L/min) were calculated over the last minute of each 2-min exercise stage in the maximal exercise test, and each minute of the 5KTT. Whole-body rates (g/min) of CHO and fat oxidation, and energy expenditure were calculated using intensity dependent equations that assume negligible protein contribution to energy expenditure [50]. The percentage contribution of CHO and fat to total energy expenditure during exercise was also calculated [27].

Statistical analysis

Analyses were performed using SPSS Ver. 25 (SPSS, Inc., Chicago, IL, USA). Two-tail α significance was set at $p < 0.05$. To address our objective, we analysed main effects and interactions between LCHF and HCLF using a 2 (condition) × 10 (intensity) repeated measures ANOVA to determine differences between LCHF and HCLF during the maximal exercise test for variables with serial measurements e.g., fat oxidation and carbohydrate oxidation (g/min, and % total EE). A 2 (condition) × 5 (distance) repeated measures ANOVA was performed to assess differences between LCHF and HCLF during the 5KTT. All the analysed variables of interest were screened for normality using Shapiro-Wilks's test. Assumption of sphericity was confirmed using Mauchly's test; variables that violated sphericity were treated with the Greenhouse-Geiser correction. Bonferroni correction was applied for multiple post-hoc comparisons. All data are presented as mean ± SD. Partial-eta squared (h2p) was used to report effect size with 0.01 considered small, 0.06 medium, and 0.14 large effects.

RESULTS

Substrate utilization and energy expenditure during VO_2max test

For rates of fat oxidation, main effects for intensity ($p < 0.001$, $\eta 2p = 0.827$), condition ($p < 0.001$, $\eta 2p = 0.936$), and interaction

effect ($p = 0.001$, $\eta 2p = 0.403$) were observed (Figure 2A; Table 2). Subsequently, rates of fat oxidation were higher in 8 out of the 10 stages (excluding, 40 and 100% VO_2max) in LCHF compared to HCLF (HCLF, 0.28 ± 0.14 g/min; LCHF, 0.72 ± 0.22 g/min; all p's < 0.015). Figure 2A shows that rates of fat oxidation increased in subjects after both dietary interventions peaking at an exercise intensity of about 60% VO_2max. However, rates of fat oxidation were significantly higher following the LCHF diet so that even at 90% VO_2max, rates were substantially higher (0.73 ± 0.29 g/min) than the highest values (0.53 ± 0.13 g/min) achieved at 60% VO_2max following the HCLF diet. For rates of CHO oxidation, main effects for intensity ($p < 0.001$, $\eta 2p = 0.971$), condition ($p < 0.001$, $\eta 2p = 0.932$), and an interaction effect ($p < 0.001$, $\eta 2p = 0.592$) were observed (Figure 2B; Table 2). Rates of carbohydrate oxidation rose exponentially during progressive exercise in both groups (Figure 2B). Specifically, rates of carbohydrate oxidation were higher at each stage in HCLF (HCLF, 2.91 ± 0.55 g/min; LCHF, 1.49 ± 0.53 g/min; all p's < 0.004).

Figure 2C compares the rates of fat and carbohydrate oxidation with increasing exercise intensity following the LCHF diet; Figure 2D compares the same measurements following the HCLF diet. For substrate utilization on the LCHF diet, main effects for intensity ($p < 0.001$, $\eta 2p = 0.959$), condition ($p = 0.013$, $\eta 2p = 0.667$), and interaction effect ($p < 0.001$, $\eta 2p = 0.908$) were observed (Figure 2C; Table 2). Specifically, rates of fat oxidation were significantly higher than rates of carbohydrate oxidation at 50 and 60% VO_2max ($p = 0.018$ and 0.043, respectively). However, rates of carbohydrate oxidation were significantly higher than rates of fat oxidation at 80, 90, and 100% VO_2max ($p = 0.043$, 0.002, and < 0.001, respectively). In contrast, for substrate utilization on the HCLF diet, main effects for intensity ($p < 0.001$, $\eta 2p = 0.978$), condition ($p < 0.001$, $\eta 2p = 0.965$), and interaction effect ($p < 0.001$, $\eta 2p = 0.971$) were observed (Figure 2C; Table 2). Specifically, when on HCLF diet, rates of CHO oxidation were significantly higher than rates of fat oxidation at each exercise intensity (all p's < 0.05).

Figures 3A and 3B shows the percentage of energy contribution from fat and carbohydrate with increasing exercise intensity following the LCHF and HCLF diets whereas figures 3C and 3D provide a direct comparison of these data. For the relative contribution of fat

TABLE 2. Metabolic responses during progressive exercise test to exhaustion

	%VO_2max										
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	***P-Value***
	Fat Oxidation (g/min)										
LCHF	0.38 ± 0.06	0.38 ± 0.06	0.52 ± 0.18	0.68 ± 0.30	1.00 ± 0.23	1.15 ± 0.22	1.06 ± 0.27	0.97 ± 0.27	0.73 ± 0.29	0.30 ± 0.36	Time, $P < 0.001$; $\eta 2p = 0.827$ Condition, $P < 0.001$; $\eta 2p = 0.936$ Interaction, $P = 0.001$; $\eta 2p = 0.403$
HCLF	0.10 ± 0.06	0.13 ± 0.07	0.19 ± 0.17	0.39 ± 0.17	0.50 ± 0.27	0.53 ± 0.13	0.44 ± 0.22	0.26 ± 0.24	0.12 ± 0.08	0.09 ± 0.02	
	CHO Oxidation (g/min)										
LCHF	0.26 ± 0.15	0.26 ± 0.15	0.24 ± 0.19	0.33 ± 0.29	0.38 ± 0.31	0.64 ± 0.34	1.13 ± 0.47	1.97 ± 0.80	3.48 ± 1.09	6.16 ± 1.56	Time, $P < 0.001$; $\eta 2p = 0.971$ Condition, $P < 0.001$; $\eta 2p = 0.932$ Interaction, $P < 0.001$; $\eta 2p = 0.592$
HCLF	0.97 ± 0.34	0.97 ± 0.34	1.32 ± 0.31	1.48 ± 0.39	1.65 ± 0.79	1.95 ± 0.62	2.76 ± 0.26	3.95 ± 0.55	5.65 ± 0.75	8.43 ± 1.18	
	% Total EE Fat										
LCHF	78.3 ± 11.1	79.7 ± 12.0	87.6 ± 14.8	90.1 ± 14.3	92.1 ± 11.8	85.1 ± 11.7	72.4 ± 11.6	59.0 ± 12.9	39.0 ± 16.0	12.9 ± 19.8	Time, $P < 0.001$; $\eta 2p = 0.926$ Condition, $P < 0.001$; $\eta 2p = 0.959$ Interaction, $P < 0.001$; $\eta 2p = 0.555$
HCLF	27.3 ± 7.3	25.7 ± 3.0	33.1 ± 14.9	38.9 ± 16.2	43.6 ± 19.8	38.9 ± 10.2	30.1 ± 9.3	16.4 ± 11.9	2.3 ± 6.0	0.0 ± 0.0	
	% Total EE CHO										
LCHF	21.7 ± 11.1	20.3 ± 12.0	12.4 ± 14.8	9.9 ± 14.3	7.9 ± 11.8	14.9 ± 11.7	27.6 ± 11.6	41.0 ± 12.9	61.0 ± 16	87.1 ± 19.8	Time, $P < 0.001$; $\eta 2p = 0.926$ Condition, $P < 0.001$; $\eta 2p = 0.959$ Interaction, $P < 0.001$; $\eta 2p = 0.555$
HCLF	72.7 ± 7.3	74.3 ± 3.0	66.9 ± 14.9	61.1 ± 16.2	56.4 ± 19.8	61.1 ± 10.2	69.9 ± 9.3	83.6 ± 11.9	97.9 ± 6.0	100 ± 0.0	

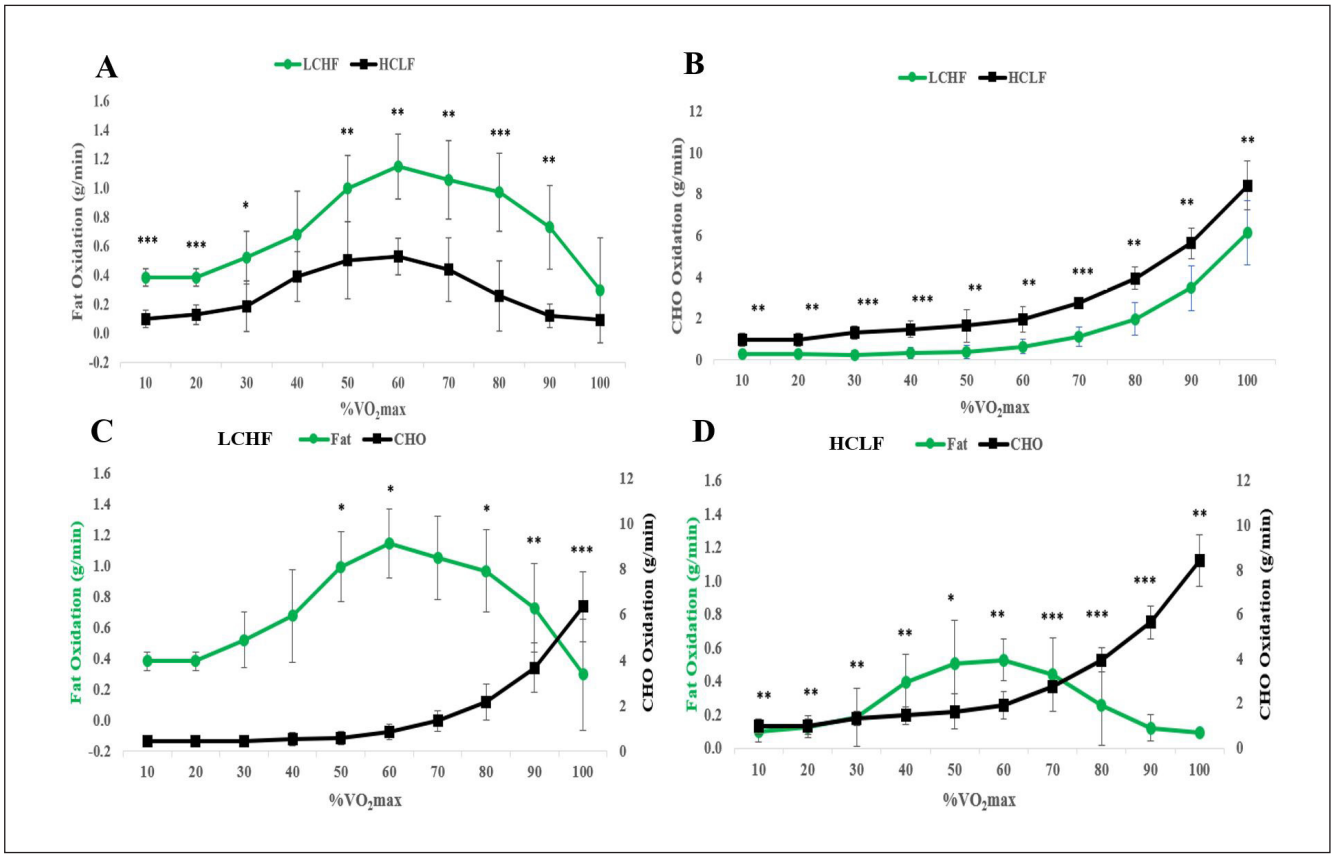


FIG. 2. Substrate utilization across a range of exercise intensities during the VO_2max test in subjects who had eaten the LCHF or HCLF diet for 6 weeks. A, rates of fat oxidation; B, rates of carbohydrate oxidation; C, substrate utilization on LCHF diet; D, substrate utilization on HCLF diet. n = 7. Data: Mean ± SD. *p<0.05, **p<0.01, ***p<0.001, significant difference between LCHF and HCLF.

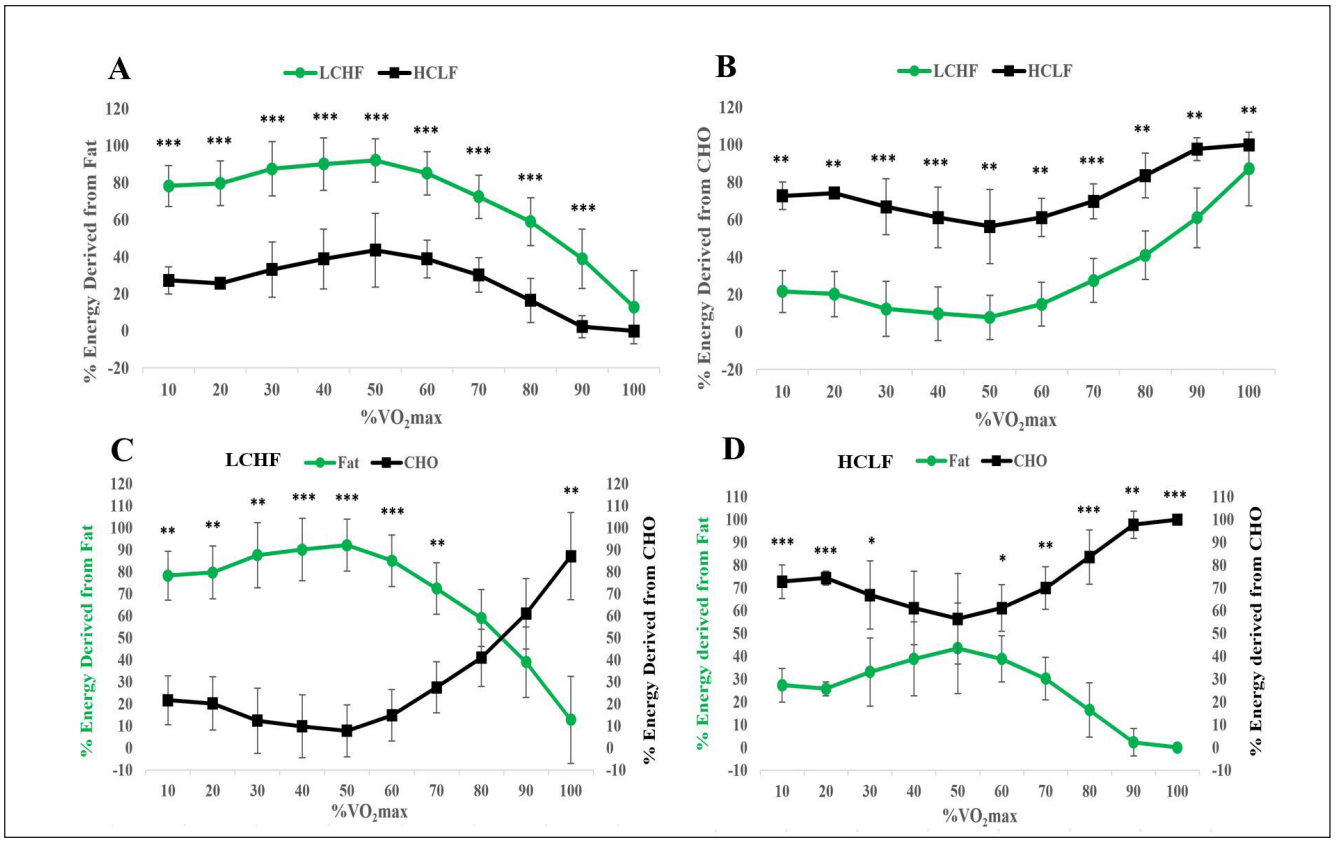


FIG. 3. Relative contribution (%) of carbohydrate and fat to energy expenditure during exercise across a range of intensities in response to consuming a LCHF or HCLF diet for 6 weeks. A, energy expenditure from fat oxidation; B, energy expenditure from carbohydrate oxidation; C, energy expenditure on LCHF diet; D, energy expenditure on HCLF diet., n = 7. Data: Mean ± SD. *p<0.05, **p<0.01, ***p<0.001, significant difference between LCHF and HCLF.

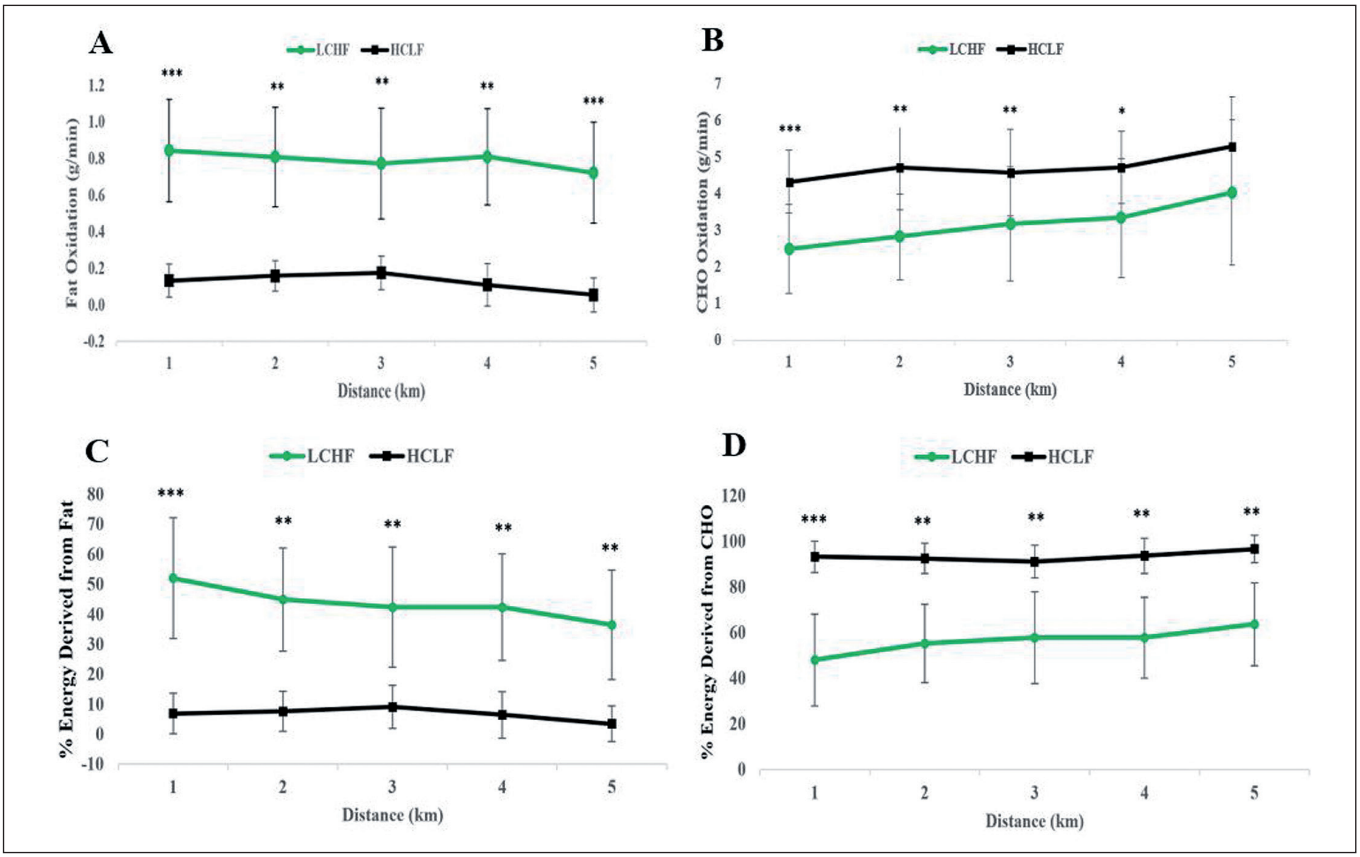


FIG. 4. Substrate utilization during 5-km running time trial in response to consuming a LCHF or HCLF diet for 6 weeks. A, rates of fat oxidation; B, rates of carbohydrate oxidation; C, energy expenditure from fat oxidation; D, energy expenditure from carbohydrate oxidation. n = 7. Data: Mean ± SD. *p<0.05, **p<0.01, ***p<0.001, significant difference between LCHF and HCLF.

to energy expenditure, main effects for intensity ($p < 0.001$, $\eta 2p = 0.926$), condition ($p < 0.001$, $\eta 2p = 0.959$), and an interaction effect ($p < 0.001$, $\eta 2p = 0.555$) were observed (Figure 3A; Table 2). The relative contribution of fat to energy expenditure was higher in 9 out of the 10 stages (excluding, 100% VO_2max) in LCHF compared to HCLF (HCLF, 25.6 ± 2.8%; LCHF, 69.6 ± 4.4%; all p's < 0.001; Figure 3A). Comparatively, for the relative contribution of carbohydrate to energy expenditure, main effects for intensity ($p < 0.001$, $\eta 2p = 0.926$), condition ($p < 0.001$, $\eta 2p = 0.959$), and an interaction effect ($p < 0.001$, $\eta 2p = 0.555$) were observed (Figure 3B; Table 2). The relative contribution of carbohydrate to energy expenditure was higher at each stage in HCLF compared to HCLF (HCLF, 74.4 ± 2.8%; LCHF, 30.4 ± 4.4%; all p's < 0.004; Figure 3B).

For energy expenditure (EE) on LCHF diet, main effects for intensity ($p < 0.001$, $\eta 2p = 0.939$), condition ($p = 0.004$, $\eta 2p = 0.771$), and an interaction effect ($p < 0.001$, $\eta 2p = 0.923$) were observed. Specifically, the relative contribution of fat to energy expenditure was significantly higher than carbohydrate at 10–70% VO_2max (all p's < 0.003). However, the relative contribution of carbohydrate to energy expenditure was significantly higher than fat at 100% VO_2max ($p = 0.003$; Figure 3C, Table 2). In contrast, for energy expenditure on HCLF diet, main effects for intensity ($p < 0.001$, $\eta 2p = 0.939$), condition ($p < 0.001$, $\eta 2p = 0.924$), and an interaction effect ($p < 0.001$, $\eta 2p = 0.762$) were observed. Specifically, when on HCLF diet, relative contribution of carbohydrate to energy expenditure was significantly higher than fat in 8 out of the 10 stages (excluding 40 and 50% VO_2max; all p's < 0.029; Figure 3D, Table 2).

Substrate utilization and energy expenditure during 5-km running time trial

Figure 4 shows the contribution of fat and carbohydrate oxidation to energy production during the 5KTT after 6 weeks adaptation to either the LCHF or HCLF diets. High rates of fat oxidation and low rates of carbohydrate oxidation were sustained throughout the 5KTT following the LCHF intervention whereas carbohydrate oxidation was substantially higher at all times following the HCLF dietary intervention (Figures 4A and 4B). Specifically, for rates of fat oxidation, a main effect for condition ($p < 0.001$, $\eta 2p = 0.899$) was observed (Figure 4A; Table 3). Rates of fat oxidation were higher at each one-km interval in LCHF compared to HCLF (HCLF, 0.13 ± 0.02 g/min; LCHF, 0.79 ± 0.10 g/min; all p's < 0.002; Figure 4A). For rates of CHO oxidation, main effects for intensity ($p = 0.009$, $\eta 2p = 0.420$), and

TABLE 3. Metabolic Responses During 5-km Running Time Trial

	Distance (km)					
	1	**2**	**3**	**4**	**5**	***P-Value***
				Fat Oxidation (g/min)		
LCHF	0.84 ± 0.28	0.81 ± 0.27	0.77 ± 0.30	0.81 ± 0.26	0.72 ± 0.27	Time, $P = 0.085$; $\eta 2p = 0.280$
HCLF	0.13 ± 0.09	0.16 ± 0.08	0.17 ± 0.09	0.11 ± 0.11	0.05 ± 0.09	Condition, $P < 0.001$; $\eta 2p = 0.899$
						Interaction, $P = 0.167$; $\eta 2p = 0.228$
				CHO Oxidation (g/min)		
LCHF	2.50 ± 1.22	2.82 ± 1.16	3.17 ± 1.55	3.33 ± 1.63	4.04 ± 1.98	Time, $P = 0.009$; $\eta 2p = 0.420$
HCLF	4.33 ± 0.84	4.71 ± 1.14	4.59 ± 1.18	4.73 ± 0.97	5.30 ± 1.34	Condition, $P = 0.003$; $\eta 2p = 0.795$
						Interaction, $P = 0.284$; $\eta 2p = 0.183$
				% Total EE Fat		
LCHF	52.0 ± 20.1	44.9 ± 17.2	42.3 ± 17.8	42.3 ± 17.8	36.4 ± 18.2	Time, $P = 0.062$; $\eta 2p = 0.302$
HCLF	6.85 ± 6.82	7.57 ± 6.65	9.00 ± 7.18	6.43 ± 7.76	3.43 ± 5.97	Condition, $P = 0.001$; $\eta 2p = 0.862$
						Interaction, $P = 0.002$; $\eta 2p = 0.504$
				% Total EE CHO		
LCHF	48.0 ± 20.1	55.1 ± 17.2	57.7 ± 17.8	57.7 ± 17.8	63.6 ± 18.2	Time, $P = 0.062$; $\eta 2p = 0.302$
LCHF	93.1 ± 6.82	92.4 ± 6.65	91.0 ± 7.18	93.6 ± 7.76	96.6 ± 5.97	Condition, $P = 0.001$; $\eta 2p = 0.862$
						Interaction, $P = 0.002$; $\eta 2p = 0.504$

condition ($p = 0.003$, $\eta 2p = 0.795$), were observed (Figure 4B; Table 3). Consequently, rates of carbohydrate oxidation were higher in 4 of the 5 one-km intervals (excluding, fifth kilometre) in HCLF (HCLF, 4.73 ± 0.35 g/min; LCHF, 3.18 ± 0.54 g/min; all p's < 0.022; Figure 4B). For the relative contribution of fat to energy expenditure, a main effect for condition ($p = 0.001$, $\eta 2p = 0.862$), and an interaction effect ($p = 0.002$, $\eta 2p = 0.504$) was observed (Figure 4C; Table 3). The relative contribution of fat to energy expenditure was higher at each one-km interval in LCHF compared to HCLF (HCLF, 6.7 ± 0.66%; LCHF, 43.6% ± 1.35%; all p's < 0.004; Figure 4C). Comparatively, for the relative contribution of carbohydrate to energy expenditure, a main effect for condition ($p = 0.001$, $\eta 2p = 0.862$), and an interaction effect ($p = 0.002$, $\eta 2p = 0.504$) was observed (Figure 4D; Table 3). The relative contribution of carbohydrate to energy expenditure was higher at each one-km interval in HCLF compared to LCHF (HCLF, 93.3 ± 0.66%; LCHF, 56.4 ± 1.35%; all p's < 0.004; Figure 4C).

DISCUSSION

The first important finding of this study was that, compared to the HCLF diet, eating the LCHF diet for 42 days significantly altered the metabolic response during both VO_2max testing and during the 5KTT but without altering physical performance either positively or negatively [47]. This refutes the null hypothesis that we tested. This establishes that the performance in both forms of exercise was not materially influenced by either the pre-exercise diet, or the nature of the metabolic response that these different diets produced during the subsequent exercise tests.

The second important point was the LCHF diet markedly increased fat oxidation and reduced carbohydrate oxidation. Importantly, lower rates of carbohydrate oxidation were not associated with any impairment of performance during either the VO_2max test or the 5KTT [47]. This contradicts the popular opinion that high rates of carbohydrate oxidation are essential to achieve and to sustain performance during high intensity exercise – the so-called "carbohydrate dependence" of high intensity exercise.

Thus, the rate of fat oxidation at 60% VO_2max increased two-fold and at 80% VO_2max more than four-fold (Figure 2A) during VO_2max testing following the LCHF diet. As a result, fat oxidation provided the majority of energy at all exercise intensities below 85% VO_2max during the VO_2max test (Figure 3A); whereas carbohydrate was the predominant fuel at all exercise intensities following the HCLF diet (Figure 3D). Even at 100% VO_2max, close to 20% of energy was derived from fat oxidation following the LCHF diet.

Figure 3C shows that following the LCHF diet, athletes were able to generate 50% or more of their energy requirements from the oxidation of fat at exercise intensities up to 90% VO_2max. Consequently, the crossover point for substrate utilization, i.e., the exercise intensity above which CHO oxidation is the predominant source of energy provision [27], occurred at ~85% VO_2max in athletes eating the LCHF diet (Figure 3C). In contrast following the HCLF diet, carbohydrate provided more than 50% of the total energy consumption at all exercise intensities from rest to 100% VO_2max (Figure 3D). Thus, for comparison, at 85% VO_2max, energy use came equally from fats and carbohydrates following the LCHF diet. Whereas at the same exercise intensity following the HCLF diet, 90% of the energy provision came from carbohydrate oxidation with only 10% from fat oxidation. Similarly, during the 5KTT, ~56% of energy was derived from fat oxidation following the LCHF diet (Figure 4C) whereas more than 93% of the energy

came from carbohydrate oxidation following the HCLF diet (Figure 4D).

These data therefore show that the "carbohydrate dependence" of higher intensity exercise is an artifact of the habitual diet eaten in the days and weeks before the exercise bout. However, this "carbohydrate dependence" can be readily modified with the adoption of a high-fat diet. This is not a novel finding, having been repeatedly shown in the past [42, 43] and more recently [24, 44–46].

The third important finding is that when adapted to the LCHF diet, subjects showed enhanced, not impaired metabolic flexibility since they retained the capacity to use carbohydrates at high rates at 100% VO_2max (Figure 2B; Figure 2C); yet they were able to provide more than 50% of their energy from fat oxidation even at an exercise intensity of 85% VO_2max (figure 2C).

In contrast, following the HCLF diet, during exercise at any intensity above 50% VO_2max, carbohydrate-adapted subjects could increase their energy expenditure only by increasing rates of carbohydrate oxidation (Figure 3D) making their metabolism "carbohydrate dependent" at all exercise intensities above 50% VO_2max. But when adapted to the LCHF diet, subjects were able to extract most of their energy from the use of fat at all exercise intensities below 85% VO_2max, with the result that their metabolism became "carbohydrate dependent" only at exercise intensities > 85% VO_2max.

Indeed, one of the potentially misleading features of Figure 1 is to imply that fat oxidation begins to fall precipitously at all exercise intensities above ~65% VO_2max, and essentially ceases during exercise at 85% VO_2max or higher. Rather our data show that there is no sudden precipitous decline in fat oxidation with increasing exercise intensity in athletes adapted to the LCHF diet. Instead, even at ~85% VO_2max, fat oxidation continues to contribute a proportion of energy equal to that of carbohydrate oxidation (Figure 3C). However, in agreement with the finding of Achten and Jeukendrup [22], the contribution of fat oxidation to total energy expenditure in carbohydrate-adapted athletes, begins to fall at exercise intensities above 60%, reaching zero at 90% VO_2max (Figure 3D).

Thus, the LCHF diet increases metabolic flexibility by allowing higher rates of fat oxidation whilst retaining the capacity to exponentially increase carbohydrate oxidation rates at exercise intensities above 70% VO_2max. Even then, high rates of fat oxidation are still maintained at those high exercise intensities. In contrast following the HCLF diet, carbohydrates become the predominant source of energy at all exercise intensities above 70% VO_2max.

In addition to the study being limited by a small sample size an important limitation of the metabolic data from the VO_2max test is that those data were not collected during steady state exercise. As a result, the respiratory exchange ratio (RER) used to calculate the relative contributions of fat and carbohydrate oxidation to total energy expenditure, will be different from values measured during more prolonged steady state exercise, more especially at higher exercise intensities. For example, when exercise intensity exceeds an individual's maximal lactate steady state, shifts in acid-base balance occurs. During increased glycolytic flux, lactate accumulation in the contracting muscle moves to the extracellular fluid and increases [H^+], which is buffered by [$HCO3^-$], thus increasing the production of CO_2 and elevating the VCO_2. As a result, indirect calorimetry overestimates carbohydrate oxidation and underestimates fat oxidation during high intensity exercise [51]. But in the context of this experiment, the net effect would have been to under- and not to over-estimate the contribution of fat oxidation to overall energy balance at higher exercise intensities following both dietary conditions. Thus, this limitation would increase, not reduce, the validity of the arguments that we present.

CONCLUSIONS

In summary our previous study [47] found that performance during either VO_2max testing or during a 5KTT was unaffected by dietary adaptation to a LCHF diet. In this study we show that the dietary change produces a dramatic alteration in the contribution of carbohydrate or fat metabolism to energy production during both forms of exercise. Importantly the major change was to increase the proportion of energy derived from fat oxidation even at high exercise intensities.

Accordingly, the study effectively challenges three currently popular doctrines. First, the belief that a high-fat diet impairs metabolic flexibility during exercise. In contrast, we show that metabolic flexibility is increased by the LCHF diet whereas it is compromised by the HCLF diet. Second, the belief that exercise of high intensity is "carbohydrate dependent". Instead, we show that this "carbohydrate dependence" of high intensity exercise is an artefact of the athlete's preceding diet. Third, the belief that because of this "carbohydrate dependence" of high intensity exercise, fat cannot substitute for carbohydrate use during high intensity exercise without impairing exercise performance. Instead, we show that adaptation to the LCHF and HCLF diets produce matching exercise performances. Which might suggest that dietary macronutrient composition may have a much smaller effect on human exercise performance than is currently believed [52].

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Conflicts of Interest

The authors have no conflict of interest to declare.

Author Contributions

P.J.P. and T.D.N. conceived the original study design. K.E.S., A.D.A., S.J.H., N.J.E., J.A., A.R., J.D.B. conducted participant testing and collected all the data. A.S.R. designed the diets and provided nutritional counselling. P.J.P. and G.L.W. analysed the data. P.J.P. and T.D.N. drafted the final manuscript. All authors have read and agreed to the published version of the manuscript.

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One hour of internal precooling with cold water/menthol enhances cycling performance in a heat/wet stress environment: A pilot study

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ABSTRACT: The aim of this study was to compare precooling durations before aerobic performance in a heat/wet stress environment. Seven heat-acclimated and trained male cyclists completed 1-hour time trials in a hot and humid environment. Before each trial, the cyclists drank (1) a neutral beverage at 23°C during the 1-hour pre-exercise resting period (Neutral), (2) an ice-slush/menthol beverage at -1°C during the last 30 min of the resting period (Pre-30), or (3) an ice-slush/menthol beverage at -1°C during the 1-hour pre-exercise resting period (Pre-60). In each condition, the cyclists drank cold water/menthol at 3°C during the exercise. Performance was significantly higher in Pre-60 than in Pre-30 and Neutral conditions (condition effect: $F(2,12)=9.50$, $p=0.003$, $\eta p^2=0.61$), with no difference between Pre-30 and Neutral. During the resting period, rectal temperature was significantly lower in Pre-60 than in Pre-30 and Neutral (condition effect: $F(2,12)=4.48$, $p=0.035$, $\eta p^2=0.43$). Thermal comfort and rating of perceived exertion were not affected by conditions, but thermal sensation was positively affected in Pre-60 during the resting period (Friedman condition effect at 40, 45 and 60 minutes: $\chi^2=6.74$; $df=2$; $p=0.035$; $\chi^2=8.00$; $df=2$; $p=0.018$; $\chi^2=4.90$; $df=2$; $p=0.086$, respectively) and exercise (Friedman condition effect at 5 and 60 minutes: $\chi^2=6.62$; $df=2$; $p=0.037$; $\chi^2=6.50$; $df=2$; $p=0.039$, respectively). This study shows that 1 hour of precooling with an ice-slush and menthol beverage (1) improved performance in a 1-hour time trial, (2) had a cumulative effect with a cold water/menthol beverage during this exercise, and (3) decreased rectal temperature during the resting period. This precooling method enhances cycling performance in a heat/wet stress environment.

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INTRODUCTION

A heat/wet stress environment negatively impacts endurance exercise [1]. The processes involved in the alteration of performance have not been fully elucidated and many factors have been advanced to explain this impact (e.g., thermoregulation). Gonzalez-Alonso et al. [2] suggested that the time to exhaustion in hot environments is inversely related to the core body temperature and directly related to the rate of heat storage. Furthermore, the decrease in performance was found to be associated with a higher skin temperature in a warm environment [3]. Other factors include an anticipatory process [4], cardiovascular adjustments [5] and dehydration [3].

Many strategies such as precooling (i.e., before exercise) and percooling protocols (i.e., during exercise) have been used to minimize the impact of the heat/wet stress environment on aerobic performance. Several have been studied, such as cold water immersion [6, 7] and cooling vests [8, 9]. However, it is sometimes difficult to apply these strategies to real sports contexts [1, 10, 11], although internal cooling with beverages is among the easiest to apply [12]. One strategy is to drink cold water/ice slurry or combined cold water/ice slurry and menthol during exercise [10, 13, 14], which was shown to be beneficial for endurance performance in the heat. Indeed, menthol was demonstrated to positively impact thermal sensation and improve performance [12]. Moreover, the authors found that the colder the ingested water is, the higher the performance will be, these results being accentuated when menthol is added to the beverages.

Precooling with cold or iced water has been suggested to enhance performance or time to exhaustion in endurance events [15, 16]. Some have also demonstrated an inverse correlation between (1) the final performance and the increase in core temperature during endurance events (i.e., the greater the increase in core temperature, the higher the performance was [17]) and (2) the final core temperature and the core temperature at the start during long distance

exercise (i.e., the lower the core temperature was at the start, the lower it was at the end [18]), both suggesting that beginning with a low core temperature could be useful for events in a heat/wet stress environment. Recently, this hypothesis was tested by Riera et al. [19], who studied the combination of precooling and per-cooling with beverages in a 30-km cycling race in a heat/wet stress environment. The authors reported no effect on performance after 30 min of precooling with a cold beverage (3°C) compared with a control beverage (23°C) on the subsequent 30 km of cycling with per-cooling (ice slush/menthol). They suggested that the volume of beverage drunk during precooling/duration of precooling (i.e., 30 min) was insufficient to induce significant effects on subsequent performance. Furthermore, another study found that a long rest interval after internal precooling by ice ingestion had the greatest benefit for exercise capacity in the heat [20].

Given (1) the apparent insufficiency of 30 min of precooling to improve cycling performance in the heat [19], (2) the positive relation between the rest interval after precooling and performance [20], and (3) a plasma half-life of menthol of 56.2 minutes (for a 100-mg L-menthol capsule) [21], the current study aimed to determine whether the positive results of cold water/menthol ingestion during exercise would be further enhanced by the addition of precooling with increased duration. We hypothesized that a combination of 1-hour internal precooling with ice slurry/menthol ingestion and internal per-cooling with cold water/menthol would restrict heat stress over the entire exercise period, which in turn would improve performance.

MATERIALS AND METHODS

Seven heat-acclimated (i.e., living and training in tropical areas) male cyclists (age: 23 ± 5 years, body mass: 70.3 ± 5.7 kg) were recruited from among local cycling teams. Each cyclist was training at least 15 hours per week and had been competing regularly in elite road races. All cyclists completed a medical screening questionnaire and gave written informed consent prior to the study, which was approved by the University Ethics Committee and conducted according to the Declaration of Helsinki.

The cyclists completed three experimental randomized sessions: (1) a control session during which they drank a neutral beverage at 23°C during the 1-hour pre-exercise resting period and cold water/menthol at 3°C during exercise (Neutral), (2) a session during which they drank an ice-slush/menthol beverage at -1°C during the last 30 min of the resting period and cold water/menthol at 3°C during exercise (Pre-30), and (3) a session during which they drank an ice-slush/menthol beverage at -1°C during the 1-hour pre-exercise resting period and cold water/menthol at 3°C during exercise (Pre-60). The experimental sessions were separated by 7 days and were undertaken in a randomized crossover design. The cyclists were instructed to avoid training sessions for 24 hours prior to testing but were allowed 60 min of light-intensity exercise 48 hours before each session. At the start of the session day, the cyclists consumed a standard breakfast that included food and 500 mL of beverage. The sessions began at the same time of day for each session (between 2:00 p.m. and 3:00 p.m.). The experimental sessions were performed in a laboratory reproducing the hot/humid conditions, which were controlled using a portable WBGT meter (HD 32.2, Delta Ohm, Caselle di Selvazzano, Italy; temperature: 30.1 ± 0.5°C; relative humidity, RH: 79 ± 0.3%). During the sessions, the cyclists were not subjected to any flow of ambient air. The L(-)menthol beverage was a 0.025% natural menthol aroma obtained from an 86% menthol-concentrated menthol solution (Robertet, Grasse, France). The ice slurry was produced with an ice slurry machine (Brema, GB 902A, Professional Slush Machine, Ice Makers, Germany). Although ice expands in volume, we carefully ensured that the volume of ice slurry (in mL of water) was precisely the same as the volume of cold water. The temperature of each beverage was measured with a digital thermometer (YSI 409B, Yellow Springs Instruments, OH, USA). A straw with a 1.5-cm diameter was connected to the lid of the water bottle to aid ingestion of the ice slurry.

The cyclists warmed up for 5 min by cycling and performed a 1-hour time trial at the fastest possible speed. Cycling exercises were performed on each participant's own bicycle fixed on a cycle trainer (Tacx Satori T1856 Tacx BV, Wassenaarn, the Netherlands). The participants' equipment corresponded to standard cycling equipment. The participants were instructed to keep the same equipment and bicycle for the entire experiment. Throughout the sessions, the cyclists did not benefit from additional motivation. During the 1 hour of pre-exercise (i.e., the resting period), the cyclists were seated and drank 8 $g \cdot kg^{-1}$ of neutral water (Neutral condition) or ice slush (Pre-60 condition) divided into five intakes at 0, 15, 30, 45 and 60 min. During the 30 min of pre-exercise, the cyclists, already seated for 30 min, drank 8 $g \cdot kg^{-1}$ of ice slush (Pre-30 condition) divided into three intakes at 30, 45 and 60 min. During exercise in the three conditions, the cyclists drank 8 $g \cdot kg^{-1}$ of cold water/menthol divided into four intakes at 0, 15, 30 and 45 min of exercise.

Rectal temperature (Trec) was monitored continuously with a rectal probe (YSI409 AC, Yellow Springs Instruments, OH, USA) self-inserted 10 cm beyond the anal sphincter. Heart rate (HR) was continuously monitored using a portable telemetry unit (Suunto Memory Belt, Suunto, Vantaa, Finland) with recording every second. Perceived thermal comfort (TC, from 1: "not uncomfortable" to 4: "very uncomfortable") and perceived thermal sensation (TS, from 1: "slightly cool" to 7: "extremely hot") were determined using scales with the range of scores adapted from Hodder and Parsons [22]. Cyclists were asked to rate their perceived exertion according to the grades of Borg's Rating of Perceived Exertion (RPE) scale [23]. Trec, HR, TC and TS were recorded every 5 min during all the precooling conditions (from 0 to 60 min) and exercise. RPE and performance were recorded every 5 min during exercise. The global performance is given by the total distance covered in 1 hour. The performance was also expressed by 5-min blocks.

Performance and RPE were analysed during exercise, whereas Trec, TS and TC were analysed during the resting and exercise

periods. Once the assumption of normality was confirmed (except for TS), parametric tests were performed. To examine our hypotheses regarding the changes in performance, Trec, TC and RPE, one-way (for global performance) or two-way (for performance expressed by 5-min blocks, Trec, TC and RPE) analyses of variances (ANOVA) with repeated measures (i.e., precooling condition × time) were conducted and Tukey's post-hoc test was assessed when required. For TS, a Friedman ANOVA and a Wilcoxon test were used to assess whether differences existed between conditions and within conditions (i.e., time measures). For technical reasons, the heart rate could not be processed. Data analysis was performed using Statistica 8.0 (StatSoft). Significance was set at $p < 0.05$. All data are presented as mean ± SD.

RESULTS

Global performance (Figure 1) was affected by condition [$F(2,12)=9.50$, $p=0.003$, $\eta p^2=0.61$]: in the Pre-60 condition (39.89 ± 1.81 km), cyclists performed better than in Pre-30 (35.84 ± 3.98 km; $p < 0.01$) and Neutral (35.47 ± 2.24 km; $p < 0.01$), and no difference was found between Pre-30 and Neutral. When expressed by 5-min blocks (Figure 2A), performance in Pre-60 (3.32 ± 0.4 km) was higher than in Pre-30 (2.99 ± 0.4 km; $p < 0.01$) and Neutral (2.96 ± 0.6 km; $p < 0.01$). Significant differences occurred from the 9th block (i.e., 45 min), with Pre-60 higher than Pre-30 and Neutral. However, performance was not affected by time. The perception of exertion (Figure 2B) increased over time [$F(11,66)=33.72$, $p < 0.001$, $\eta p^2=0.85$], but no differences were observed for condition [$F(2,12)=2.01$, ns, $\eta p^2=0.23$] and condition × time [$F(22,132)=1.09$, ns, $\eta p^2=0.15$].

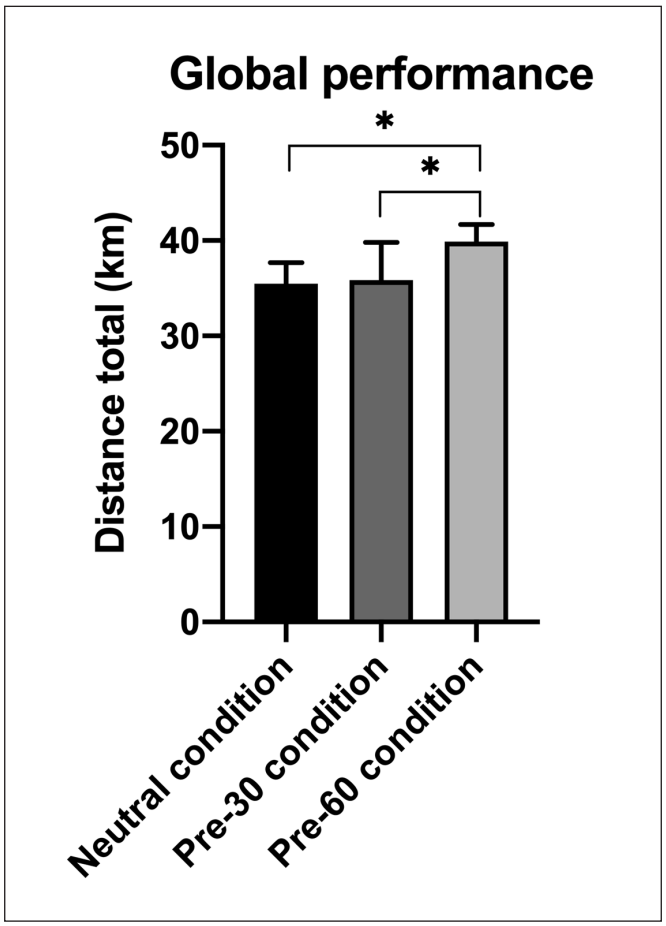


FIG. 1. Comparison of global performance between Neutral, Pre-30 and Pre-60 conditions. Significant differences are indicated as follows: *$p < 0.01$.

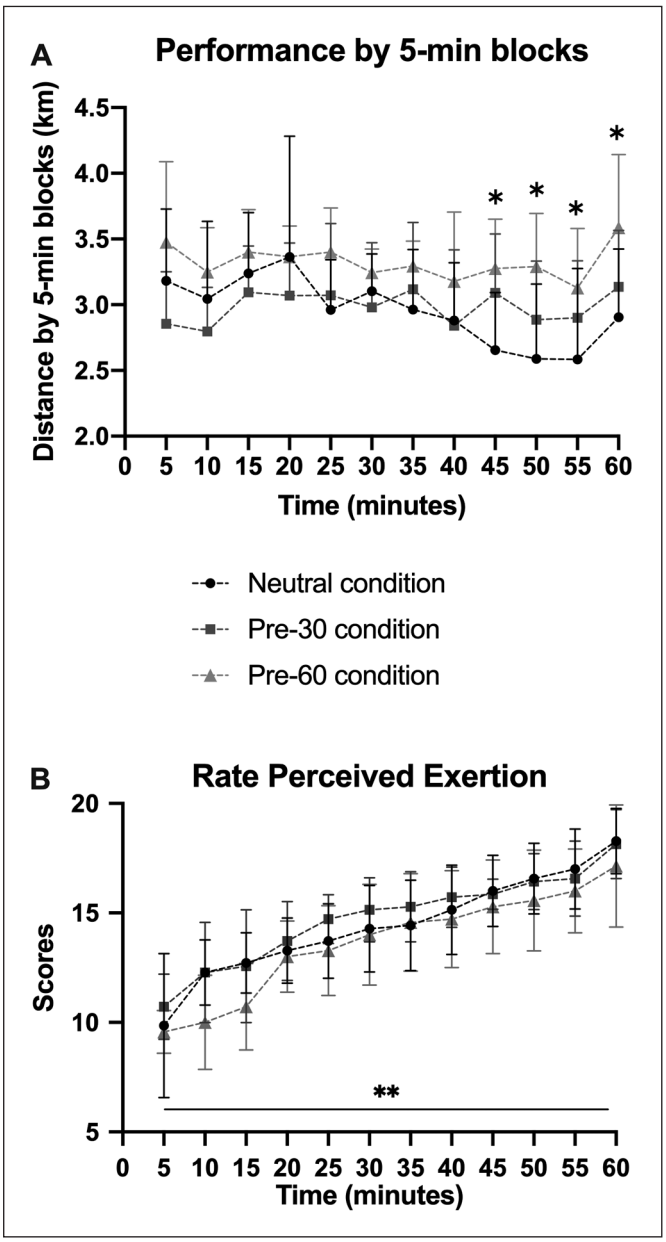


FIG. 2. Comparison of performance by 5-min blocks (A) and the rating of perceived exertion (B) between Neutral, Pre-30 and Pre-60 conditions. Significant differences are indicated as follows: *$p < 0.01$ and **$p < 0.001$.

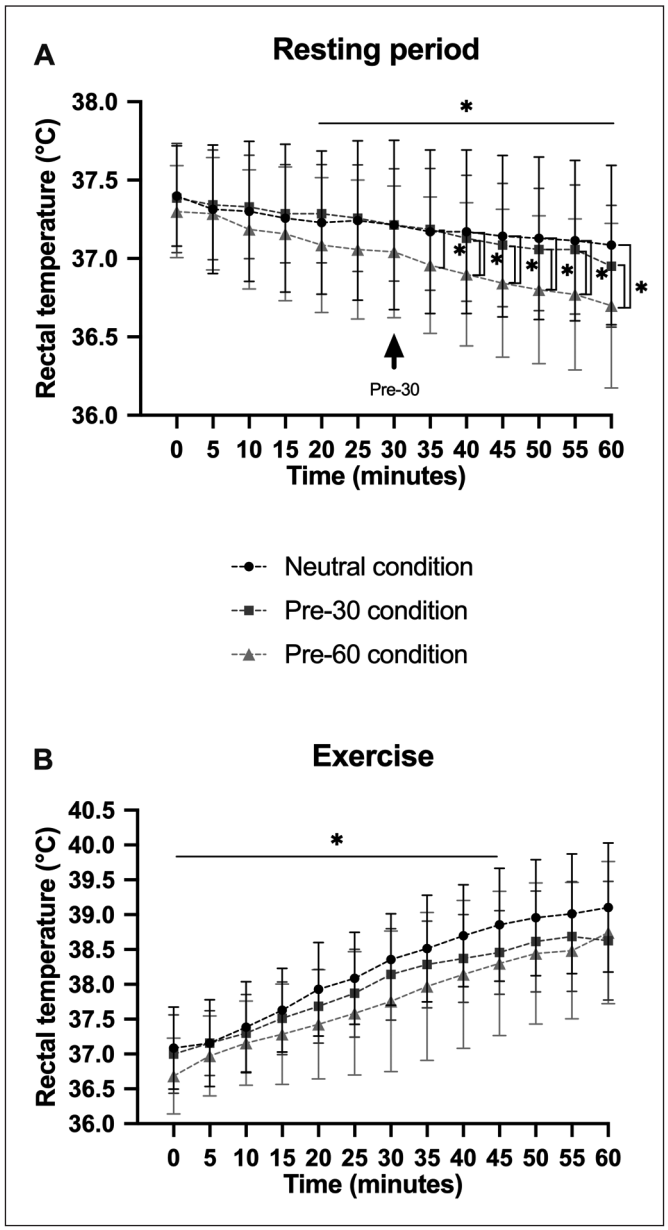


FIG. 3. Comparison of rectal temperature during resting period (A) and exercise (B) between Neutral, Pre-30 and Pre-60 conditions. Significant differences are indicated as follows: *p < 0.05.

During the resting period, the mean Trec (Figure 3A) was affected by condition [$F(2,12)=4.48$, $p=0.035$, $\eta p^2=0.43$]; by time [$F(12,72)=25.30$, $p < 0.001$, $\eta p^2=0.81$], with a decrease during the resting period at each time from the 20th minute ($p < 0.05$); and by condition × time [$F(24,144)=1.97$, $p=0.008$, $\eta p^2=0.25$]. Tukey's post-hoc analysis indicated that the mean Trec was lower in the Pre-60 condition compared with the Neutral ($p=0.049$) and Pre-30 conditions ($p=0.069$) from the 40th (T40: $p=0.002$; from T45 to T60: $p < 0.001$) and the 35th minute (T35 and T40: $p=0.04$; T45: $p=0.016$; T50: $p=0.006$; T55: $p < 0.001$; T60: $p=0.01$). During exercise (Figure 3B), mean Trec increased over time [$F(12,72)=81.90$, $p < 0.001$, $\eta p^2=0.93$]. The post-hoc test showed that mean Trec increased at each time ($p < 0.05$) up to 40 min, with no difference for the last four blocks (T45, T50, T55 and T60). No differences were found for condition [$F(2,12)=1.62$, ns, $\eta p^2=0.21$] or condition × time [$F(24,144)=1.21$, ns, $\eta p^2=0.17$].

During the resting period, TC was not different between conditions [$F(2,12)=0.03$, ns, $\eta p^2=0.00$], time [$F(12,72)=0.78$, ns, $\eta p^2=0.12$] or condition × time [$F(24,144)=0.63$, ns, $\eta p^2=0.10$] (data not shown). During exercise, only TC increased over time [$F(12,72)=3.84$, $p < 0.001$, $\eta p^2=0.39$], but no differences were observed for condition [$F(2,12)=0.31$, ns, $\eta p^2=0.05$] and condition × time [$F(24,144)=0.44$, ns, $\eta p^2=0.07$] (data not shown). Regarding TS during the resting period, a Friedman ANOVA indicated a decrease between times measures from 0 to 60 min for the Pre-30 condition (Friedman $\chi^2=29.86$; $df=12$; $p=0.003$) and the Pre-60 condition (Friedman $\chi^2=38.94$; $df=12$; $p < 0.001$). Significant differences were observed between conditions at 40 min (Friedman $\chi^2=6.74$; $df=2$; $p=0.035$) and 45 min (Friedman $\chi^2=8.00$; $df=2$; $p=0.018$), but the difference was not significant for 60 min (Friedman $\chi^2=4.90$; $df=2$; $p=0.086$). TS was significantly lower in the Pre-60 condition compared with the Neutral condition at 40 min ($T=0$, $Z=2.02$, $p < 0.05$) and 45 min ($T=0$, $Z=2.02$, $p < 0.05$), but the lower score in the Pre-60 condition compared with the Neutral condition was not significant ($T=0$, $Z=1.83$, $p=0.068$) (data not shown). During exercise, a significant increase between time measures from 0 to 60 min was observed for the Pre-30 condition (Friedman $\chi^2=36.52$; $df=12$; $p < 0.001$), but it was not significant for the Pre-60 condition (Friedman $\chi^2=20.47$; $df=12$; $p=0.059$). Differences were observed between conditions at 5 min (Friedman $\chi^2=6.62$; $df=2$; $p=0.037$) and 60 min (Friedman $\chi^2=6.50$; $df=2$; $p=0.039$). Compared with the Neutral condition, TS in the Pre-60 condition scored lower at 5 min, although not significantly ($T=0$, $Z=1.83$, $p=0.068$), and was significantly lower at 60 min ($T=0$, $Z=2.02$, $p < 0.05$) (data not shown).

DISCUSSION

The aim of this study was to determine whether a combination of 1-hour internal precooling with ice slurry/menthol ingestion and internal per-cooling with cold water/menthol would restrict heat stress over the entire exercise period and improve performance. The most important results were the following: (1) the combination of 1 hour of internal precooling with ice slush/menthol at -1°C and internal per-cooling with cold water/menthol improved performance during the subsequent 1-hour exercise when compared with both the Pre-30 and Neutral conditions, and (2) during the resting period, rectal temperature was significantly lower in Pre-60 than in Pre-30 and Neutral conditions.

Precooling for 60 min significantly increased performance compared with Pre-30 and Neutral conditions (+4.05 ± 3.81 km; +4.42 ± 1.29 km, respectively), with no difference between the

latter two. Whereas Riera et al. [19] examined precooling durations and suggested that longer precooling periods (i.e., > 30 min) might improve subsequent performances, others focused on the effect of length of time after the precooling [20]. Indeed, Naito et al. [20] found that a long rest interval after internal precooling by ice ingestion had the greatest positive effect on exercise capacity in a hot and humid environment. The authors assumed that core temperature (i.e., rectal temperature) and heat storage would be reduced before the start of exercise. Although our protocol differs from theirs, the present Pre-60 condition, with the start of precooling ingestion at least 60 min before the start of the effort, may have been a long enough rest interval to allow the core temperature to drop. This was corroborated by the mean rectal temperature (a good reflection of core temperature), which was lower in the Pre-60 condition than in Pre-30 and Neutral conditions. This reduction in core temperature induced by 60 min of precooling led to a decrease in heat storage, which might have prolonged the time to reach critical temperatures during exercise. As Hasegawa et al. [24] suggested that a decrease of 0.3°C in core temperature could lead to an increase in aerobic performance in a hot and humid environment, the present 0.6°C reduction induced by the ice slurry in the Pre-60 condition may have favoured the improvement in cycling performance. In addition, it was found that the absorption of ice slush reduced body temperature more than the absorption of the same quantity of cold water [11]. The temperature of the ingested beverage could thus explain the difference observed between the two 60-min precooling conditions (Pre-60 and Neutral conditions).

Despite the low temperature of the ingested solution [12–14, 20, 25, 26] and the additive effect of menthol with cold beverage [12], our results did not show a significant difference between the Pre-30 condition (i.e., ice-slush/menthol beverage at -1°C during the last 30 min of the resting period) and Neutral condition (i.e., neutral beverage at 23°C during the 1-hour pre-exercise resting period) for performance or rectal temperature. In accordance with other studies [19, 27], these results seem to confirm that 30 min of precooling is not enough to improve cycling performance.

During the time trial, the increase in Trec was due to the metabolic heat production generated by the exercising muscles. However, we assumed that the limited evacuation process due to the heat/wet stress environment would induce a similar increase in Trec independently of condition. Regarding performance, Neutral was lower than Pre-60, despite ingestion of cold water/menthol during exercise for both conditions. When expressed by blocks, performance was significantly affected starting from 45 min: from this point onwards, Neutral performance was negatively affected by the heat/wet stress environment, and this result was expected even in natives of tropical climate (i.e., a hot and humid environment) [28]. Pre-60 performance was not as negatively impacted by the environment as Pre-30 and Neutral, and thus it would seem that precooling for 1 hour with ice slush/menthol (Pre-60) enhanced the effect of per-cooling by decreasing thermal stress and heat storage. González-Alonso et al. [2] suggested that the time to exhaustion (i.e., cycling performance until volitional exhaustion) in hot environments is inversely related to the initial temperature and directly related to the rate of heat storage. This argument was corroborated by the significant decrease in Trec for Pre-60 compared with the other pre-exercise conditions.

The increase in performance noted in Pre-60 may also have been linked to the use of menthol. Indeed, as the plasma half-life of menthol is 56.2 minutes for a 100-mg L-menthol capsule [21], Pre-60 might have resulted in an increased concentration of menthol in the brain compared with Pre-30. Menthol could thus act as a stimulant on the central nervous system by inhibiting the recapture of dopamine and/or by facilitating its release [29, 30]. This stimulation enhances ambulatory activity in rats [29, 30]. Menthol is considered effective in the treatment of mental fatigue and may possess an action similar to that of psychostimulants [30–32] by enhancing the intensity of the afferent signals induced by cold water/menthol ingestion during exercise. These processes partly corroborate the central regulator model in the brain introduced by St Clair Gibson and Noakes [33].

Moreover, the absence of a Trec difference between Pre-30 and Neutral conditions at the end of the precooling period might be ascribed to the menthol effect, which limits thermoregulation [34]. The cooler effect of menthol on TRPM8 and TRPA1 could affect thermoregulation [35] and explain the smaller decrease in Trec in Pre-30 than Pre-60: menthol would block the thermoregulation while the greater amount of ice ingested in Pre-60 would outperform the effects of menthol. However, we assumed that these effects were marginal and the low menthol concentration used in our study partially explained this result. Nevertheless, we also assumed that the main factor to explain the lack of decrease in Trec was the quantity of ice slush given in the 30-min period. The absorption of large quantities of a cold drink (or ice slush) results in greater core temperature reduction than the ingestion of smaller quantities of water at the same temperature. Ross et al. [36] found that ingestion of 500 g and 1000 g of ice slush reduced Trec by 0.25°C and 0.60°C, respectively. In our study, we used 8 $g \cdot kg^{-1}$ (corresponding to 562.2 ± 45.6 g) of ice slush/menthol for 30 min without decreasing Trec. Yet, the absorption of the ice slush/menthol over a longer period significantly decreased Trec (i.e., Pre-60). Yeo et al. [25] found a significant decrease in gastrointestinal temperature after ingestion of 8 $g \cdot kg^{-1}$ over 30 min compared with the ingestion of an ambient beverage (30.9°C) in a heat/wet stress environment. We had some concerns in comparing the ambient beverage used in their study (30.9°C) to our Neutral condition with water at 23°C. Indeed, we could not conclude as to whether the lack of a reduction in Trec was due to the delta between ice slush and neutral water or the effect of menthol.

No differences between conditions were found for TC during the precooling period. These results, in accordance with those of Riera et al. [19], suggest that hydration induced by neutral water or ice slush/menthol did not influence the feeling of comfort in acclimated

participants. TS was significantly affected by time during the rest period and decreased at the end of the precooling with ice slush (i.e., Pre-30 and Pre-60 conditions). In 2012, Yeo et al. [25] demonstrated that precooling with 8 $g \cdot kg^{-1}$ of cold drink for 30 min in a hot and wet environment induced a significant decrease in thermal sensation. In our study, the observation that TS was positively affected by time in precooling with ice slush seems to confirm that a precooling hydration protocol with a very low temperature (e.g., ice slush/menthol for 30 or 60 min) would be positive for subjective perception, such as the thermal sensation in a heat/wet stress environment. This was corroborated by the between-condition differences observed at the end of the resting period, with a lower score on TS in Pre-60 compared with the Neutral condition. During exercise, TC and TS increased significantly over time, which is an obvious consequence of exercising in a tropical environment.

Although no between-condition differences were observed in TC, we found some in TS at exercise initiation (i.e., 5 min) and after exercise (i.e., 60 min). The results obtained at the end of the resting period, with (1) a decrease of the TS score in the Pre-60 condition and (2) a lower score in Pre-60 than the Neutral condition, would explain the lower score in the Pre-60 condition compared with the Neutral condition at the beginning of the effort, thus emphasizing a short-lasting effect. Although this effect disappeared during the effort, probably because of exercise-induced hyperthermia, it is interesting to note that this difference seemed to reappear at the end of the effort, at 60 min, although the difference was not statistically significant. The cyclists seem to have perceived less heat sensation at the end of exercise when they had benefited from 1 hour of internal precooling with cold water/menthol. Last, as TS was positively affected by time during the rest period in this condition, it is possible that the 1 hour of internal precooling helped limit the increase in TS during the cycling performance and thus contributed to enhancing it.

Despite the higher performance in Pre-60, RPE was affected by time but not by condition. These results suggest that the difficulty perceived by the cyclists increased similarly whatever the precooling conditions. As studies failed to show improved performance with 30 min of precooling [19] and no difference was found in our study between Pre-30 and Neutral, we assume that the higher performance in Pre-60 was due to the effect of 1 hour of ice-slush precooling with menthol, which biases the central nervous system by increasing performance without affecting the RPE. Indeed, as menthol is known to exhibit analgesic properties through peripheral and central mechanisms [37], the combination of ice slush and menthol during Pre-60 may have had an analgesic effect, allowing the cyclists to perform better without impacting RPE.

CONCLUSIONS

This study showed that 1 hour of precooling with an ice-slush and menthol beverage (1) improved cycling performance in a 1-hour time-trial, (2) had a cumulative effect with a cold water/menthol beverage during exercise, and (3) decreased rectal temperature during the pre-exercise resting period. The decrease in the rectal temperature during the 1-hour precooling period could explain the higher performance in the Pre-60 condition, but the cumulative effect of menthol on pre- and per-cooling might have enhanced the intensity of afferent signals within the central nervous system. As this is an exploratory study, caution is needed in interpreting the results, given the small samples. These results will have to be confirmed in future studies with larger samples. In addition, further data are needed to determine the efficiency of this method for other exercise durations. Finally, future studies should also focus on the possibility of reducing the precooling time by combining several strategies, such as internal with external.

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Conflict of interest declaration

The authors have no conflict of interest to declare.

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Relationships between training dose and record power outputs in professional road cyclists: insights and threats to validity

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ABSTRACT: Testing short-term (4–8 weeks) correlations between training dose and performance in professional road cyclists can help improve their training and performance. Multilevel mixed-modeling was used to correlate training dose (Time, Edwards' Trimp-eTRIMP, Training Stress Score-TSS, time spent in power output zones-Z1, Z2, Z3, Polarization Index-PI) and Record Power Output (RPO) over 1 minute (RPO1), 5 (RPO5), 20 (RPO20), and 40 minutes (RPO40) across four different time periods: training dose of the previous month with RPOs of the subsequent month (Monthly-analysis); training dose of the 8 weeks preceding All, Grand tours, One-day races with RPOs of these races. In Monthly-analysis, small positive relationships between all the training dose parameters, except for PI, and RPO1, RPO5, RPO20, RPO40 were found ($p \leq 0.001$). In Grand tours analysis, Z3 showed a positive association with RPO40 (r: 0.45; $p = 0.007$, moderate) and was positively related to RPO1 and RPO5 (r between 0.32 and 0.34; $p = 0.053$–0.059, moderate). PI was small positively related to RPO1 ($r = 0.29$, $p = 0.076$, small). In One-day races analysis, eTRIMP was positively related to RPO5 ($r = 0.30$, $p = 0.035$, moderate), Z1 negatively related to RPO40 ($r = -0.31$, $p = 0.031$, moderate), PI positively related to RPO5 ($r = 0.24$, $p = 0.068$, small) and Z2 was negatively related to RPO20 ($r = -0.29$, $p = 0.051$, small). A certain degree of responsiveness to training dose exists in professional road cyclists. To improve RPOs an appropriate preparation pattern seems to be increasing high intensity training for Grand Tours and fostering high intensity and overall training load (eTRIMP and TSS) in a more polarized-fashion for one-day races. Systematic and precise data collection during training and racing is highly advocated.

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INTRODUCTION

High-level endurance sports require a careful management of training dose with the right balance between training load and recovery to achieve the best performance [1, 2]. Modeling the dose-response relationship between training and performance is crucial because it allows to have greater proactivity (i.e. planning the input based on an expected response) in manipulating training dose, rather than reacting to a response (performance or test) [3].

In endurance sports, the training dose is commonly described by two main concepts: (i) training load (TL), i.e. variables which take into account both volume and intensity of the exercise session [4]; (ii) training intensity distribution (TID), i.e. how intensity is distributed over time during exercise [5]. Training dose could be distinguished as external or internal depending on whether it refers to the objective measure of the work that an athlete completes (i.e.: work, power, distance, velocity) or to the individual psychophysiological response to cope with the external load (i.e.: heart rate, perceived exertion) respectively [1, 6].

Despite evidence suggested that a higher overall training load [7] and a polarized training intensity distribution [8–11] could induce superior training adaptations and performance gains in non-professional endurance athletes, only a few studies have investigated the relationship between training load and performance in competitive athletes [3, 12]. Sanders et al. [3] monitored external and internal training load, measured as Bannister Training Impulse (TRIMP), Edwards TRIMP, Lucia TRIMP, individualized TRIMP, training stress score (TSS), session ratings of perceived exertion (sRPE), in a group of cyclists over 10 weeks during the preparation period. They observed a moderate increase in maximal oxygen consumption and power output at 2 $mmol \cdot L^{-1}$ and small increases in power output at 4 $mmol \cdot L^{-1}$, Wmax, mean absolute (W) and relative power output ($W \cdot kg^{-1}$) during the 8-min maximal power test repeated after the training period. From large to very large positive relationships between both external and internal training load and performance outcomes, measured as percentage changes in power outputs at blood

lactate concentration of 2 [mmol·l^{-1}] and 4 [mmol·l^{-1}] and 8-min maximal power test [3].

On the contrary, Foster et al. [12] did not find relationships between changes in time trial performance and training time or sRPE during a 6-week period in a group of cyclists, runners, and speed skaters. Interestingly, the same authors [12] monitored variations in training load and time trial performance in a small subgroup of athletes for a longer period and suggested the presence of a log curve relationship. Unfortunately, these data were just explorative and observational.

Making an attempt to describe the relationship between training dose and performance in professional road cycling, one of the main problems is to define performance among different races. In fact, in mass-start road cycling races, performance may not be simply identified with the order of arrival or with the time taken to complete the race [13]. In cycling, differently from some other endurance sport (i.e., running and swimming), different races have different distances, altimetric profile (flat, semi-mountainous, mountainous) and tactical dynamics [14]. Furthermore, personal race result is not the primary goal of gregarious cyclists, whose the main assigned task is helping the team leaders obtain the best placement possible at the finish line. Although extensive research has been conducted on the physiology of professional cyclists [15–17] and the exercise intensity and load during different cycling races [18–20], evidence regarding a clear link between training dose and racing performance seems to lack in the literature.

A possible solution could be using, as performance variables, the three main physiological laboratory parameters (maximal oxygen consumption, lactate threshold and efficiency) indicated by Joyner and Coyle as the main determinant factors in endurance sports [21]. However, it has not been clearly established whether physiological laboratory parameters are positively correlated or not with performance in professional mass-start road cycling races and so if they represent or not a valid and absolute performance parameter. Indeed, the few studies that reported a positive correlation between physiological laboratory parameters and performance in professional road cycling only considered time trial races [22]. Moreover, regularly performing lab tests with professional cyclists is very difficult due to the high number of travel and races (especially during the competitive period, from January to October), thus alternative cycling performance parameters would be preferable in order to build a dose-response model with a sufficient frequency of data collection also during the competitive period. In the last years, there has been a rapid increase in the capacity to capture real-time data through portable mechanical power meters [23]. They represent an important tool to monitor an index of physical performance such as power output both in races and daily training sessions. One of the most widely used power meters-derived physical performance indicator is the Record Power Profile [24]. It can be defined as the highest mean recorded power output (RPO) over a given duration) [24]. The commonly considered durations are: 1, 5, 30 and 60 s or 5, 10, 20, 30, 45, 60, 120, 180, and 240 min [24]. Van Erp and colleagues [25] recently suggested that RPOs could be used as physical performance parameters. They showed that RPOs over short durations (< 5 min) were higher for a top-10 result compared to a no top-10 in one team which achieved great success with sprinters [25]. Moreover, Leo and colleagues [26] showed how Record Power Profile combining both classic RPOs and RPOs after a total amount of work (1000–3000 kJ) predicted the final general ranking and UCI points scored during the multistage race Tour of the Alps.

Only two studies have investigated the relationship between training dose and Record Power Profile. Pinot and Grappe [27] reported a significant correlation between average weekly training load (sRPE) and annual increase in RPOs for durations between 5 minutes and 4 hours in a six-year (from the Under 19 to the Professional category) longitudinal case study on a world-class cyclist. Leo and Colleagues [28] reported a significant correlation between changes in training characteristics and changes in the power profile between early- and mid-season, but not between mid- and late-season in Under 23 cyclists. However, to our knowledge, no studies have investigated the relationship between training dose and RPOs within a relative short period (i.e.: 4–8 weeks) in professional cyclists.

Therefore, the aim of this study was to test whether there is a short-term correlation between training load measurements and training intensity distribution with some RPOs over different durations (between 1 and 40 min) in professional road cyclists. Definition of training dose-physical performance relationships may assist to develop training strategies more effectively to improve road cycling performance.

MATERIALS AND METHODS

Participants

Forty-six male professional cyclists, members of a World Tour professional cycling team, participated in this study (mean ± SD: 29.6: ± 5.0 yrs, height: 181.0 ± 5.9 cm, body weight: 71.4 ± 7.9 kg). Cyclists participating in the study won some of the most important road cycling competitions during the analyzed period: Olympic Games, World Championship, Giro di Lombardia and stages at Giro d'Italia, Tour de France and Vuelta a España. Annually, they rode an average of 28876 ± 3294 km, raced on average 74 days, and totalized 360 ± 493 UCI points.

Ethics

The study was approved by an independent review board in accordance with the Declaration of Helsinki for the Human Rights and a written informed consent was signed by all the participants prior to commencing the research as a common procedure for the World Tour professional cycling team they belonged to.

Data collection

Over a period of 4 consecutive seasons (from the 2016 to the 2019 season), heart rate (HR) and power output (PO) data were daily

collected during both training and races, using a HR chest belt and power meters (SRM GmbH, Jülich, Germany or DURACE FC-R9100-P, Shimano, Sakai, Osaka, Japan) that were zeroed before every ride. The accuracy of these power meters was reported in a previous study [29]. For each cyclist, data from one to four seasons were analyzed. Daily data were visually checked by three researchers with pluriannual experience in cycling training and data analysis. When a data was incorrect due to technological issues (i.e. unusual high or low GPS, heart rate or power data) or incomplete due to faults in the start and stop of the registration, it was excluded. The dataset was exported to Microsoft Excel and explored for data spikes that were manually eliminated. The inclusion criterium was the presence of at least 20 files per month for the analyzed period considered. The percentage of complete data was 85%.

Training Dose Indices: Training load and Training Intensity distribution

Training dose indices were monitored daily both during training sessions and races. Training load (TL) was measured using both heart rate and mechanical power, according to Edwards' TRIMP (eTRIMP) and Training Stress Score, respectively.

eTRIMP [30] was calculated based on the time spent in five HR zones, multiplied by a zone-specific arbitrary weighting factor and then summated to provide a total TRIMP score: zone 1: 50–59% HRpeak, weighting factor = 1; zone 2: 60–69% HRpeak, weighting factor = 2; zone 3: 70–79% HRpeak; weighting factor = 3; zone 4: 80–89% HRpeak, weighting factor = 4; zone 5: 90–100%; weighting factor = 5. HRpeak was defined as the highest HR registered by the participant during training or race of the analyzed season.

TSS [31] was calculated using the following formula:

$$TSS = [(t * NP^{TM} * IF^{TM})/(FTP * 3600)] * 100$$

where t indicates the duration of the training session in seconds, NP™ the normalized power [31] and IF™ the ratio between NP™ and the functional threshold power (FTP). FTP was defined as the highest power output a cyclist can maintain in a quasi-steady state for approximately 60 min [32]; it was estimated by subtracting the five percent to the highest mean of twenty minutes power output recorded in race or training (RPO20) [33] and was updated on an annual basis.

Training intensity distribution was calculated using a three-zone power-based model: FTP was used to separate Zone 2 and Zone 3, while the 80% of the FTP was arbitrarily used to separate Zone 1 and Zone 2 because it represents an exercise intensity close to the first ventilatory threshold. The Polarization Index (PI) [34] was the second index used to monitor the training intensity distribution. PI has the advantage of summarizing in a single variable the entire intensity distribution. Essentially, as this number increases, TID polarization increases (higher percentages of time spent in both high- (Z3) and low-intensity exercise (Z1), compared to training time spent in medium intensity exercise (Z2). In the same way, if PI decreases, TID polarization decreases (i.e. higher percentages of time spent in Z2). In the training dose-performance relationships, eTRIMP, TSS, Z1, Z2, and Z3, were calculated as the sum of the daily values registered during the period taken into consideration. PI was calculated considering the sum of Z1, Z2 and Z3 for the period analyzed according to the following formula [34]:

$$Polarization\ Index\ (AU) = \\ = log10(Zone1/Zone2 * Zone3 * 100)$$

where Zone is the fraction (given percentage/100) of the training volume in Zone 1, 2, and 3.

Physical Performance: Record Power Outputs (RPOs)

RPOs over four different time durations calculated using a cycling performance software analyzer (Today's Plan Pty Ltd, Australia) were taken into consideration: 1 min, 5 min, 20 min and 40 min (RPO1, RPO5, RPO20 and RPO40). As indicated by Pinot and Grappe [24] the term "record power output" is the highest power output produced by the cyclist and it is not his maximum achievable. Since in our database cyclists' weight was not regularly updated, RPOs were calculated only in term of absolute (W) and not relative ($W \cdot Kg^{-1}$) power.

Training Dose-Physical Performance relationship

The training dose variables were correlated to RPOs across four different time periods.

i. TL and TID of the previous month with RPOs recorded during the subsequent month (Monthly analysis).
ii. TL and TID of the 8 weeks preceding all goal races with RPOs recorded during these races (All races analysis);
iii. TL and TID of the 8 weeks preceding grand tours (Giro d'Italia,Tour de France, Vuelta Espana) goal races with RPOs recorded during these races (Grand Tours analysis);
iv. TL and TID of the 8 weeks preceding one-day goal races with RPOs recorded during these races (One-day races analysis).

The goal races were selected with the help of the team's head of performance who examined backwards the training programs of each cyclist.

Statistical Analysis

All training dose and physical performance parameters for all the four different time periods are presented as mean ± standard deviation. After normality of data was checked, multilevel mixed-model analysis (R: A Language and environment for statistical computing, Vienna, Austria) was employed to explore the relationship between TL and TID measures (eTRIMP, TSS, Z1, Z2, Z3, PI) with performance measures (RPO1, RPO5, RPO20, RPO40) in all the four time frames (Monthly, All races, Grand Tours, and One-day goal races analyses). The training related measures were included in the mixed model as

a fixed effect (the variable on which we want the inference being made), while individual cyclist was included as a random effect to take into account the dependency of the repeated measures. All models included random intercept and random slope terms to account for potential inter-individual variability in the baseline performance and different responsiveness to training load, respectively, as previously done in elite sport analyses [35]. Alpha level was set *a priori* at 0.05. Effect sizes were calculated using Cohen's d [36]. Uncertainties in the correlation coefficients are presented as 95% confidence intervals and interpreted as trivial (0–0.09), small (0.1–0.29), moderate (0.3–0.49), large (0.50–0.69), very large (0.70–0.89), nearly perfect (0.90–0.99), perfect (1.00) [36].

From the statistical analysis emerged that p values of some small-to-moderate relationships were included between 0.05 and 0.1. For this reason, *a posteriori* an alpha level of 0.1 was considered to include among the Results p levels < 0.1 and discuss those relationships accordingly. It is acknowledged that for those relations the chance of occurring a Type I error was inflated to 10%.

RESULTS

All the training dose and physical performance parameters for the four different time periods considered are presented in Table 1.

Monthly analysis

There were significant ($p \leq 0.001$) small (r between 0.10 and 0.29, Fig 1) positive relationships between all the training load measures, except for PI, and all the four absolute RPOs (RPO1, RPO5, RPO20, RPO40). PI showed small significant positive associations with RPO1 ($r = 0.10$, $p = 0.040$) and RPO40 ($r = 0.15$, $p \leq 0.001$).

All races analysis

There were no significant relationships between any of the training load variables and RPOs (r between -0.12 and 0.16, all $p > 0.079$, Fig 2)

Grand Tour analysis

Z3 showed a moderate positive associations with RPO40 ($r = 0.45$, $p = 0.007$). With alpha set at 0.1, Z3 was positively related to RPO1 and RPO5 (r between 0.32 and 0.34, $p = 0.053$–0.059, moderate). Similarly (alpha at 0.1), PI was positively related to RPO1 ($r = 0.29$, $p = 0.076$, small,). There were no relationships between any of the others training indices and RPOs (Fig. 3).

One-day goal races analysis

eTRIMP was positively related to RPO5 ($r = 0.30$, $p = 0.035$, moderate). Z1 was negatively related to RPO40 (r = -0.31,

TABLE 1. Training dose and physical performance parameters for the four time periods considered: Monthly Analysis, All Races Analysis, Grand Tours Analysis and One-day Races Analysis. Data are presented as mean ± SD.

	Time periods	Monthly Analysis 4 weeks	All Races Analysis 8 weeks	Grand Tours Analysis 8 weeks	One-day Races Analysis 8 weeks
Training Dose	**Time (hr)**	78 ± 7	150 ± 16	151 ± 19	148 ± 21
	eTRIMP (AU)	8573 ± 1568	17041 ± 2959	17020 ± 3473	16657 ± 3664
	TSS (AU)	3290 ± 513	6536 ± 955	6481 ± 885	6547 ± 1245
	Z1 (hr)	54 ± 8	104 ± 15	106 ± 18	98 ± 16
	Z2 (hr)	12 ± 3	22 ± 6	22 ± 7	22 ± 7
	Z3 (hr)	6 ± 2	11 ± 4	11 ± 4	13 ± 5
	Z1 (%)	76 ± 5	76 ± 5	76 ± 5	74 ± 5
	Z2 (%)	16 ± 3	16 ± 3	16 ± 4	16 ± 4
	Z3 (%)	8 ± 2	8 ± 3	8 ± 3	9 ± 3
	PI (AU)	1.58 ± 0.12	1.58 ± 0.13	1.55 ± 0.13	1.61 ± 0.14
Physical Performance	**RPO1 (W)**	591 ± 61	585 ± 56	614 ± 73	575 ± 56
	RPO5 (W)	434 ± 33	435 ± 36	452 ± 35	427 ± 32
	RPO20 (W)	363 ± 28	399 ± 29	392 ± 26	350 ± 28
	RPO40 (W)	330 ± 25	366 ± 26	363 ± 22	324 ± 28

Abbreviations: TIME, total exercise time; eTRIMP, Edwards TRIMP; TSS, Training Stress Score; Z1: time spent in Zone 1; Z2: time spent in Zone 2; Z3: time spent in Zone 3; PI: polarization index; RPO1–RPO5–RPO20–RPO40: Record Power Output for 1–5–20–40 minutes durations.

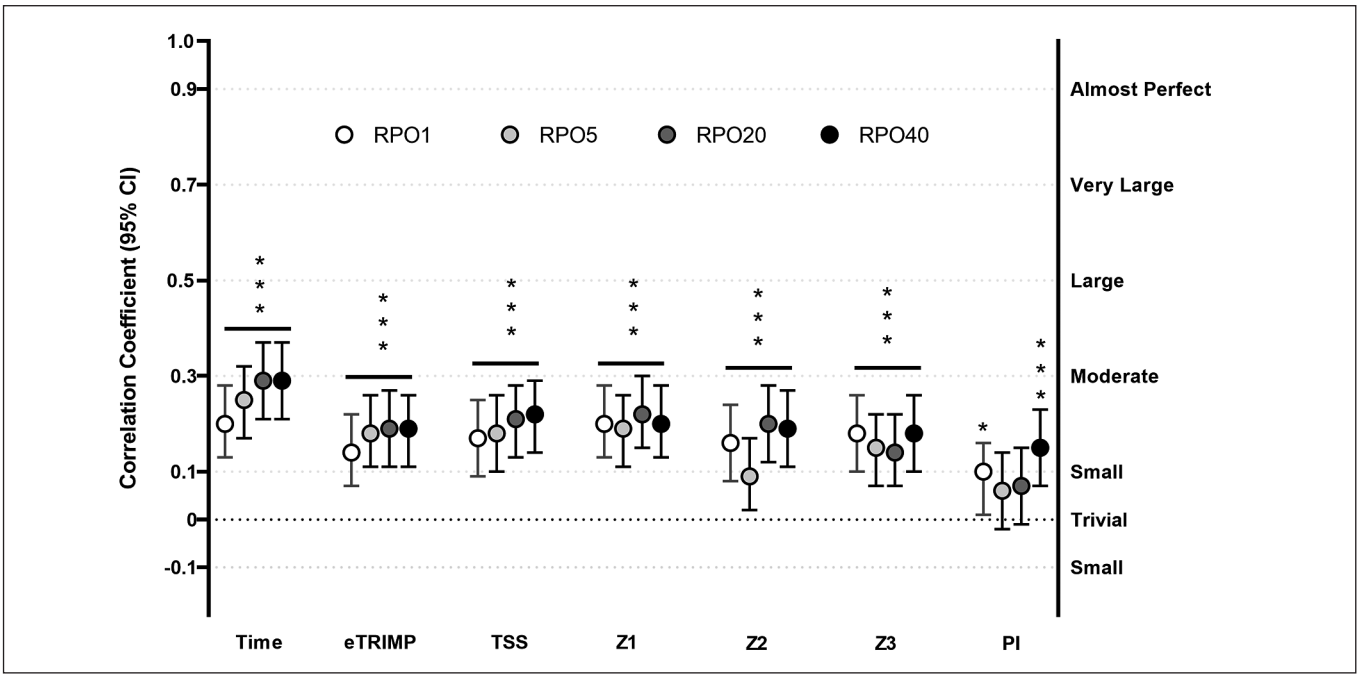


FIG. 1. Relationship between monthly training load and training intensity distribution and Record Power Outputs for four different durations (1, 5, 20, and 40 min) registered in the subsequent month. Correlation coefficients (r) are presented with 95% confidence intervals (CI). Abbreviations: TIME, total exercise time; eTRIMP, Edwards TRIMP; TSS, Training Stress Score; Z1: hours spent in Zone 1; Z2: hours spent in Zone 2; Z3: hours spent in Zone 3; PI: polarization index; RPO1 – RPO5 – RPO20 – RPO40: Record Power Output for 1–5–20–40 minutes durations. Number of observations = 1278; Riders: 46; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

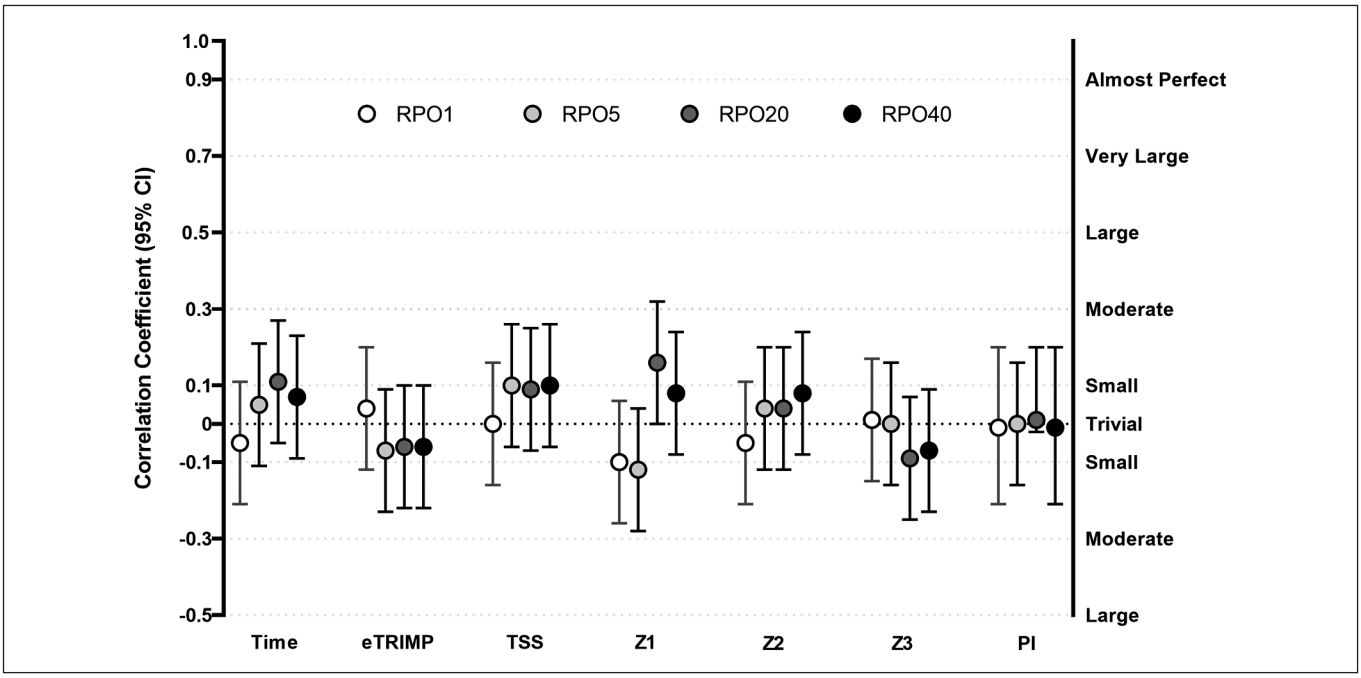


FIG. 2. Relationship between training load and training intensity distribution of the 8 weeks preceding all goal races (A) and absolute Record Power Outputs registered during these races. Abbreviations: TIME, total exercise time; eTRIMP, Edwards TRIMP; TSS, Training Stress Score; Z1: hours spent in Zone 1; Z2: hours spent in Zone 2; Z3: hours spent in Zone 3; PI: polarization index; RPO1 – RPO5 – RPO20 – RPO40: Record Power Output for 1 – 5 – 20 – 40 minutes durations. Number of observations: 276; Riders: 30.

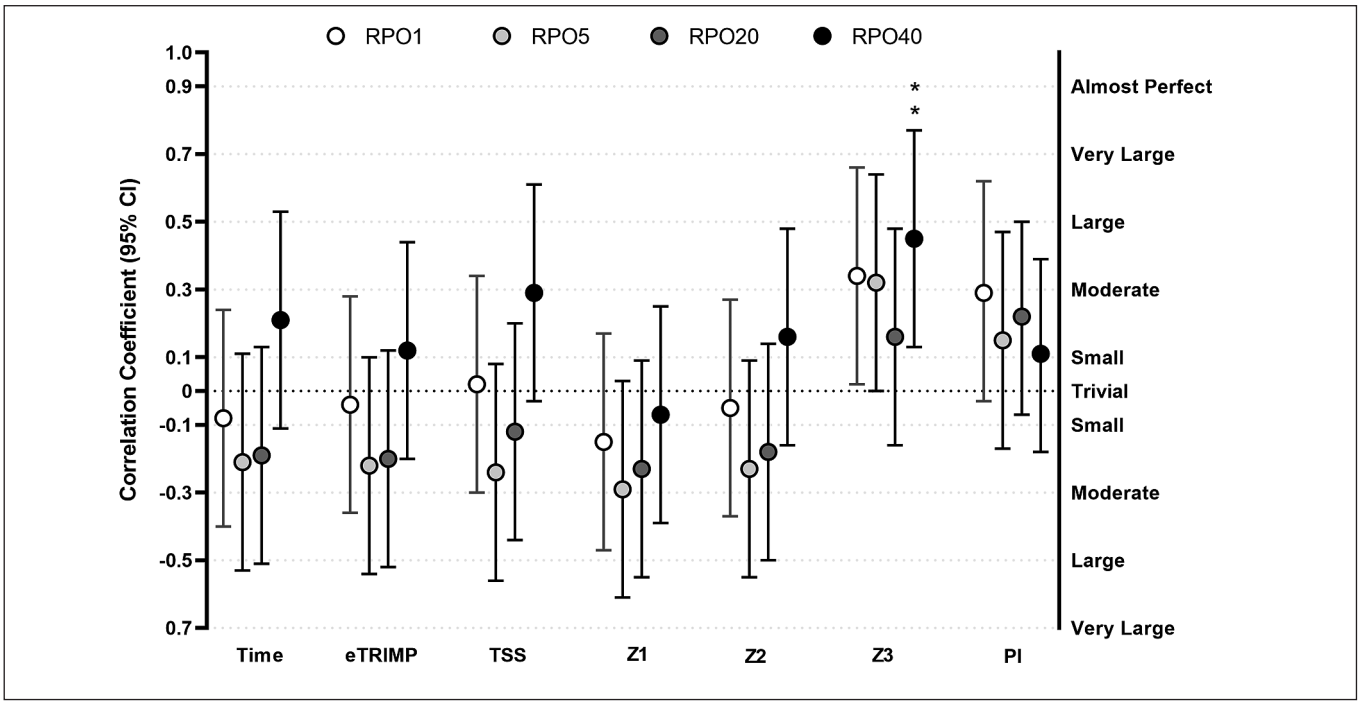


FIG. 3. Relationship between training load and training intensity distribution of the 8 weeks preceding grand tours goal races and absolute Record Power Outputs registered during these races. Abbreviations: TIME, total exercise time; eTRIMP, Edwards TRIMP; TSS, Training Stress Score; Z1: hours spent in Zone 1; Z2: hours spent in Zone 2; Z3: hours spent in Zone 3; PI: polarization index; RPO1 – RPO5 – RPO20 – RPO40: Record Power Output for 1–5–20–40 minutes durations. Number of observations: 74; Riders: 21; ** = $p < 0.01$.

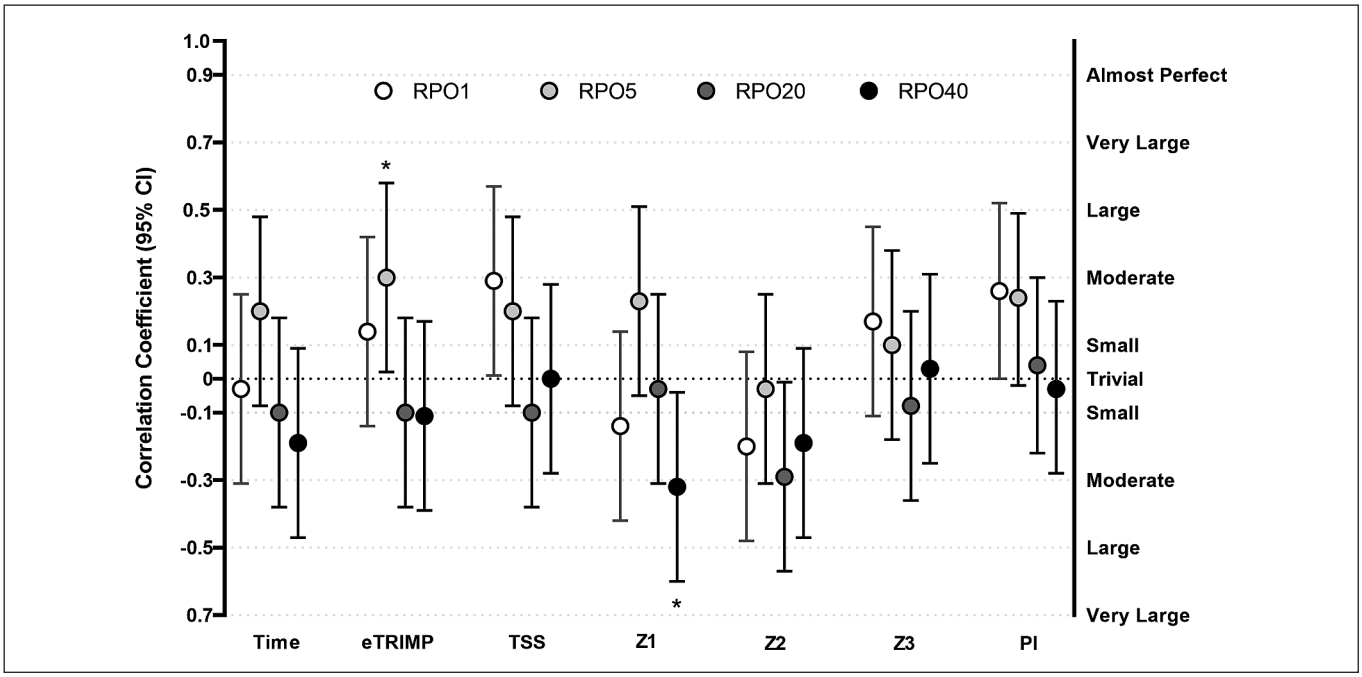


FIG. 4. Relationship between training load and training intensity distribution of the 8 weeks preceding one-day goal races and absolute Record Power Outputs registered during these races. Abbreviations: TIME, total exercise time; eTRIMP, Edwards TRIMP; TSS, Training Stress Score; Z1: hours spent in Zone 1; Z2: hours spent in Zone 2; Z3: hours spent in Zone 3; PI: polarization index; RPO1 – RPO5 – RPO20 – RPO40: Record Power Output for 1–5–20–40 minutes durations. Number of observations: 94. Riders: 18; * = $p < 0.05$.

p = 0.031, moderate). When alpha was set at 0.1, PI was positively related to RPO5 (r = 0.24, p = 0.068, small) and Z2 negatively related to RPO20 (r = – 0.29, p = 0.051, small). There were no relationships between any of the others training indices and RPOs (Fig. 4).

DISCUSSION

The main findings of the present study highlighted that higher monthly training dose indices were associated with higher indices of physical performance (i.e. RPOs) recorded in the next month, however the magnitude of the relationships found were small. Only trends and a few significant small-positive relationships were found between some training dose indices and some indices of physical performance achieved during all races, Grand Tours, and one-day goal races. Descriptive data seems to be in accordance with previous studies on professional road cyclists regarding both training exposure (~900–950 hours per year) [27] and RPOs for the difference time durations [24]. In a recent interesting study, Emig and Peltonen [37] performed a big data analysis (≈14,000 individuals) correlating training dose and performance in runners of different performance levels. Interestingly, they observed an initial linear increase of performance with TRIMP, a plateau around a certain value of TRIMP, and then a statistically significant drop which may be due to overtraining. While the cited study comprehended a wide range of training loads and performance levels, we considered only a narrow selection of performance level, which corresponds to the highest one (i.e. professional level). Hence, it might be that our study considered only the plateau section of Emig and Peltonen's relationship, which represents professional athletes working at very high workloads, near the highest point of functional over-reaching [38] just before the threshold of overtraining, [39] and already possessing very high level of physical performance. This might be the reason why we observed only trends or small relationships between training dose and performance. In addition, the very large difference in the numerosity of the samples between the two studies can be a further reason that can explain the diversities of the main results.

Our findings are different from previous studies investigating the relationship between training load and performance in competitive cyclists. Sanders and Colleagues [3] found large to very large relationships between training load and performance. This could be due to the different performance measures utilized that have both pros and cons to bear in mind: a 8-min time trial test, in the study by Sanders et al. [3], which is standardized but less ecological, and field RPOs in the present study which are ecological but less standardized and need to be critically evaluated regarding validity and reliability [40]. Furthermore, in the present study, data from *All races*, *Grand Tour, One-day goal races analyses* were all collected during the competitive periods of the seasons, while Sanders and colleagues [3] studied only the pre-season training period. This latter typically consists in low-intensity high-volume training and usually changes in performance are greater in this period compared to those achieved in all the other periods of the seasons [41]. On the other hand, the competitive period of professional road cyclists typically involves more time spent at high-intensity and more periods of high physical and psychological stress [42]. It is therefore reasonably fair assuming that the detection of relationships between changes in performance and training dose is easier in the first scenario proposed by Sanders et al. [3] than in ours. Accordingly, Leo and Colleagues [28], in the other study correlating training dose and performance on competitive cyclists, reported as changes in training characteristics correlated with changes in the power profile in early- and mid-season, but not in late-season in U23 competitive cyclists.

Monthly analysis

Differently from other analyses, the monthly analysis highlighted a significant positive effect of all training dose variables on RPOs. This may be due to the much higher number of observations included in the Monthly analysis (n = 1278) compared to All races (n = 276), Grand tour (n = 74) and One day (n = 94) goal races analyses, which could have facilitated the achievement of statistical significance. In addition, professional road cyclists' training workload presents within season fluctuations according to the different macrocycles (e.g. general base preparation, racing, event preparation) [43]. In this perspective, while the three goal races analysis included only "racing" and "event preparation" macrocycles, Monthly analysis incorporated also the "general base preparation" macrocycle and thus probably included more workload fluctuations compared to other analysis, increasing the chances to observe significant relationships between training dose and physical performance parameters. The mixed modelling approach used in the present study may be considered an appropriate tool to detect this periodical fluctuation during the seasons within and between individuals [44].

It should be bore in mind that elite cyclists, such as those considered in the present study, are usually subjected to very high training loads all the yearlong and for many years [45]. This issue might influence the detection of a relationship between training dose and physical performance as they may already have reached the plateau of their maximum physical performance potential. Despite this, the significant positive effects of training dose on absolute RPOs could suggest that a certain degree of responsiveness to training dose persists even in professional endurance athletes.

All races, Grand Tour, One-day goal races analyses

In Grand Tour analysis the moderate positive relations of RPO40 to Z3 and trends to moderate positive relations of RPO1-5 to Z3, could suggest to foster high-intensity (Z3) training during the preparation of these competitions. This may happen because excessively extensive loads may lead to a reduction in the activity of the pineal gland, adrenal glands, and testis which are already under great stress in these kind of competitions [46], where cyclists perform twenty-one consecutive days of race with only 2–3 days of rest. However, this should be contextualized within the very high exercise volume (about

22 hours a week) performed by the professional road cyclists analyzed in this study, and this should not be misunderstood as a recommendation to perform low volume training programs in the eight weeks preceding cycling grand tours. In One-day races analysis, the moderate positive relations of eTRIMP with RPO5, of Z1 with RPO40 and of PI – with RPO1, and the tendency of Z2 to be small negatively related to RPO20, could suggest to foster high complessive training load (eTRIMP) with a more polarized intensity distribution in preparation of these competitions. This reflects the physiological model of these races, which are long races not including long climbs with the final result often decided through explosive short duration efforts (i.e < 5') . Thus, those races could require both a high level of stamina and anaerobic qualities, which may require high training load with a certain amount of high intensity training (high eTRIMP with a more polarized intensity distribution).

However, all these considerations might be seen more as speculations instead of factors supported by strong evidence, as they are derived from the observation of trends and/or relationships with very large confidence intervals. A qualitative and quantitative representative example of all observed significant relationships and trends (Fig. 5) shows a very high inter- and intraindividual variability. Figure 5 represents an example of each cyclist's variations in RPO1 in grand tours following an increase of one hour spent in Z3 (the so-called: "fixed effect") in the previous 8 weeks. With regards to inter-individual variability, it can be observed that, although the average results highlighted a tendency to a positive effect of Z3 on RPO1, different cyclists showed different average behaviors with someone even recording a negative average fixed effect (i.e., they generally worsen their RPO1 after an increase of Z3). For what concerns intraindividual variability, it can be observed that each cyclist's fixed effect confidence intervals are greater than the mean fixed effect itself, ranging from positive to even negative values. This suggests that at individual level an increase of training load could lead both to improve and to worsen RPOs, both in different cyclists and even within the same cyclist. This might suggest that professional cyclists are already exposed to high

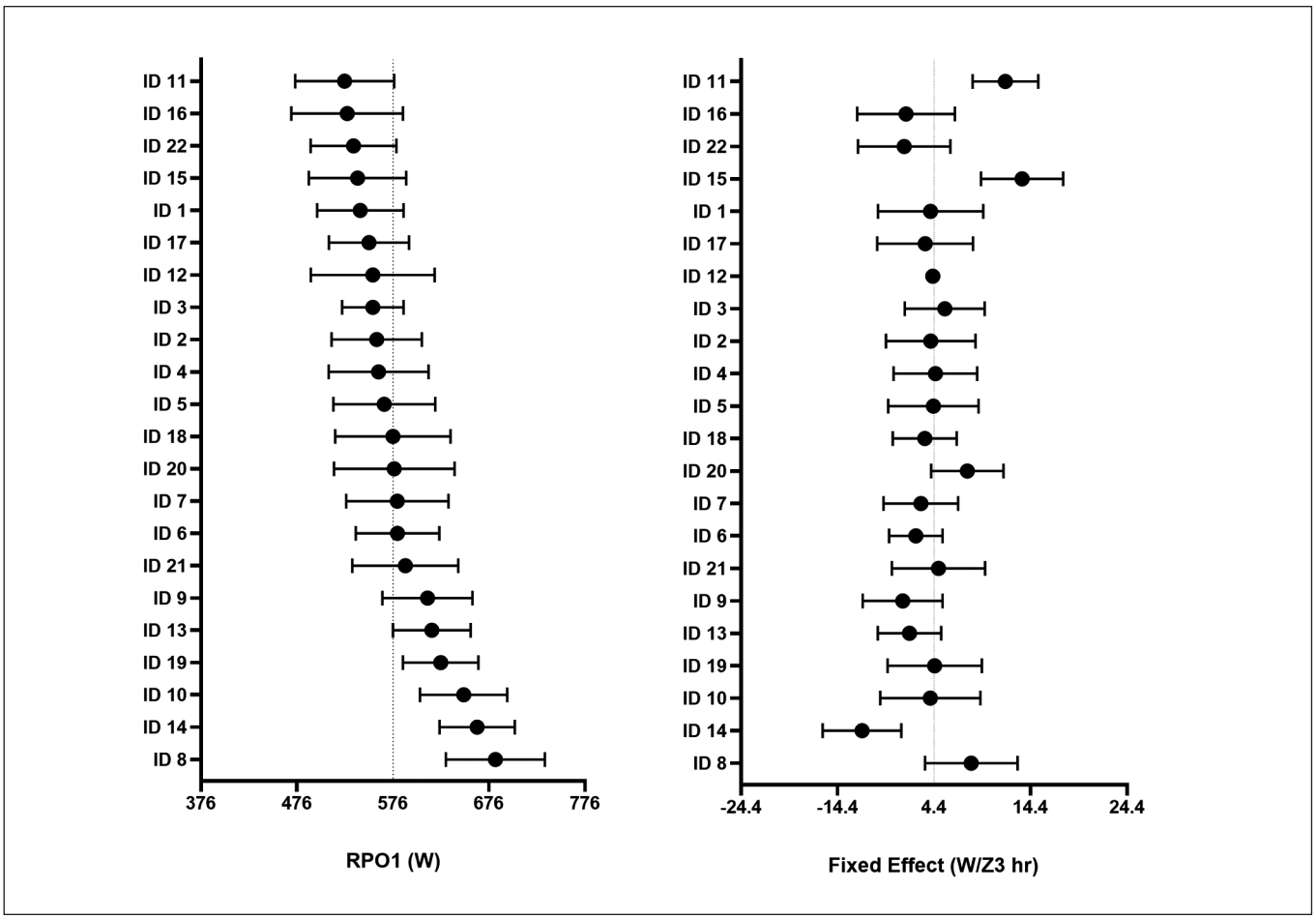


FIG. 5. Individual variations in RPO1 for Grand Tours analysis following an increase of one hour spent in Z3 ("fixed effect") during the eight weeks preceding grand tours. Each subject's fixed effect is represented as mean (black circles) and standard deviation(lines). Abbreviations: Z3: hours spent in Zone 3; RPO1: Record Power Output for 1-minute duration.

average level of training loads, and thus a further increase in physical stress could lead in some cases to non-functional overreaching and a consequent decrease in performance [39].

Among the factors that may have contributed to the high variability of some results, there is certainly the issue that RPOs can be influenced by other factors not included in the analysis, such as the category of the race [25] (Monuments, World Tour, Hors Catégorie, category 1) and the race type (flat, semi-mountainous, mountainous) [14]. In addition, in the present study, psychological factors were not considered and analyzed but it must be acknowledged that they can represent an important stimulus for the achievement of RPOs.

Limitations and future directions

Important limitations of the present study, that might represent threats to its validity, must be acknowledged. First, a retrospective analysis was performed on a database not collected and daily checked for scientific purposes, consequently it had some missing data we tried to solve using narrow inclusion criteria. In addition, in Grand tours and One-day races analyses, a low number of observations were recorded for some subjects. Regarding this issue, possible solutions for future studies could be a daily controlled data collection and an increase in the number of data available by extending the data collection over multiple years or by including more than one team like in another research [37].

From a conceptual point of view, the use of RPOs as a performance measure remains questionable. In fact, RPOs could be daily influenced by factors such as: motivation, tactical factors, role of the cyclist, category of the race, and race type. This may have mixed up the results in All-races and One-day races analyses. One of the possibilities to overcome this issue is to introduce some of these factors influencing RPOs as further covariates in the model: the role of the cyclist (leader, domestique, etc....), category of race (Monuments, World Tour, Hors Catégorie, category 1), race type (flat race, semi mountainous stage, mountainous stage). In addition, in Grand tours, the ability to repeat high-level performances for consecutive days could be a more valid performance index than considering one isolated best performance such as RPOs. Furthermore, RPOs does not consider repeated efforts over time which could also be crucial in deciding race results. Regarding this, introducing a new power meters derived performance parameter, ordering power files in descending order and then calculating the average of the first hour, can be one of the possible solutions. It is suggested that future studies look also at different methods to express training intensity distribution [43], other than those used in the present study, to describe their relationships with performance indices.

Unfortunately session-RPE [47] was not included within the training dose parameters as it was not systematically collected by the team staff. Session-RPE is an internal load measure considering not only physiological factors but also the psychological ones [48] and it has been shown to be more sensitive to accumulated fatigue than HR [49]. Since the neurobiological context, in turn, greatly influenced by the background levels of psycho-emotional stress, influences fitness adaptations subsequent to imposed training stressors [50], session-RPE could be a more sensitive workload measure compared to HR- and power-based load parameters when investigating the relationship between training dose and performance.

Lastly, strength training in the gym was not included in training dose as it was not systematically recorded. Since it has been shown as strength training induces functional adaptations promoting cycling performance [51] future studies will also have to consider gym's strength training load when investigating the relationship between training dose and performance in road cyclists.

CONCLUSIONS

This explorative study is the first that tries to understand whether a clear relationship exists between training load and performance in professional road cyclists across all season's periods.

Monthly analysis highlighted a significant positive effect of all training dose variables on RPOs suggesting that a certain degree of responsiveness to training dose persists even in professional endurance athletes.

Mixed results with very high levels of intra- and inter-individual variability were found in the analysis on goal races (all races, grand tours, one-day) with trends to significance which may suggest: (i) increase high intensity training (Z3) in preparation of grand tours; (ii) fostering high intensity training (Z3) and high complessive training load (eTRIMP and TSS) with a more polarized distribution in preparation of one-day races.

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Conflict of interest

The authors declare no conflict of interest.

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Management of proximal rectus femoris injuries – do we know what we're doing?: A systematic review

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ABSTRACT: Rectus femoris (RF) injury is a concern in sports. The management RF strains/tears and avulsion injuries need to be clearly outlined. A systematic review of literature on current management strategies for RF injuries, and to ascertain the efficacy thereof by the return to sport (RTS) time and re-injury rates. Literature search using Medline via PubMed, WorldCat, EMBASE, SPORTDiscus. Eligible studies were reviewed. Thirty-eight studies involving hundred and fifty-two participants were included. Majority (n = 138; 91%) were males, 80% (n = 121) sustained RF injury from kicking and 20% (n = 31) during sprinting. The myotendinous (MT), (n = 27); free tendon (FT), (n = 34), and anterior-inferior iliac spine (AIIS), (n = 91) were involved. Treatment was conservative (n = 115) or surgical (n = 37) across the subgroups. 73% (n = 27) of surgical treatments followed failed conservative treatment. The mean RTS was shorter with successful conservative treatment (MT: 1, FT: 4, AIIS avulsion: 2.9 months). Surgical RTS ranged from 2–9 months and 18 months with labral involvement. With either group, there was no re-injury within 24 months follow-up. With low certainty of evidence RF injury occurs mostly from kicking, resulting in a tear or avulsion at the FT and AIIS regions with or without a labral tear. With low certainty, findings suggest that successful conservative treatment provides a shortened RTS. Surgical treatment remains an option for failed conservative treatment of RF injuries across all subgroups. High-level studies are recommended to improve the evidence base for the treatment of this significant injury.

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INTRODUCTION

There appears to be a high incidence of muscle injuries in elite sports [1–4]. Most of these injuries occur in the lower extremities (68–88%), with 25% being indirect (non-contact) thigh muscle strains [2, 5–7]. The total time lost from activity due to muscular injury in male soccer players is estimated at around 20–37% at professional level, [1, 3, 8–14] and 18–23% at amateur level [15, 16] hence a major concern for teams and players [1, 3, 10, 17]. Quadriceps strains are prevalent in sporting codes involving kicking and repetitive sprinting actions such as soccer and rugby [2, 3, 17–19]. Ekstrand *et al.* [3] found these injuries to be the second most prevalent muscle injury in professional soccer players after hamstring injuries, leading to more missed games than other thigh injuries such as hamstring and groin injuries. A high re-injury rate (17%) is also reported [3].

The rectus femoris (RF) is a bi-articular muscle situated anteriorly on the quadriceps muscle group. It assists in knee extension, hip flexion and stabilization of the pelvis on the femur when bearing weight [20]. Its high proportion of type II fibres (65%) makes the RF highly susceptible to injury [17, 21]. A kicking injury mostly involves the thigh of the kicking leg and is frequently diagnosed as a RF muscle strain, [17, 22] often injured during eccentric loading [17, 23]. The common site of RF injuries is intramuscular strains of the musculotendinous junction [17, 23]. Serner *et al.* [22] found that a vast majority of RF injuries (94%) involved the proximal tendons, more commonly affecting the indirect tendon (56%) than the direct tendon insertion [22].

Following muscle injury there is a gradual healing process, to regain muscle strength to pre-injury level [24]. Severe re-injury may be incurred post return to sport (RTS) without optimal regain of tensile strength [25, 26]. The highest risk is the initial 2 weeks after RTS [24, 27]. Despite efforts to improve evidence on the management of muscle injuries, (British Athletics hamstring studies) [28, 29] there is still little scientific basis or evidence for the majority of the treatment protocols [30].

In the sports medicine outpatient setting the senior author has identified RF to be a common injury of concern alongside hamstring and groin injuries. Despite this, there is no standardized approach to treating RF injuries in elite athletes [31]. This is undesirable given the medical and socioeconomic burden for the injured player and the team as the safe RTS post-injury remains to be scientifically evaluated [32, 33]. The management of RF injuries has historically been either successful conservative treatment or surgical treatment following failed conservative treatment. This approach, however, remains controversial with no high-level evidence supporting either a conservative or a surgical approach as superior. Tailored evidence-based treatment approach for RF injuries would be efficient in addressing this shortfall in the sports medicine setting. It will also allow a practical and timely application of treatment principles for RF injuries to assist in successful RTS.

RF injury is subgrouped to guide on the specific anatomical management strategy. The subgroups include myofascial (MF) strains, myotendinous (MT) strains, free tendon (FT) tear and anterior inferior iliac spine (AIIS) avulsion. AIIS represents the bony origin of the direct head RF. The origins of the two RF tendons extend distally as the FT region end as the MT region where the tendon transitions into muscle. The MF injury involves any region of the RF with fascial extension [20].

The purpose of this systematic review is to report the existing best evidence on current management strategies for RF injuries based on the current concepts in management of RF injuries [20, 34]. We ascertained the efficacy of these management strategies as measured by time to RTS and re-injury rate.

MATERIALS AND METHODS

This literature review was conducted according to the PRISMA statement [35]. The protocol was registered with the International Prospective Register for Systematic Reviews (PROSPERO, Registration number: CRD42020180962). The systematic review was conducted on CADIMA version 2.2.1, an open-access online evidence synthesis and data extraction tool that facilitates the reporting and conduction of systematic reviews.

Literature search strategy

A comprehensive literature search was conducted electronically between 31/01/2020 and 30/06/21 using the following databases: MEDLINE via PubMed, WorldCat, EMBASE, SPORTDiscus. Combinations of the following keywords were applied, using OR / AND / NOT operators: "rectus femoris injury / anterior inferior iliac spine avulsion / sport / athlete / management / treatment". The details of the search strategy are outlined in Supplementary Table S1.

Study selection criteria

Study selection was performed by two independent reviewers (LB and LH). The selection criteria were as outlined below:

– Randomised control trials (RCT) and observational studies (cohort studies, case-control studies, case series, case reports) published between 1979 and 2021.
– Athletes who were diagnosed with RF injury with or without an AIIS avulsion, from a kicking or sprinting mechanism, confirmed with imaging.
– Male or female athletes (12–45 years old).
– Acute, chronic, and re-injuries.
– The management/treatment strategies outlined (i.e., conservative, or surgical).
– RTS time and/or re-injury follow-up outcome
– Articles written in English.

All studies were reviewed in parallel by title/abstract and by full text by two independent reviewers (LB and LH). Eligible studies were independently selected. Disagreement regarding the inclusion of a paper was resolved using a mediator (AS).

Quality assessment

We ranked the level of evidence for all included studies from I to V according to the Oxford Centre for Evidence-Based Medicine (OCEBM) criteria [36] (Supplementary Table S2). The methodological quality assessment of each included study was then assessed by two authors (LB and LH) independently using a modification of the Newcastle Ottawa scale for evaluating the methodological quality of case reports and case series [37]. Each applicable question was answered "YES" or "NO" and scored as 'high quality' when all 5/5 criteria were fulfilled, 'moderate quality' when 4/5 criteria were fulfilled and 'low quality' when only 3/5 or fewer criteria were fulfilled [38]. Questions 4, 5 and 6 were excluded since they apply to studies involving adverse drug reactions [37]. Study assessment included (a) representativeness of the case(s), (b) ascertainment of exposure, (c) ascertainment of outcome, (d) adequacy of follow-up, and (e) adequacy of reporting. The results are available in Supplementary Table S2.

The quality assessment and a consistency check were conducted on CADIMA. Differences in individual assessments were discussed and consensus was reached between the two reviewers in all cases.

Data extraction

The two independent reviewers conducted the data extraction process in parallel on CADIMA [39]. Additional articles from other sources were incorporated.

Article information was extracted including the study details (title, authors, year, design, and aim), participant characteristics (number of participants, age, gender, sporting activity, mechanism of injury, and diagnosis and diagnostic modalities), and treatment details (non-surgical vs. surgical), surgical indications and time from injury to surgery, time from injury to RTS (for conservative treatment), or time from surgery to RTS (for surgical treatment), and re-injury occurrence.

Injury classification

Based on reported details in the studies, the RF injuries were divided into four subgroups: [40, 41] 1) myofascial (MF) injuries, 2) myotendinous (MT) injuries, 3) free tendon (FT) injuries, and 4) anterior inferior iliac spine (AIIS) avulsion fractures. Injury combinations were also reported if it was described like that in an included study.

RESULTS

Literature search

The initial database search yielded 285 records and a further 11 records were identified from other sources. Duplicates were removed and the title and abstracts of 258 studies were evaluated. We excluded 187 records based on study selection criteria, leaving 71 records for full-text evaluation. After a full-text review, 38 studies were included. Reasons for exclusion following full-text review are listed in Supplementary Table S3, and a flow diagram of the study selection process is presented in Figure 1. A consistency check on the eligibility criteria application by both reviewers yielded a Kappa value of 0.94, which is considered 'excellent agreement'. Inclusion disagreements were settled by discussion and consensus with the moderator (AS) in seven studies.

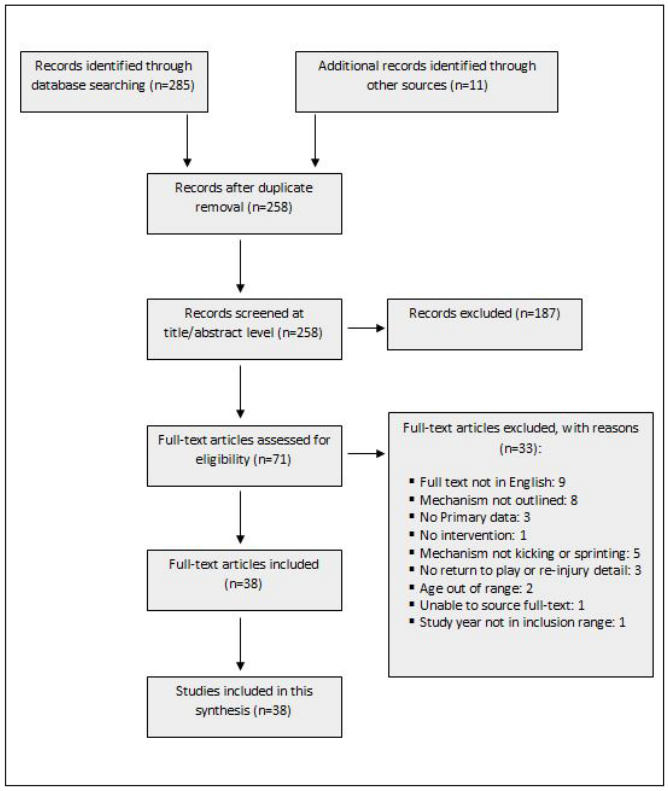


FIG. 1. Flow diagram of the study selection process.

Description of included studies

Study design & quality

Of the 38 included studies, 13 were case series and 25 were case reports, and all studies were ranked at an OCEBM level of IV. Assessment of methodological quality revealed fourteen of the studies as high quality (36.8%), [21, 42–51] six as moderate quality (15.8%) [52–57] and eighteen as low quality (47.4%) [58–74] (Supplementary Table S2). The risk of bias is inverse to the study quality.

Study participants

From 38 studies 152 participants were included. The majority (n = 138; 91%) was males sustaining RF injuries during either soccer, American football, athletics, softball, baseball, or rugby (Table 1).

Summary of injury detail of participants

Amongst the 152 participants, 80% (n = 121) sustained RF injury as a result of kicking [21, 43–53, 55, 58, 60, 61, 63–69, 71–73, 75–77] and the remaining 20% (n = 31) were injured during sprinting [21, 42, 49, 54, 56, 57, 60–62, 74, 75, 77].

Following the RF injury classification model, [40, 41] the mechanism of injury, diagnostic modality, intervention, and primary outcome measure for each RF injury sub-group (MF, MT, FT and AIIS avulsion) amongst the included studies are described in Table 1.

Myofascial injuries

No isolated MF injuries were reported in the included studies. All MF injuries reported were combined injuries with a labral tear and either a MT, [58] FT or AIIS injury [49, 63].

Myotendinous injuries

Twenty-seven athletes in seven studies suffered a MT injury [48, 58, 68, 69, 72, 77, 78] mainly sustained from playing soccer (74%), and American football (19%).

Mechanism of injury: A variety of MT injury patterns relates to kicking, with 88% resulting in a tear at either the central aponeurosis (n = 4) [48] or MT junction (n = 11) [68, 69, 72, 78]. All MT injuries from the sprinting group occurred at the MT junction [77].

Diagnostic modality: All athletes were evaluated using either a Magnetic Resonance Imaging (MRI) [48, 58, 60, 68, 69] or an ultrasound (US) scan [72, 78].

Intervention: Conservative approach or surgical treatments were reported for MT injuries but no standardized management amongst the studies was reported (Table 2).

Three studies (n = 18) reported conservative management [72, 77, 78]. In these athletes the majority sustained a form of MT tear during kicking (66%, n = 12). The details of the conservative program reported varied with either an eccentric program [72]

TABLE 1. Summary of studies included.

Injury type (Number of studies)	Number of athletes (n)	Type of sport (n)	MOI (n)	Diagnostic Modality (n)	Intervention (n)	Primary outcome measure (RTS time, Re-injury)
Myotendinous [48, 58, 68, 69, 72, 77, 78] (n = 7)	27	Soccer (20) American football (3) Softball (2) Baseball (2)	Kicking (17) Sprinting (10)	MRI (15) US (12)	Conservative (18) Surgical (9)	RTS: Conservative: 1 month (4 weeks) Surgical: 6 (2–9) months Re-injury: None in 24 months
Free tendon [21, 43–45, 49, 51, 61–63, 79] (n = 10)	34	Soccer (20) American football (12) Athletics – Track (2)	Kicking (21) Sprinting (13)	US (1) MRI (30) MRA (3)	Conservative (17) Surgical (17)	RTS: Conservative: mean 14.5 (4–36) weeks Surgical: 4.6 (2–9) months – Surgery as first line: 3 months – Surgery (failed conservative): 5 months Re-injury: None between 2 and 35 months follow up
Avulsion fracture [42, 46, 47, 49, 50, 52–57, 64–67, 71, 73–76, 80, 81] (n = 23)	91	Soccer (26) Athletics (6) Rugby (1) Fighting sport (1) Gym (1) Not specified (56)	Kicking (83) Sprinting (8)	X-ray (69) CT Scan (7) MRI (15)	Conservative (80) Surgical (11)	RTS: Conservative: 2.9 (1.5–9) months Surgical: 6 (1.5–18) months Re-injury: None between 12 and 24 months follow up

No isolated myofascial injuries were reported in the included studies. n = number of athletes; MOI = Mechanism of injury; MRA = Magnetic resonance arthrogram; MRI = Magnetic resonance imaging; US = Ultra sound; CT = Computerized tomography scan; RTS = Return to sport.

or an US-Guided Percutaneous Needle Electrolysis (PNE) protocol [78] (Table 2).

There were five studies reporting on athletes (n = 9) with MT injuries who underwent surgical intervention [48, 58, 68, 69, 77]. The main mechanism of injury was kicking (89%, n = 8) and they sustained some form of MT tear [3, 6, 7, 68]. The indications for surgical intervention in all athletes were failed conservative treatment (Table 2).

The delay to surgery varied between 5–39 months (Table 2). The intra-operative findings were fibrosis or scar tissue formation, and surgical interventions mainly included scar tissue/fibrosis excision (n = 7). One athlete with a calcification underwent arthroscopic excision [58].

Primary outcome measure (RTS, re-injury): The primary outcome was gauged by the RTS period and/or the re-injury rate of either intervention. The RTS, re-injury and follow-up reporting were inconsistent throughout the studies. (Table 2).

Athletes treated conservatively RTS within four weeks after either post-platelet-rich plasma (PRP) injection [72] or US-Guided PNE protocol [78]. No re-injury detail was reported in the PRP group [72] and in the US-Guided PNE group [78] there was no re-injury at 5 months follow-up. Hughes *et al.* [77] reported on six athletes treated conservatively in the MT injury group, the RTS outcome was not outlined. No re-injury was reported at their 18–36 months follow-up appointments inclusive of those that had surgical intervention (n = 2) [77].

In four of the five studies (n = 7) on athletes treated surgically; a mean RTS at 6 (2–9) months was reported [48, 58, 68, 69]. In three of these athletes there was no report on re-injuries [58, 68, 69]. In the other four athletes there were no re-injuries at 12 months follow-up [48].

TABLE 2. Details of myotendinous (MT) treatment per study.

MT INJURIES CONSERVATIVE TREATMENT					
AUTHOR, YEAR	**NUMBER OF ATHLETES**	**MECHANISM**	**INJURY DESCRIPTION**	**CONSERVATIVE PROGRAM DETAIL**	**RTS, RE-INJURY**
Patel *et al,* 2019 [72]	1	Kicking	RF mid-substance incomplete partial thickness tear	Non-steroidal anti-inflammatory drugs and hip flexor and quads stretching exercises; PRP at 6 weeks plus an eccentric program	RTS: 4 weeks (1 month) post PRP Re-injury: NR
Hughes *et al,* 1995 [77]	6	Sprinting	Proximal RF Incomplete tear, intrasubstance strain	Not outlined	RTS: NR Re-injury follow up: no limitation at 18–36 months
Fermín Valera-Garrido *et al,* 2020 [78]	11	Sprinting: 3 Kicking: 8	Grade II RF injury at the MT junction.	US-Guided Percutaneous Needle Electrolysis (PNE). The PNE technique was performed under ultrasound guidance on the muscle injury using an intensity of 1.5–2 mA during 3 s, five times (1.5–2:3:5), according to the protocol by Valera-Garrido and Minaya-Muñoz followed by a specific rehab and reconditioning program.	RTS: 15.62 ± 1.80 days Re-injury: No injury at 5 months (20 weeks)

MT INJURIES SURGICAL TREATMENT							
AUTHOR, YEAR	**NUMBER OF ATHLETES**	**MECHANISM**	**INJURY DESCRIPTION**	**OPERATION INDICATION**	**DELAY TO SURGERY**	**SURGICAL TECHNIQUE**	**RTS, RE-INJURY**
Wittstein, 2011 [48]	4	Kicking	RF Central aponeurosis tear	Failed conservative (scar tissue)	12 (6–24) months	Failed conservative (scar tissue)	Mean RTS: 9 (7–12) months; Re-injury: At 12 months, two symptomatic players at 1 and 2 years respectively; both subsided with NSAIDs, manual therapy and rehabilitation
El-Husseiny *et al,* 2012 [58]	1	Kicking	RF tear (with calcification) and labral tear	Failed conservative treatment (calcification, labral tear)	8 months	Arthroscopic excision of calcification and labral repair	RTS: 8 weeks Re-injury follow up: NR
Hughes *et al,* 1995 [77]	2	Kicking: 1 Sprinting: 1	Proximal RF Incomplete tear, intrasubstance strain	Failed conservative treatment (fibrosis)	5 and 39 months respectively	Fibrous tissue excision	RTS: NR Re-injury follow up: no limitation at 18–36 months
Straw *et al,* 2003 [68]	1	Kicking	Rupture of the rectus femoris muscle at the proximal MT junction	Failed conservative treatment	12 months	Muscle suturing to proximal tendon	RTS: 6 months Re-injury follow-up: NR
Taylor, 2012 [69]	1	Kicking	Rectus femoris muscle belly tear	Failed conservative (scar tissue)	15 months	Scar tissue release and Kessler suture of torn muscle ends with an artificial LARS system	RTS: 8 months, Re-injury follow up: NR

MT = Myotendinous; FT = Free tendon; AIIS = Anterior inferior iliac spine; PRP = platelet-rich plasma injection; NR = Re-injury follow up not reported; RTS = Return to sport.

Free tendon

The FT tear group involved 34 athletes from ten studies [21, 43–45, 49, 51, 61–63, 79]. FT injury may involve the direct and indirect tendon individually or both at the same time [49, 63]. This may be with or without involvement of the conjoint tendon, [51] MT or MF structures [49].

Mechanism of injury: Most of the injuries sustained were from kicking (64%, n = 22) playing American football or soccer [21, 43–45, 49, 51, 61, 63, 79].

Isolated FT tears were reported in 82% (n = 27/34) of athletes from six studies [21, 43–45, 49, 61, 62]. Isolated direct tendon presented as the common culprit (71%, n = 24/34) and the majority of them resulted from kicking (58%, n = 14/24) [21, 43–45, 61, 62]. In four studies of the remaining athletes (n = 10), four sustained an indirect tendon injury; [49, 79] of which three had a tear with partial-thickness labral tears [49]. Two athletes had both a direct and indirect tendon tear during kicking and sprinting respectively [49, 63] while four sustained a tear at the conjoint tendon from a kicking mechanism [51].

TABLE 3. Details of free tendon (FT) treatment per study.

FT INJURIES CONSERVATIVE TREATMENT							
AUTHOR, YEAR	**NUMBER OF ATHLETES**	**MECHANISM**	**INJURY DESCRIPTION**	**CONSERVATIVE PROGRAM DETAIL**	**RTS, RE-INJURY**		
Hsu *et al,* 2005 [43]	2	Kicking	Direct head	Isokinetic and isometric strengthening	RTS: 4 weeks (1 month) Re-injury: None at 8 months and 3 years respectively		
Foote *et al,* 2013 [49]	4	Kicking: 2 Sprinting: 2	Indirect free tendon tear with labral tear (3) Direct and Indirect avulsion (1)	Rest followed by controlled rehabilitation	RTS: 36 weeks (9 months) No re-injury at 15 months		
Gamradt *et al,* 2021 [61]	10	Kicking: 2 Sprinting: 8	Direct RF	Not outlined	Mean RTS: 69.2 (21–208) days i.e., mean 10 weeks Re-injury follow up: Not reported		
Esser *et al,* 2015 [63]	1	Kicking	Direct and Indirect RF	Core, pelvic, thigh strength rehabilitation	RTS: 8 weeks (2 months) Re-injury follow up: Not reported		
FT INJURIES SURGICAL TREATMENT							
AUTHOR, YEAR	**NUMBER OF ATHLETES**	**MECHANISM**	**INJURY DESCRIPTION**	**OPERATION INDICATION**	**DELAY TO SURGERY**	**SURGICAL TECHNIQUE**	**RTS, RE-INJURY**
Bottoni *et al,* 2009 [62]	1	Sprinting	RF avulsion without AIIS avulsion (FREE TENDON-DIRECT)	Direct tendon avulsion – Patient preference	NR	Fibre-wire locking stitch and bone tunnel fixation to AIIS	4 months, NR
Adler *et al,* 2014 [44]	1	Kicking	RF complete avulsion without AIIS involvement – chronic (FREE TENDON-DIRECT)	Failed Conservative (scar tissue)	15 months	Direct head re-contour over superior acetabular ridge with PEEK Corkscrew anchor	6 months, No injuries between 8 and 12 weeks follow up
García *et al,* 2011 [45]	5	Kicking	Proximal RF ruptures – FREE TENDON – DIRECT	Direct tendon avulsion – Done as first line of management	9.1 days (5–14 days)	Kranckow stitches × 3, suture anchor repair plus Intra-op direct PRP – Post-op NWB 3–4 weeks – Eccentric train @5–6 weeks	2.5 months, No re-injuries at 35 (13–63) months follow up
Irmola *et al,* 2007 [21]	5	Kicking: 4 Sprinting: 1	Proximal avulsion of RF (no AIIS involvement) – (FREE TENDON-DIRECT)	Failed conservative (3–4 cm retraction of avulsed free tendon)	53 (18 to 102) days	Suture anchor repair	9 (5–10) months, No re- injuries reported at 20 (9–45) months follow-up
Ueblacker *et al,* 2015 [51]	4	Kicking	Proximal RF avulsion without bony involvement (FREE TENDON-CONJOIN	First line management: > 2 cm retraction of avulsed segment	60 +/- 88 days	Suture anchor repair of proximal RF avulsion	4 (3–5) months, No re-injuries at 35 +/- 6 months
Huri *et al,* 2014 [79]	1	Kicking	RF indirect tendon free tendon avulsion	Failed conservative (scar tissue)	24 months	Suture anchor repair with PDS (poly-dioxanone) sutures	2 months No re-injury at 6 & 24 months

MT = Myotendinous; FT = Free tendon; AIIS = Anterior inferior iliac spine; PRP = platelet-rich plasma injection; NR = Re-injury follow up not reported; RTS = Return to sport.

Diagnostic modality: Most athletes were evaluated using MRI as the diagnostic modality. Magnetic resonance arthrogram (MRA) was used to diagnose 3 athletes [49] while only one athlete was diagnosed with an US scan [63].

Intervention: Conservative (n = 17) [43, 49, 61, 63] and surgical interventions (n = 16) [21, 44, 45, 51, 62] were reported in four and five studies respectively in athletes with FT injuries.

Most athletes that underwent conservative treatment sustained the injury during sprinting (59%, n = 10/17) [49, 61]. The rehabilitation programs were not outlined and the duration of the rehabilitation programs was not clearly specified [61]. The treatment protocols are summarized in Table 3.

The surgical techniques and indications vary amongst studies. All studies (n = 17) reporting surgical treatment employed a core principle of re-anchoring the torn tendon to its origin. The athletes included fifteen kickers and two sprinters [21, 44, 45, 51, 62, 79]. The details of the surgical techniques are described in Table 3.

García *et al*. [45] conducted surgical intervention on five athletes immediately after injury (delay to surgery: mean 9.1 (5–14) days post-injury). The surgical indications in other studies varied and amongst them included patient preference (n = 1), [62] > 2 cm tendon retraction on MRI (n = 4) [51] and a failed conservative treatment program (n = 7) [21, 44, 79]. Scar tissue formation was found in most athletes from the failed conservative treatment program [44, 79].

Primary outcome measure (RTS, re-injury): The mean RTS time was 14.5 (4–36) weeks for the conservative treatment group [43, 61, 63]. The RTS time was longer at 36 weeks in three athletes treated conservatively with indirect tendon avulsions involving the labrum. No conservatively treated athletes had a re-injury on follow-up [43, 49]. Two studies (n = 11) did not present re-injury follow-up [61, 63].

The mean RTS period after surgery was 5 (2–9) months in all studies for all injury patterns and surgical techniques used, as noted in Table 3 [21, 44, 45, 51, 62, 79]. The RTS time was less than 6 months when surgery was performed acutely [45, 51, 62] and longer with surgery after failed conservative therapy [21, 44]. Where reported there were no injuries noted in the re-injury follow-up periods ranging between 2 and 35 months [21, 44, 45, 51, 79].

Avulsion fracture of rectus femoris insertion on AIIS

Ninety-one athletes sustained a RF injury with an AIIS avulsion fracture in twenty three studies included in this systematic review [42, 46, 47, 49, 50, 52–57, 64–67, 71, 73–76, 80, 81].

Mechanism of injury: Over 90% of the avulsions (n = 83/91) were sustained during kicking [46, 47, 49, 50, 52, 53, 55, 64–67, 71, 73, 75, 76, 80] and the remainder occurred during sprinting [42, 54, 56, 57, 74, 75, 81]. The majority of these injuries (95%) occurred in adolescent males (n = 87). In 61% (n = 56/91) of the athletes the specific sport was not outlined, [71] and where reported most RF injuries were sustained during kicking in soccer players (29%, n = 26) [46, 47, 49, 50, 52, 53, 55, 64–67, 73, 75, 76, 80].

Diagnostic modality: RF avulsion injuries in nine studies were diagnosed on plain X-rays only (n = 69) [49, 55–57, 65, 71, 73, 7 4, 76, 80, 81]. In three studies computed tomography (CT scan) was used for further evaluation (n = 7), [53, 66, 67] while MRI was the investigation modality of choice for athletes in the remaining studies (n = 15) [42, 46, 47, 50, 52, 54, 64, 75].

Intervention: Conservative treatment was used in most athletes (87.9%, n = 80) [49, 53, 56, 57, 64–66, 71, 74–76] of which the majority (70%) were adolescents in one pooled study on avulsion fractures [71]. The conservative program details in this particular study were however not outlined [71]. The conservative treatments per study are outlined in Table 4.

Surgical treatment was conducted in 10 studies (n = 11) and in all cases, it was done after a failed conservative treatment program. The majority (81%, n = 9) of these were from kicking injuries [42, 46, 47, 49, 50, 52, 54, 55, 67, 71, 73]. The surgical indications included non-union, [46, 49, 50, 67] mal-union [52, 54] and heterotrophic ossification [42, 47, 52]. In some of these cases there was a secondary impingement that warranted surgical correction [49, 52, 54, 67]. The delay to surgical intervention ranged between 2 and 24 months.

Table 4 shows the surgical details for the reported studies. The surgical approach was either a Smith-Petersen approach (n = 7) [46, 47, 50, 52, 55] or arthroscopic (n = 4) [42, 49, 54, 67]. The procedure was mainly an open reduction and internal screw fixation (ORIF) (n = 5) [46, 50, 55, 73] or surgical excision of the avulsed segment (n = 4) [42, 47, 52, 54].

Primary outcome measure (RTS, re-injury): The RTS and re-injury rates were poorly reported for AIIS avulsion injuries, with most studies only reporting one of the two. The RTS period amongst the conservative treatment group was not outlined in three studies (n = 66), [56, 71, 75] however, ranged between 1.5 and 9 months (mean 2.9 months) in the reported studies (n = 14) as noted in Table 4. In most studies, no re-injury follow-up was reported, and in four studies involving twelve athletes, no re-injuries were reported on follow-up appointments at specifically 3, [74] 6, [57] 20 [80] and 24 months [56, 75] respectively (Table 4).

The mean RTS period for all the surgically treated athletes was 6 months (1.5–18 months), (Table 4). Matsuda *et al.* [54] reported a longer RTS time of 18 months due to AIIS avulsion fracture complicated by non-union. Studies that reported on re-injury did not have any injuries in athletes between 1- and 2-year follow-up period [42, 46, 50, 52, 55].

The modified Harris Hip Score and Non-arthritic Hip Score were used in two studies as a measure to gauge post-operative outcome [50, 67]. Both athletes scored 100 on follow-up, of which one athlete's pre-operative score gauged improvement post-intervention [67]. Objective outcome measures were not reported in any other studies.

TABLE 4. Details of anterior inferior iliac spine (AIIS) treatment per study.

	AIIS AVULSION CONSERVATIVE TREATMENT				
AUTHOR, YEAR	**NUMBER OF ATHLETES**	**MECHANISM**	**INJURY DESCRIPTION**	**CONSERVATIVE PROGRAM DETAIL**	**RTS, RE-INJURY**
Foote *et al*, 2013 [49]	1	Kicking	Avulsion of reflected RF /Indirect head with partial labral tear	Conservative (Controlled Rehabilitation)	RTS: 9 months Re-injury follow-up: No injury at 15 months follow up
Atalar *et al*, 2007 [53]	1	Kicking	AIIS Avulsion	Conservative (NSAIDs, rehabilitation)	RTS: 8 weeks (2 months) Re-injury follow up: Not reported
Yildiz *et al*, 2005 [56]	1	Sprinting	Bilateral (Sequential) avulsion fracture of the AIIS, occurring first in the right and then the left AIIS (4 months apart).	Conservative (gradual rehabilitation program) – both sides	RTS: not detailed, Re-injury follow up: No injury at 2 year follow up
Mader, 1990 [57]	1	Sprinting	AIIS Avulsion	Conservative (2 days complete strict bedrest, progression to full weight-bearing as symptoms improved)	RTS: 6 weeks (1.5 months) No re-injury at 6 months
Pogliacomi *et al*, 2019 [64]	1	Kicking	RF MT junction rupture AIIS avulsion	Conservative: (× 3 ten-day interval Serial PRP ultrasound-guided injections and a specific rehabilitation protocol)	RTS: 90 days (12 weeks), Re-injury follow up: Not reported
Reina *et al*, 2010 [65]	2	Kicking	AIIS avulsion fracture (chronic and acute respectively)	Conservative (physiotherapy program)	RTS: 2 and 3 months respectively, Re-injury: Not reported
Serbest *et al*, 2015 [66]	4	Sprinting	AIIS avulsion fractures	Conservative (rest, NSAIDs, gradual rehabilitation)	RTS at 10 weeks, Re-injury follow up: not reported
Schuett *et al*, 2015 [71]	56	Kicking	AIIS avulsion	Not outlined	RTS: Not outlined Re-injury: 1 non-union (referred for ORIF – declined), 25 hip pains, and 8 multiple injuries at 4-month follow-up.
Gomez, 1996 [74]	1	Sprinting	Bilateral AIIS avulsion fractures	Conservative (ICE pack, NSAIDs, limited weight-bearing – 7 days. Followed by Full weight-bearing, range of motion exercises including hip extension, hip flexor strength and conditioning on stationary bicycle.	RTS at 10 weeks Re-injury: None at 3 months follow up
Uzun *et al*, 2014 [75]	9	Kicking: 6 Sprinting: 3	AIIS avulsion fractures	Not outlined	RTS: not reported, No re-injury at 24 months
Aksoy *et al*, 2014 [76]	1	Kicking	Avulsion fracture of the right AIIS	Conservative (gradual rehabilitation program)	RTS: 12 weeks, Re-injury follow up: not outlined
Lasky-McFarlin *et al*, 2020 [80]	1	Kicking	Bilateral AIIS avulsion fractures: an acute fracture on the right and healing fracture on the left.	Conservative (The 5-phase rehabilitation protocol outlined by Metzmaker and Papas)	RTS: 8 weeks Re-injury: nil at 20 weeks
Cameron & Wallace, 2020 [81]	1	Sprinting	Asynchronous bilateral AIIS apophyseal avulsion fractures	Conservative (Rest, activity modification)	RTS: 3 months Re-injury: not outlined

MT = Myotendinous; FT = Free tendon; AIIS = Anterior inferior iliac spine; PRP = platelet-rich plasma injection; NR = Re-injury follow up not reported; RTS = Return to sport.

TABLE 4. Details of anterior inferior iliac spine (AIIS) treatment per study (continuation).

RF AIIS AVULSION FRACTURE SURGICAL DETAILS								
AUTHOR, YEAR	NUMBER OF ATHLETES	MECHANISM	OPERATION INDICATION	DELAY TO SURGERY	SURGICAL TECHNIQUE	INTRAOPERATIVE INJURY DESCRIPTION	RTS	RE-INJURY
Nakano *et al*, 2018 [42]	1	Sprinting	Failed conservative (physiotherapy): extra-articular anterior hip impingement (after 6 months)	6 months	Arthroscopic excision	AIIS avulsion fracture	2 months	Nil at 24 months
Matsuda *et al*, 2012 [54]	1	Sprinting	Failed conservative (rest, activity modification, NSAIDs): mal-union of AIIS (after 3 months)	9 months	Arthroscopic: fluoroscopic templating with excision of mal-united AIIS and labral re-fixation	Direct head avulsion fracture with non-union at the AIIS and surrounding callus formation	18 months	NR
Milankov *et al*, 2011 [47]	1	Kicking	Failed conservative (rest, RTS with persistent pain, underwent initial op at 4 months), – underwent excision	4 months	Modified Smith – Petersen approach: Excision of avulsed AIIS segment	Bony protuberance at the adjacent left superior rim with fraying of the labrum with RF fibers attached. No pseudo-arthrosis	4 months	Complication 2 years post-op: (heterotopic ossification in vastus intermedius tendon and its femoral insertion) – MRI showed heterotopic ossification with was excised via a modified Smith – Petersen approach: RTS = 4 months
Foote *et al*, 2013 [49]	1	Kicking	Failed Conservative (Physiotherapy, controlled rehabilitation) 6 months	6 months	Arthroscopic: debridement, labral repair and synovectomy	Pt 1: A mass of exuberant callus around the left AIIS Pt 2: Right AIIS avulsion 2.5cm distally	7 months	NR
Scillia *et al*, 2017 [50]	1	Kicking	Failed conservative (physical therapy, acupuncture) after 12 months	12 months	Modified Smith Petersen approach: excision of avulsed segment and suture anchor repair and bone wax application	avulsion of both heads of the RF and a chondrolabral separation	6 months	Nil at 18 months
Alhaneedi *et al*, 2015 [52]	1	Kicking	Failed conservative treatment (NSAIDs, physiotherapy): after 3 months	24 months	Surgical excision: anterior hip approach	Well corticated heterotrophic ossification in the right RF near the AIIS	1.5 months	Nil at 12 months
Rajasekhar *et al*, 2000 [55]	2	Kicking	Both Failed conservative: Pt 1 = (rest, analgesia, physiotherapy): exuberant callus removed at 2 years AND Pt 2 = rest and analgesia with surgery acutely).	2 and 0 years	Pt 1: Modified Smith Petersen approach; A mass of exuberant callus was excised Pt 2: Re-fixation of avulsed fracture with a 6.5mm screw and washer	Right AIIS avulsion	NR	NIL in both at 18 and 12 months
Carr II *et al*, 2017 [46]	1	Kicking	Failed conservative (rest, 2 rounds of gradual therapy): after 5 months	18 months	Anterior Smith-Petersen approach: Excision of 8mm callus and avulsed segment, sub-spinal decompression	Peripheral focal synovitis at the level of AIIS with mal-union, superolateral labral tear	5 months	Nil at 12 months
Shibahara *et al*, 2017 [67]	1	Kicking	Failed conservative: Non-union of AIIS and antero-superior labral tear after 6 months	4 months	Arthroscopic: labral repair, AIIS decompression with motorized round burr and femoroplasty	Hypertrophic mal-united bony fragment at the Right AIIS	4 months	NR
Saluan et al, 1997 [73]	1	Kicking	Failed conservative (rest, ice)	11 months	Modified Smith Petersen approach: scar tissue excision and re-fixation of avulsed segment	Avulsion of AIIS	6.5 months	Re-injury: not reported

MT = Myotendinous; FT = Free tendon; AIIS = Anterior inferior iliac spine; PRP = platelet-rich plasma injection; NR = Re-injury follow up not reported; RTS = Return to sport.

DISCUSSION

The RF is the most commonly injured muscle in the quadriceps group. RF injuries have longer RTS times than hamstring and groin injuries and have a high re-injury rate [82–84]. This is the first systematic review reporting on RF injury management. The level of evidence in all 38 included studies is low with all studies being either case reports or case series. Surprisingly this indicates that although a significant injury, not much evidence-based research regarding the treatment is available. It is further supported by the heterogeneity of treatment approaches and evidenced by the moderate and low methodological quality reported in most studies e.g., treatment protocols differ, RTS not reported, re-injury not reported. The synthesis therefore points to a low certainty of evidence on the findings.

The sub grouped analysis based on the anatomical location allows for decision making around recovery or prognosis in the form of RTS and re-injuries [85]. The injury location and characteristics from imaging provide the anatomical site, percentage of cross-sectional involvement or presence of peri-fascial fluid. These findings provide guidance during the rehabilitation period e.g. proximal tendon injuries with > 50% cross-sectional involvement and pre-fascial fluid, are associated with a longer RTS [20]. The implication is that kicking would be delayed longer during rehabilitation than in a MT strain to avoid a possibility of re-injury or tendon retraction [20]. Hence careful anatomical location and severity do have therapeutic and prognostic implications which guide the decision making process and RTS for each RF injury subgroup. The outcome based on intervention for each injury subcategory in the studies are summarized in figure 2.

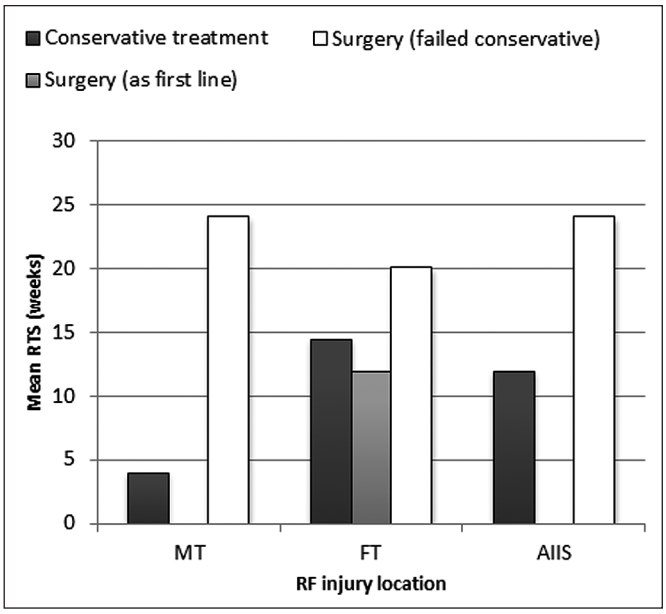


FIG. 2. Rectus femoris (RF) injury treatment outcomes.

Myotendinous injuries

RF injury is common with kicking or sprinting [3, 17–19]. This was a consistent finding amongst the inclusions describing MT injuries. We found these to occur similarly across studies. Most kicking injuries resulted in tears on the MT area which need surgical intervention following failed conservative therapy [48, 58, 68, 69, 77]. The low certainty of evidence suggests that upon diagnosis of an MT tear surgical intervention may be warranted sooner to avoid prolonged RTS times. An MRI in this case may assist in evaluating the extent of soft-tissue damage that occurred with the injury to determine the appropriate intervention. Fermín Valera-Garrido *et al.* [78] through a combination of US-Guided PNE 48 hours after grade II MT junction injuries and a specific rehabilitation program achieved optimal injury repair. RTS was also within a short period (15.62 ± 1.80 days) and no re-injuries were reported on follow-up [78].

Athletes who sustained MT strains during sprinting may be treated successfully with conservative rehabilitation modalities [77]. However, insufficient detail on the conservative programmes renders it impossible to compare conservative approaches or replicate them. Lack of consistent reporting on outcomes (RTS and re-injury outcome) for MT injuries treated conservatively shows the lack of uniformity or evidence-guided approach with regards to the treatment of MT injuries.

In the surgical intervention studies on MT injuries, the mean RTS is 6 months post-intervention, and no re-injuries were documented in the first 12 months or longer follow-up. The incomplete reporting on outcome measures makes it difficult to establish the superiority of either intervention. A successful RTS time could be shortened by a proper evaluation and evidenced-based intervention guided by MRI imaging to reduce the delay to surgery time for those cases needing surgical intervention.

Free tendon tear

The majority of FT tears to the RF are reported during kicking (63%) and involve the direct tendon (72%) [21, 43–45, 61, 62]. This is contrary to an earlier finding by Serner *et al.* [22] that a vast majority of RF injuries (94%) involved the proximal tendons, commonly the indirect tendon (56%) in comparison to the direct tendon insertion [22]. Tears may in some instances involve the direct and indirect tendons concurrently; [49, 63] the acetabular labrum [49] or the conjoint tendon [51]. MRI remains a key investigation tool for the evaluation of FT tears. Ultrasound imaging may also be used successfully, [63] and may be valuable in resource-limited settings. If clinically indicated, MRA (arthrogram) is shown to be helpful in the evaluation of intraarticular pathologies such as labral tears [49].

Most athletes that underwent conservative treatment were from the sprinting group (n = 10) [49, 61]. The conservative program was not outlined [61]. Surgical intervention mostly followed failed conservative treatment [21, 44]. Irmola *et al.* [21] reported a 3–4 cm retraction of the avulsed segment while Adler *et al.* [44] reported scar tissue intraoperatively. This highlights the aspect of a longer

delay to surgery which could go up to 15 months hence contributing to a lengthened recovery and RTS period.

The consideration of treatment modality based on indication was shown to yield early surgical intervention in some studies such as Ueblacker *et al.* [51] and García *et al.* [45] who acutely performed surgical repair in FT tears. These indications were either a direct tendon avulsion, [45] > 2 cm tendon retraction [51] on MRI or the patient's preference [62]. The lack of standardized protocols accounts for this heterogeneity of indications which may be explored in future studies for an evidence-based approach.

Both conservative and surgical interventions amongst the studies show a good outcome with little to no complications on long-term follow-ups. With the limited evidence, successful conservative treatment yielded a quicker RTS within 14.5 (4–36) weeks [43, 61, 63] over the surgical approach that reported 5 (2.5–9) months. However, RTS was found to be longer at 9 months when there was labral involvement; in this case from a free indirect tendon avulsion. In these athletes, none had a re-injury at 15 months follow-up [49]. The standard surgical approach involved re-anchoring the torn tendon to its origin (suture anchor repair) [21, 44, 45, 51, 62].

When surgical intervention was conducted acutely [45, 51] there was essentially no difference in the respective RTS time of athletes treated surgically and conservatively as both RTS in roughly 3 months post-intervention. More high yield studies will need to be conducted to substantiate this early finding and possible confounding factors. Nonetheless, the limited evidence suggests that surgical intervention remains a solution for athletes with a failed conservative treatment evidenced by no re-injuries on long-term follow-up postoperatively [21, 44].

With either intervention, there were no re-injuries noted in the follow-up periods ranging between 2 and 35 months with minimal complications. Irmola *et al.* [21] reported on only one athlete that sustained a lateral cutaneous nerve hypersensitivity on follow-up which resolved within a year.

Anterior inferior iliac spine avulsion fracture

Most (90%) RF avulsion fractures occur at the AIIS in adolescent males from a kicking mechanism and were reported in soccer (29%) [46, 47, 49, 50, 52, 53, 55, 64–67, 73, 75, 76]. X-ray in this subgroup is shown to be effective as a primary imaging tool [49, 55–57, 65, 71, 73, 74, 76]. In some instances, computed tomography (CT) scan and MRI may play a role as in the cases presenting with features of extra-articular impingement [46, 52, 67].

Conservative treatment proved to be effective in most avulsion fractures with a mean RTS of 2.9 months in the studies that reported RTS [49, 53, 57, 64–66, 74, 76] compared to surgical interventions with a mean RTS of roughly 6 months. In either of the

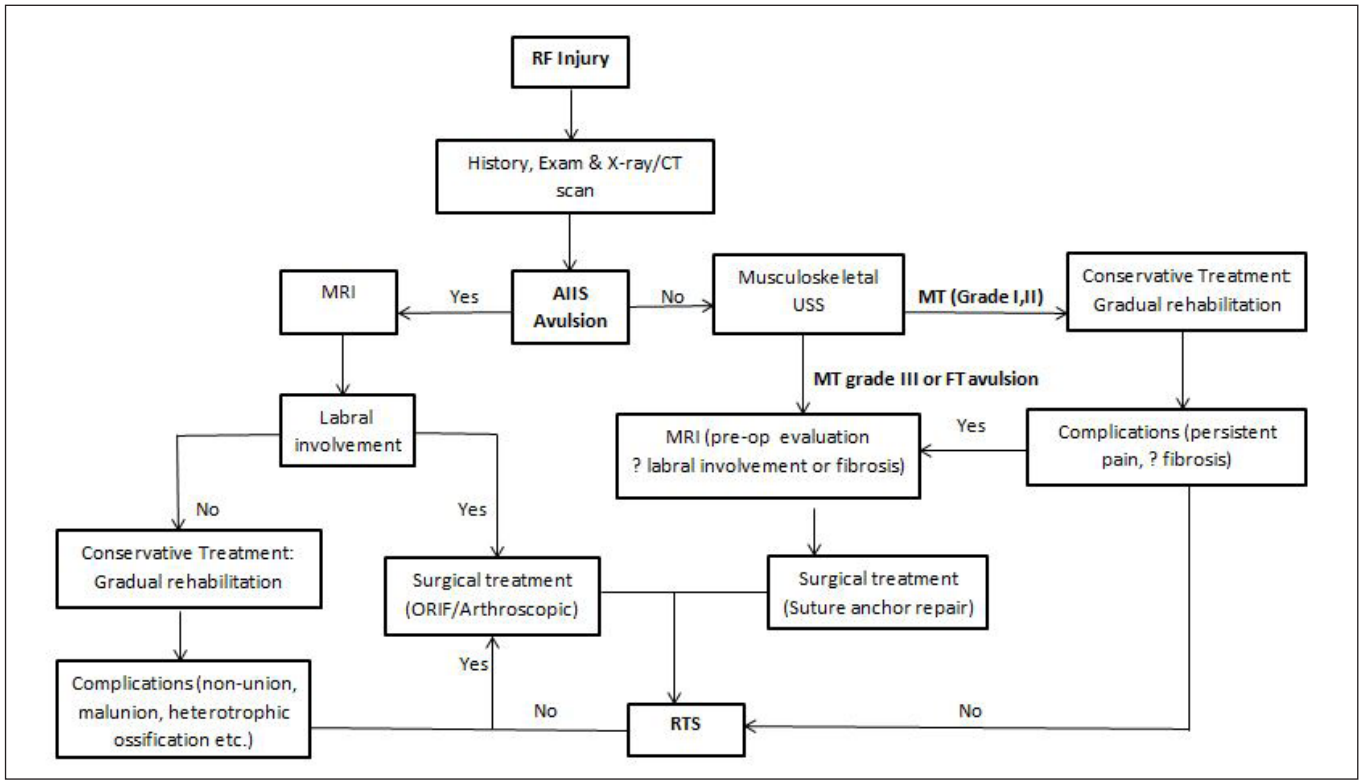


FIG. 3. Rectus femoris (RF) injury treatment algorithm.

interventions, RTS may be longer with associated labral tears as is the case with FT tears. Most studies reporting on re-injury follow-up had no re-injuries between 12- and 24-months reviews. Hence neither surgical approach nor technique yielded superior outcomes.

The small number (n = 9) that needed surgical intervention were mostly from the kicking cohort (n = 7, 81%). Indications for operation range from non-union, [46, 49, 50, 67] mal-union [52, 54] and heterotrophic ossification [42, 47, 52]. In all these instances conservative treatment had failed. In some of these cases, there can be secondary impingement that warrants surgical correction [49, 52, 54, 67]. This is evidenced by a long delay to intervention ranging between 2 and 24 months after a trial of conservative treatment. Despite the delay, surgical treatment remains a viable option when conservative treatment fails as all athletes returned to sport and had no re-injuries on follow-up [49, 52, 54, 67]. The surgical approach can either be arthroscopic [42, 49, 54, 67] or open fixation, [46, 47, 50, 52, 55] and involves an ORIF or excision of the avulsed segment and suture anchor repair to AIIS origin. After failed conservative treatment there usually was fibrosis or exuberant scar tissue formation consistent with a longstanding injury.

Practical application

Based on low certainty of evidence; in practice careful evaluation of the injury with guided imaging are paramount to an anatomical diagnosis for a guided treatment plan with a timely RTS and less likelihood of complications as outlined in Figure 3. Future high-level research is warranted to validate these findings.

The assessment of the effectiveness of the intervention based on both RTS and re-injury outcomes is challenging as most studies did not report re-injury follow-up. Along with the low-level evidence of the included papers a comparison of the intervention-based outcome remains challenging. Conversely, for hamstring [33, 86–88] and Anterior Cruciate Ligament (ACL) [89–92] injuries extensive research has been done regarding surgical and conservative intervention with detailed rehabilitation plans. The relatively long RTS time of RF injuries warrant similar attention.

Limitations

The major limitations in this systematic review consist of the low level of evidence of the included studies, no outline of the conservative intervention program in most papers and incomplete reporting of both the primary outcome measures namely RTS and re-injury follow-up evaluation. These factors along with the heterogeneity in reporting amongst the studies made it difficult to conduct a meta-analysis.

The reported studies have a limited number of athletes to allow clustering based on either the age groups or sporting code (team or individual sports) hence presents a challenge of confounding factors associated with the risk associated with individual or team sports and a wide age group [93, 94]. Regarding the GRADE (Grading of Recommendations, Assessment, Development and Evaluations) assessment [95, 96]. With the effectiveness question at hand and only case series/ reports in our inclusions, we were not able to provide evidence of effectiveness (causality). We could also not perform a summary table of findings as per GRADE standards but could only make comments about associations.

Future Research

More research on the topic is needed regarding standardised treatment protocols, time to RTS and the incidence of re-injury. It is therefore proposed that future research should follow a form of multi-centre randomized controlled trials including a detailed conservative program and a standardized surgical program with long-term follow-up also determining RTS time and re-injury rate. Such research is required for all the different RF injury regions.

CONCLUSIONS

Based on the low certainty of evidence we conclude that RF injury occurs mostly from kicking. This mechanism is associated with more complicated injuries amongst the different injury groups (MT, FT, AIIS avulsion injury). Kicking commonly leads to either a tear or avulsion at the FT and AIIS regions with or without a labral tear. With low certainty, it is suggested that successful conservative treatment provides a shortened RTS outcome amongst the injury regions. Surgical treatment also remains an option for failed conservative treatment of RF injuries across all the injury groups. The complicated cases are treated successfully through surgical means either primarily or after a failed course of rehabilitation. Primary surgical interventions seem to have similar recovery rates and low failure rates and can be considered in elite athletes where prolonged RTS can have far-reaching consequences. Conservative and surgical intervention in the different injury groups had limited to no complications evidenced by the lack of re-injuries on follow-up. With this low evidence synthesis, more high-level studies are strongly recommended to improve the evidence base for the treatment of this significant injury.

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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Declaration

The authors declare no conflict of interest.

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SUPPLEMENTARY MATERIAL

Supplementary Table S1: Search strategy

Search string	Database or further sources	Results	Date	Comments
rectus femoris AND injury AND running rectus femoris strain AND injury AND anterior inferior iliac spine	SPORTDISCUSS	147	2020-04-12	COMBINED RF "AND" AIIS Avulsion search
rectus femoris AND Injury AND Treatment "OR" Anterior inferior iliac spine AND Avulsion AND Treatment	MEDLINE	50	2020-04-14	RF "OR" AIIS Avulsion
((anterior inferior iliac spine avulsion AND treatment)) OR (Rectus femoris AND Injury AND Treatment AND outcome AND ("1979/01/01" [PDat]; "2020/12/31" [PDat]) AND Humans [Mesh])	PUBMED SEARCH	88	2020-04-14	AIIS avulsion "OR" RF Injury

RF = Rectus femoris; AIIS = Anterior inferior iliac spine

Supplementary Table S2: Methodological quality assessment outcome MS Excel file

Supplementary Table S3: Exclusions and Reasons

	Study	Reason for Exclusion
1	Knobloch *et al,* 2007	Full text not assessable, Article not in English (German)
2	Takahara *et al*	Full text not assessable, Article not in English (Japanese)
3	Kayipmaz *et al,* 2011	Full text not assessable, Article not in English (Turkish)
4	Langer & Selesnick, 2010	No Outcome: Return to Play outcome
5	Temple *et al,* 1998	Injury mechanism not outlined, 1 athlete with mechanism was > 45
6	R Zini *et al,* 2014	Injury mechanism not outlined
7	Sonnery-Cottet *et al,* 2017	Injury mechanism not clear: "eccentric mechanism"
8	Ali *et al,* 2015	No outcome. Only "Improvement" reported
9	Balius *et al,* 2009	Injury mechanism not outlined ("during football")
10	Bartl *et al,* 1997	Full text not assessable, Article not in English (German)
11	Calderazzi *et al,* 2018	No primary data (systematic review)
12	Dean *et a,* 2016	No primary data (Technical report)
13	Eberbach *et al*, 2017	No primary data (systematic review)
14	Incedayi *et al,* 2014	Injury mechanism not outlined
15	Linni *et al*, 2000	Full text not assessable, Article not in English (German)
16	Novais *et al*, 2018	Mechanism not kicking or sprinting (direct trauma)
17	Pierannunzii *et al,* 2010	Mechanism not kicking or sprinting ("active extension of hip from flexed position")
18	Schwobel *et al,* 1985	Full text not assessable, Article not in English (German)
19	Sinikumpu *et al,* 2018	Injury mechanism not outlined
20	Stancak, 2016	Full text not assessable, Article not in English (Czech)
21	Stancak, 2016	Full text not assessable, Article not in English (Czech)
22	Sulko *et al,* 2010	Full text not assessable, Article not in English (Polish)
23	Weber *et al*, 2010	Mechanism not kicking or sprinting (Forced knee flexion during fall)
24	Yun *et al*, 2009	Age out of range (52 years)
25	Zini *et al,* 2018	Injury mechanism not outlined
26	Yildiz *et al,* 2003	No full-text, Abstract not sufficient
27	Jethwa *et al,* 2020	Age out of range (53 years old)
28	Cho *et al,* 2020	Outcome (RTS or re-injury) not outlined – reports improvement in hip range of motion and athlete walking at week 3
29	Maalouly et al, 2020	Mechanism not kicking or sprinting – Hip hyperextension
30	Sinikumpu, 2018	Mechanism not outlined
31	Lempainen, 2018	Mechanism not kicking or sprinting – sudden pain during hip extension or forceful flexion
32	Kayani *et al,*2021	No outcome
33	Santos et al, 2021	No intervention or outcome reported

Fatigue score as a promising complementary training monitoring tool: a pilot study in elite rugby sevens players

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ABSTRACT: The aim of this study was to compare physical and hormonal responses of seventeen elite rugby sevens players over a 6-week intense training block (IT) and a consecutive 2-week tapering period (TAP), using a fatigue cut-off score of 20 as a potential moderating variable. Training was monitored by daily training load (TL) and strain (TS) (using the session rating of perceived exertion [sRPE]) and also the weekly total score of fatigue (TSF; 8-item questionnaire tool). Testing and 24 h urinary cortisol (CL), cortisone (CN), adrenaline (AD) and noradrenalin (NAD) concentrations were also analysed before (T0) and after IT (T1) and after the TAP (T2). Players were assigned to group 1 with a TSF above 20 (G1 $>$ 20, n = 9) and group 2 with a TSF below 20 (G2 $<$ 20, n = 8) according to the French Society for Sports Medicine guidelines. TSF (effect size [ES] from 1.17 to 1.75), TL (ES from 0.81 to 1.06) and TS (ES from 1.23 to 1.40) were higher in G1 $>$ 20 than in G2 $<$ 20 over IT. Likewise, performance standards (ES from 1.58 to 2.61) and AD levels were lower (ES = 3.20), whereas CL and CL/CN ratio (ES from 1.60 to 3.47) were higher in G1 $>$ 20 than in G2 $<$ 20. After the TAP, TSF, TL and TS returned to baseline values for both groups, with an increase in performance standards and normalization in hormone levels. We suggest that a TSF greater than or equal to 20 could be considered as a fatigue threshold generating hormone disturbance and performance decrement, making it a potentially useful preventive and complementary training monitoring tool.

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INTRODUCTION

Rugby sevens has been an Olympic sport since 2016, resulting in a growing interest in the determinants of performance among players. Rugby sevens is considered as a physically demanding team sport requiring players to participate in frequent bouts of intense activities such as sprinting, physical collisions, and tackles interspersed by short bouts of low intensity activity such as walking and jogging [1]. Thus, performing in this team sport requires robust physical and psychological qualities, especially when performing at the highest level [2]. Managing training load and fatigue is considered an important component of the training process, especially in high training load sports such as rugby sevens; and optimizing training load will potentially result in an optimized performance [3–8]. Several parameters were previously employed to investigate potential physiological mechanisms underlying the progression towards excessive training (i.e., overreaching) that can result in detrimental performance. In this context, various physiological, haematological, biochemical, hormonal, and immunological parameters along with cardiovascular responses have been proposed as markers of these adaptations; however, nowadays there is no consensus on which measures are the most appropriate [3, 9–13]. Although the specific physiological factors underlying the progression towards overtraining syndrome remain unclear, research strongly highlights the importance of a psychological role in this context [14–16]. In fact, psychological factors, such as perceived training stress, anxiety and mood state, may also play a crucial role in high-level sports performance. Several practical tools have become available to team sports' coaches to monitor the complex event of the stress/recovery balance in athletes and thus enable prevention of overreaching or overtraining [3, 7, 15, 17]. Self-reported measures (scales and questionnaires) are valid, practical, and simple tools for monitoring TL-induced psychological stress and fatigue [3, 7, 8, 11, 16–18]. The short questionnaire of fatigue, which stems from the large questionnaire of the French Society for Sports Medicine [17, 19, 20], allows an assessment of training stress, load, anxiety and strain in athletes [10, 18, 21] and has already been suggested as a helpful

complement to the session rating of perceived exertion (sRPE) method for quantifying internal training load (TL) [3–7]. Interestingly, several studies have reported a significant relationship between the total score of fatigue (TSF) and the intensity of training variation as well as hormonal, performance and heart rate variability response-related training [3, 17, 20]. These findings suggest that both physiological and psychological parameters should be an integral part of the training process. Monitoring the latter sets of parameters could not only promote recovery, but also hopefully identify and prevent early signs of overtraining as previously suggested [14–16]. In this context, some authors [18, 19, 21] have proposed a TSF of 20 (arbitrary unit, AU) as a cut-off value for substantial fatigue in athletes. In this context, Atlaoui et al. [10] found that in response to an increase of training load, one swimmer showed a larger decrease in performance associated with a larger increase in TSF scores (from 19 AU to 28 AU) compared with the remaining swimmers of the study. Furthermore, Elloumi et al. [22] found that rugby players who presented higher TSF (mean 21 ± 3.5) exhibited larger significant hormone alterations than those who were less fatigued after an international competition. However, this cut-off value remains suggestive, for now relatively approximate, and to the best of our knowledge, no study has assessed its effectiveness. Therefore, the present pilot study aimed to compare physical and hormonal responses of seventeen elite rugby sevens players over a 6-week intense training block (IT) and a consecutive 2-week tapering period (TAP), using a fatigue cut-off score of 20 as a potential moderating variable.

MATERIALS AND METHODS

Part of the dataset of this project has been published elsewhere [3]. The present study uses a different set of data with a subset of data that has been included in the previous study and another subset of data which is published here for the first time.

Participants

Elite rugby players (rugby sevens, n = 17) from the Tunisian national team voluntarily participated in the study. They all regularly took part in national and international matches and their training schedule was as follows: 5 to 6 training weekly sessions (10–12 hours). Once the general preparation period was over, and up to the time of any international competitions, the players were used to training with the national team (2 training sessions daily, 3–4 hours) in addition to two rugby sevens games at the weekend, with only one day off weekly. The players participated in five high level international rugby sevens tournaments per year (organized by the International Rugby Board). The participants' dietary intake was consistently administered, supervised and assessed by the national team's nutritionist. All players were healthy, with no observed condition or treatment impeding or limiting their participation. Participants filled in a written informed consent form after having been informed of the study protocol, which has been approved by the institutional Ethical Committee. After having conducted our experiment, we assigned all the players to two groups according to the French Society for Sports Medicine guidelines and the suggestion by Chatard et al. [21]: group 1 with a TSF above 20: G1 > 20, and group 2 with a TSF below 20: G2 < 20.

Training

The training programme consisted of 6-week IT (intense training block) and of 2-week TAP (tapering). Training sessions were focused on rebuilding physical conditioning of the players including an improvement of their aerobic capacity. Training included high-intensity interval runs, physical-technical circuits, and game-like activities with small groups and large spaces, with the intent that the intensity during the 4- to 6-minute series would be very high. The intensity, duration (volume) and frequency of sessions gradually increased during the period of IT and the duration and frequency declined steadily during the period of TAP. The players also performed sessions of speed and coordination training where speed, coordination and agility circuits were performed. Two specific-strength training sessions in the gymnasium (30–45 minutes) were performed before the field training to complement the physical training programme. For more details on the strength training programme, see Bouaziz et al. [3].

Procedures and tests

The study was conducted during the preparation period for the rugby sevens World Cup held in 2013. Evaluation sessions (anthropometric performance measures) were conducted at the same time of the day at the National Center of Medicine and Science in Sports, Tunis, Tunisia (temperature: 18 ± 2°C, and relative humidity 44 ± 8%) where players were assessed at three time points:

1) At (T0): previously to the training programme,
2) At (T1): after the 6 weeks of IT training (intense training block),
3) At (T2): after a 2-week TAP (tapering) that came immediately after IT.

The physical assessments were part of the players' fitness assessments according to sevens World Cup rules (Figure 1). Body mass, height, and percent body fat (% BF) were assessed using calibrated tools [23].

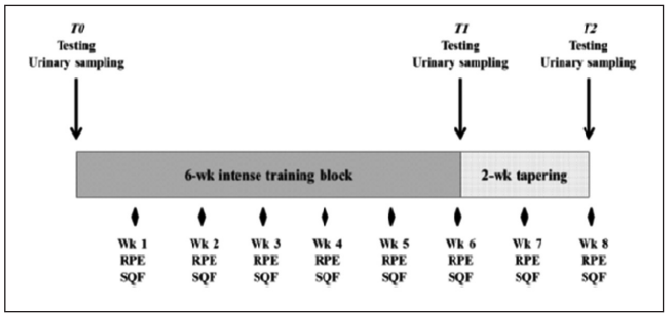


FIG. 1. Schematic overview of the study design.
Note: sRPE: session-rating of perceived excretion. SQF: short questionnaire of fatigue.

Physical tests

The players performed the following physical tests: 30-m sprints (sprint), five-jump test (leg explosiveness), Illinois agility run (agility), Australian lactic test (mostly anaerobic test), one maximum repetition (1-RM) of bench press and half squat (strength), and the Yo-Yo intermittent recovery test level 2 (Yo-Yo IRT2 – endurance). For more details see Bouaziz et al. [3].

Training load monitoring

Training load, monotony and strain for each participant were collected approximately 30 min after the end of each session and were calculated according to the sRPE method [4]. The weekly training strain was then calculated as the product of weekly training load and monotony. The mean training load and strain were also calculated for the 6-week IT and the 2-week TAP. The training load, monotony and strain are expressed in arbitrary units (AU).

Short questionnaire of fatigue

Chatard et al. [21] described the short questionnaire of fatigue which consists of eight questions focusing on: the perception of training, leg pain, concentration, efficacy, sleep, infection, anxiety, irritability, and general stress (questions being assessed on a 7-point scale: from 1 point (not at all) to 7 points (very much)). The summed 8 responses allowed calculation of the TSF (total score of fatigue). The TSF, TL (training load) and TS (training strain) during the IT (6-week) and TAP (2-week) were independently averaged for each group, in order to assess the possible association between these variables and (i) the physical performance and (ii) the 24 h urinary hormonal excretion changes during these two periods.

Urine samples

Each week during the protocol, urinary samples were collected from all the participants over a 24 h resting period [3]. Catecholamine and urinary glucocorticoid concentrations were assessed [high performance liquid chromatography (HPLC)] [24, 25]. Intra- and inter-assay coefficients of variation were < 3% for catecholamines and < 1% for glucocorticoids (both were expressed in $\mu g \cdot mg^{-1}$ of creatinine per 24 h; furthermore they were determined in duplicate).

Statistical analysis

Data are presented as mean ± SD and statistical analyses were performed using the SPSS package (SPSS Inc., Chicago, IL, version. 16.0). After checking the normality of data distribution using the Shapiro-Wilk test, an independent t-test was performed to determine significant differences between groups in baseline values. To assess and compare physical and hormonal responses in sevens rugby players according to low and high TSF, a two (G1 > 20 and G2 < 20) × 3 (time: pre-training, post-6-week IT and post-2-week TAP) analysis of variance (ANOVA) with time as the repeated within-participant factor was used. Bonferroni post-hoc testing was then performed to identify any differences following a significant group × time interaction effect. For each variable (test and hormone level), partial eta-squared values (ηp2) were used for effect size calculation (with ηp2 up to 0.059 = small; between 0.059 and 0.138 = medium and greater than 0.138 = large) [26]. Additionally, between-group standardized mean differences or effect sizes (ES) of pre-training, pre-training to post-6-week IT and pre-training to post-2-week TAP in performance and hormone changes were calculated using Cohen's *d* and corrected by Hedge's *g* as our sample size was small (< 20) to avoid a biased estimation of the population effect size provided by Cohen's *d*. According to Cohen, ES can be classified as small ($0 \le d \le 0.49$), medium ($0.50 \le d \le 0.79$), and large ($d \ge 0.80$) [27]. The level of significance was set at $p \le 0.05$.

RESULTS

All participants attended all training sessions with no test or training-related reported injuries. Table 1 shows anthropometrics and physical performances and Table 2 shows urinary hormone concentration results.

Pre-training data

Pre-training data showed no statistically significant differences for anthropometric, physical tests, and urinary hormone variables between groups except for AD (ES = 1.68) and AD/NAD ratio (ES = 2.02).

TSF, TL and TS

The TSF, TL and TS are reported in Figures 2A, 2B and 2C, respectively. TSF increased until reaching a peak value over the 5th week during the 6-week IT period in both groups. This increase was associated with simultaneously increased values of TL and TS with the highest score recorded during the 5th week. Significant interactions were found (training × group) for TSF, TL and TS ($F(1,14) = 30.48$, $\eta p2 = 0.69$; $F(1,14) = 9.17$, $\eta p2 = 0.40$; $F(1,14) = 11.29$, $\eta p2 = 0.45$, respectively). Post-hoc analysis revealed that the increase in TSF was significantly larger in G1 > 20 compared to G2 < 20 at the 2nd, 3rd, 4th, 5th and 6th week of the IT period (ES from 1.17 to 1.75; $p < 0.01$). Similarly, the increase in TL and TS was significantly larger in G1 > 20 compared to G2 < 20 at the 3rd (ES = 1.23 and ES = 0.81, respectively) and the 5th (ES = 1.06 and ES = 1.42, respectively) week of the IT period. Conversely, all the parameters decreased significantly during the 2-week TAP. TSF, TL and TS decreased significantly during the TAP in both groups ($p < 0.01$). No significant difference in TSF, TL and TS values was recorded between groups during TAP.

Testing performances

Significant interactions were found (training × group) for 20-m sprint, 1RM squat (SQT) and 1RM bench press (BP) performances ($F(1,14) = 4.15$, $\eta p2 = 0.23$; $F(1,14) = 6.28$, $\eta p2 = 0.31$ and $F(1,14) = 10.87$, $\eta p2 = 0.44$, respectively). Indeed, after the IT period (T1), all performances significantly decreased in G1 > 20

TABLE 1. Anthropometric and physical performance data over the 8-wk training period in GTSF > 20 and GTSF < 20.

	GTSF > 20 (n = 9)			GTSF < 20 (n = 8)			η_p^2 (group)/ *p* value	η_p^2 (Time)/ *p* value	η_p^2 (time × group)/ *p* value
	T_0	T_1	T_2	T_0	T_1	T_2			
Age (year)	24.8 ± 3.8	-	-	22.7 ± 1.3	-	-			
Height (cm)	1.82 ± 0.07	-	-	1.84 ± 0.06	-	-			
Body mass (kg)	86.8 ± 8.4	85.0 ± 7.9*	85.1 ± 7.9*	88.1 ± 5.8	86.6 ± 6.2*	86.7 ± 6.1*	0.01/0.70	0.72/0.000	0.01/0.85
Fat mass (%)	14.2 ± 3.0	12.2 ± 2.6*	12.2 ± 2.7*	11.6 ± 1.4	10.0 ± 1.4*	9.9 ± 1.5*	0.23/0.06	0.79/0.000	0.05/0.52
Lean mass (kg)	74.4 ± 6.9	74.6 ± 7.0	74.7 ± 7.1	77.8 ± 4.8	77.9 ± 4.8	78.0 ± 4.7	0.08/0.30	0.32/0.004	0.009/0.88
10-m sprint (s)	1.82 ± 0.10	1.88 ± 0.07**	1.79 ± 0.09*	1.82 ± 0.04	1.84 ± 0.05*	1.80 ± 0.04*	0.003/0.85	0.56/0.000	0.16/0.08
20-m sprint (s)	3.13 ± 0.08	3.17 ± 0.09*	3.07 ± 0.09*	3.12 ± 0.06	3.14 ± 0.07*	3.09 ± 0.06*	0.004/0.83	0.65/0.000	0.23/0.03
30-m sprint (s)	4.28 ± 0.17	4.41 ± 0.15**	4.28 ± 0.14	4.31 ± 0.10	4.36 ± 0.09*	4.29 ± 0.09*	0.000/0.98	0.41/0.001	0.10/0.23
AGT (s)	16.78 ± 0.37	17.25 ± 0.34*	16.32 ± 0.50*	16.65 ± 0.31	16.95 ± 0.31*	16.37 ± 0.19*	0.01/0.72	0.63/0.000	0.09/0.26
FJT (m)	11.8 ± 0.5	11.4 ± 0.4**	12.8 ± 0.6*	11.4 ± 0.8	11.2 ± 0.8*§	12.5 ± 1.3*	0.1/0.24	0.62/0.000	0.004/0.95
LT (m)	718.9 ± 42.5	709.9 ± 41.8	736.3 ± 35.8*	696.4 ± 24.7	692.4 ± 23.3	715.1 ± 16.4*	0.1/0.24	0.73/0.000	0.03/0.68
Yo-YoIRT2 (m)	1728.9 ± 394.9	1604.4 ± 395.7**	1902.2 ± 423.8*	1731.4 ± 199.6	1651.4 ± 184.3*§	1954.3 ± 188.2**	0.003/0.84	0.92/0.000	0.08/0.31
1RM SQT (kg)	166.4 ± 19.9	152.6 ± 18.3**	170.4 ± 18.6*	165.6 ± 10.7	158.9 ± 12.8*§§	170.3 ± 10.2*	0.003/0.87	0.92/0.000	0.31/0.006
1RM BP (kg)	116.2 ± 8.8	106.3 ± 10.7**	118.6 ± 9.3*	112.9 ± 11.2	108.6 ± 10.4*§§	117.4 ± 12**§§	0.002/0.87	0.87/0.000	0.44/0.000

Note: GTSF > 20: group of players with total score of fatigue above 20; GTSF < 20: group of players with total score of fatigue below 20; AGT: agility test; FJT: five jump test; LT: Lactic test; YoYoIRT2: YoYo intermittent recovery test level 2; 1RM: maximum repetition; SQT: squat; BP: bench press. * Statistical difference within group from T_0; * $p < 0.05$, ** $p < 0.01$. § Statistical difference from GTSF > 20 at the same time of the training program; § $P < 0.05$, §§ $P < 0.01$.

TABLE 2. Changes in urinary hormones and their ratios over 8-week training program in GTSF > 20 and GTSF < 20.

	GTSF > 20 (n = 9)			GTSF < 20 (n = 7)			η_p^2 (group)/ *p* value	η_p^2 (Time)/ *p* value	η_p^2 (time × group)/ *p* value
	T_0	T_1	T_2	T_0	T_1	T_2			
CL de 24 h ($\mu g \cdot mg^{-1}$ of creatinin)	17.4 ± 1.4	24.7 ± 2.6**	17.9 ± 1.4	16.8 ± 0.6	21.9 ± 1.0**§§	17.0 ± 0.5	0.25/0.051	0.95/0.000	0.35/0.003
CN de 24 h ($\mu g \cdot mg^{-1}$ of creatinin)	22.5 ± 1.9	24.7 ± 2.4*	22.9 ± 1.8	21.7 ± 1.1	25.2 ± 1.7**§	21.9 ± 1.0	0.01/0.70	0.88/0.000	0.30/0.007
CL/CN ratio	0.78 ± 0.05	1.00 ± 0.10**	0.78 ± 0.06	0.77 ± 0.03	0.87 ± 0.06*§§	0.78 ± 0.02	0.17/0.12	0.89/0.000	0.55/0.000
AD de 24 h ($\mu g \cdot mg^{-1}$ of créatinin)	10.4 ± 0.5	6.2 ± 1.3**	12.3 ± 0.7*	9.4 ± 0.8	8.1 ± 0.9*§§	10.0 ± 1.5	0.03/0.56	0.85/0.000	0.47/0.003
NAD de 24 h ($\mu g \cdot mg^{-1}$ of créatinin)	24.4 ± 1.2	18.5 ± 1.0**	26.6 ± 1.1*	25.0 ± 1.1	18.5 ± 0.8**	27.6 ± 1.2*§	0.09/0.70	0.98/0.000	0.13/0.14
AD/NAD ratio	0.43 ± 0.02	0.34 ± 0.10**	0.46 ± 0.07*	0.38 ± 0.03	0.44 ± 0.05**§§	0.40 ± 0.05*	0.08/0.28	0.35/0.003	0.56/0.000

Note: GTSF > 20: group of players with total score of fatigue above 20; GTSF < 20: group of players with total score of fatigue below 20; CL: cortisol; CN: cortisone; AD: adrenaline; NAD: noradrenaline. * Statistical difference within group from T0; * $p < 0.05$, ** $p < 0.01$. § Statistical difference from GTSF > 20 at the same time of the training program; § $P < 0.05$, §§ $P < 0.01$.

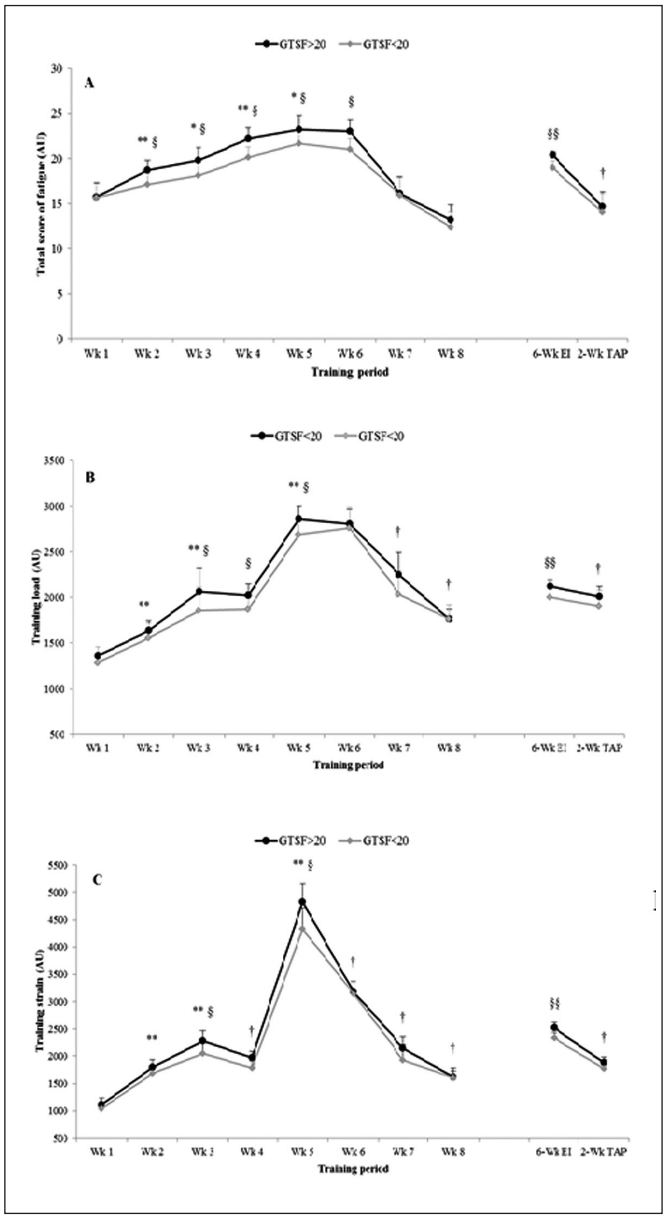


FIG. 2. Total score of fatigue (A), training load (B) and training strain (C) recorded over the 8-week training program in GTSF > 20 and GTSF < 20.
Note: *: higher than the precedent value, *$p < 0.05$, **$p < 0.01$; †: lower than the precedent value, †$p < 0.05$, ††$p < 0.01$; §: higher than the GTSF < 20, §p < 0.05, §§p < 0.01.

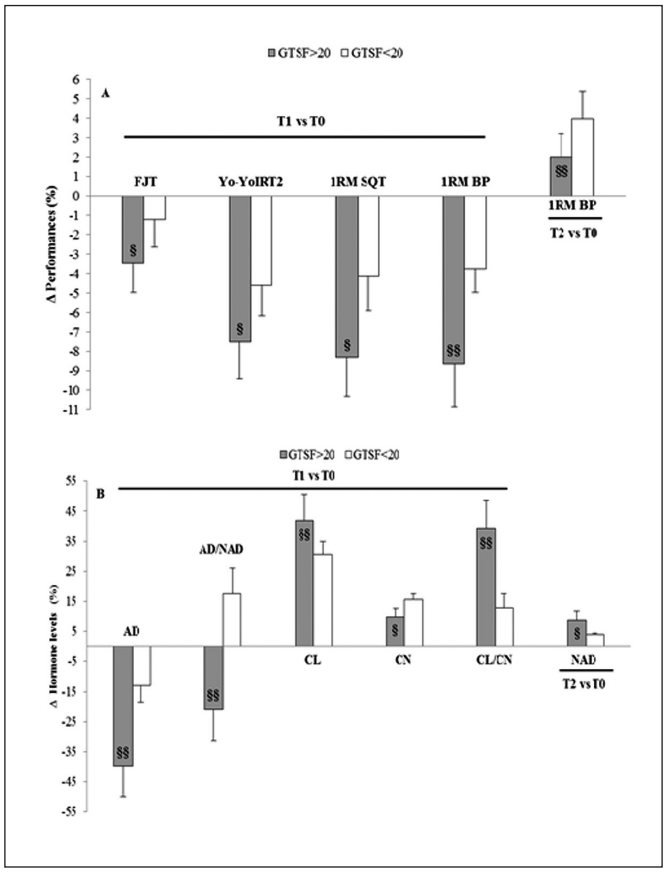


FIG. 3. Changes in testing performances (A) and urinary hormonal levels (B) over the two periods of the training program in GTSF > 20 and GTSF < 20.
Note: GTSF > 20: group of player with a total score of fatigue above 20; GTSF < 20: group of players with a total score of fatigue below 20; FJT: five jump test; YoYoIRT2: YoYo intermittent recovery test level 2; 1RM: one maximum repetition; SQT: squat; BP: bench press, AD: adrenaline; NAD: noradrenaline; AD/NAD: Adrenaline/Noradrenaline ratio; CL: cortisol; CN: cortisone; CL/CN: cortisol/cortisone ratio. §: different from the GTSF < 20; §p < 0.05, §§p < 0.01.

and G2 < 20. Conversely, the TAP (T2) resulted in a significant increase in all testing performances in both groups (Figure 2A). At T1, the decreases in performances of the five-jump test (FJT) (Δ-3.5% vs Δ-1.2%; p < 0.05, ES = -1.58), Yo-YoIRT2 (Δ-7.5% vs Δ-4.6%; p < 0.05, ES = -1.63), 1RM SQT (Δ-8.4% vs Δ-4.1%; p < 0.01, ES = -2.19) and 1RM BP (Δ-8.6% vs Δ-3.8%; p < 0.01, ES = -2.61) were significantly larger in G1 > 20 compared to G2 < 20. At T2, the increase in 1RM BP was significantly larger in G2 < 20 compared to G1 > 20 (Δ+4% vs Δ+2%; p < 0.05, ES = 1.55).

Urinary hormonal changes

Significant interactions were found (training × group) for CL, CN, CN/CL ratio, AD and AD/NAD ratio values ($F(1,14) = 7.46$, $\eta p2 = 0.35$; $F(1,14) = 5.95$, $\eta p2 = 0.30$; $F(1,14) = 16.90$, $\eta p2 = 0.55$; $F(1,14) = 12.36$, $\eta p2 = 0.47$ and $F(1,14) = 17.73$, $\eta p2 = 0.56$, respectively). After the 6-week IT, CL, CN and CL/CN ratio increased significantly while AD and NAD levels decreased significantly in both groups. Compared to T0, CL, CN and CL/CN ratio in T2 returned to baseline values whereas AD and NAD remained significantly higher, especially in G1 > 20 (Figure 2B). At T1, the increase in CL (Δ+41.8% vs Δ+30.5%; ES = 1.60) and CL/CN ratio (Δ+39.2% vs Δ+12.8%; ES = 3.47) and the decrease in AD (Δ-39.8% vs Δ-12.9%; ES = -3.20) were significantly larger in G1 > 20 compared to G2 < 20. AD/NAD ratio increased in G2 < 20

and decreased in G1 > 20 (Δ+17.7% vs Δ-21.0%; ES = 4.05). In addition, CN level was significantly higher in G2 < 20 compared to G1 > 20 (Δ+15.7% vs Δ+9.9%; ES = 2.36). At T2, the increase in NAD level was significantly larger in G1 > 20 compared to G1 < 20 (Δ+8.8% vs Δ+4.0%; ES = 2.17) (Figure 3).

DISCUSSION

The aim of the present study was to examine the effectiveness of a cut-off level of fatigue score of 20 in elite rugby seven players during an 8-week training camp, including a 6-week intense training block (IT) and 2-week tapering (TAP). Accordingly, we compared physical and hormonal responses of two groups of players using this score as a potential moderator variable (G1 > 20 and G2 < 20). The main findings indicated that a high training load programme generated a significantly large increase (with large effect size) in TSF, TL and TS in G1 > 20 compared to G2 < 20, which was associated with significantly greater alteration in hormone levels and physical performances in the G1 > 20. The data also demonstrated that following the 2 weeks of TAP all variables returned to baseline values in both groups while the NAD level remained higher in G1 > 20 compared to G2 < 20. This result is concomitant with similar improvement in both groups of physical performance, except the 1RM BP, which became higher in G2 < 20.

It was pointed out that managing athlete stress and fatigue is crucial in monitoring athlete loads. This is particularly important in terms of the measures which may offer insights into whether the athlete is adapting positively or negatively to the training and competition stress. The present data corroborate several previous studies that investigated a "global" sense of the relationship between the perceptual fatigue-related training and physiological, hormonal, neuromuscular and cardiovascular parameters [11, 17, 20]. Indeed, a deeper approach has been recommended by the French Society for Sport Medicine to detect and to prevent an early state of fatigue, when they suggested a TSF of 20 as the threshold of this fatigue state [19]. In this context, several authors have adopted the threshold score of 20 since it is considered as an alarm signal of a state of fatigue or non-functional overtraining [18, 21, 22]. However, further confirmation studies are needed in this regard.

The high TL and TS observed during the initial 6-week IT is concomitant with the larger increase of urinary CL and CN levels and CL/CN ratio and conversely with the larger decrease of urinary AD and NAD levels in G1 > 20 compared to G2 < 20. Previous studies examining the effect of training programmes on salivary or plasma catabolic hormones have presented discrepant results in team-sport athletes [11, 20, 28, 29]. Kraemer et al. [30], Coutts et al. [28, 29] and Campos et al. [11] reported significantly higher resting saliva or plasma cortisol levels with performance impairments in soccer and rugby players as well as individual athletes. Conversely, Elloumi et al. [17] reported decreased performance in rugby league players over a 14-week training programme despite unaltered resting saliva cortisol levels. The discrepant results could be explained by several factors such as sampling methods, circadian rhythm, and cortisol metabolism. It is well accepted that cortisol secretion follows a circadian rhythm with significant fluctuation of its plasma or salivary concentrations between awakening and the evening nadir. In fact, the major benefit of 24 h urinary collection is that the measure of the urinary hormone excretion represents both a good reflection of hormonal secretion under the time of sampling and a non-stressful measurement [31, 32].

The present study also highlighted a significant increase in CL and CN levels as well as CL/CN ratios between T0 and T1. Likewise, TL, TS and TSF showed higher values associated with a significantly larger decline in physical performance (large effect) in G1 > 20 compared to G2 < 20. When considering previous studies examining CL, CN and CL/CN ratio changes over intensified training periods [9, 10]; it appears that such higher hormone levels may be explained in part by a higher responsiveness of the hypothalamo-pituitary-adrenal axis to physiological adaptation of the neuroendocrine system to chronic exercise demands, without ruling out a potential modification of the clearance of these hormones. Interestingly, consistently with the findings of Atlaoui et al. [9] and Rouveix et al. [13], the increased CL/CN ratio as well as CL and CN levels was associated with increased TSF, TL and TS and decreased physical performances. In addition, Atlaoui et al. [9] reported that the CL and CN concentrations of one swimmer, who had high fatigue scores, were higher than those of the other less fatigued swimmers. In line with this, Elloumi et al. [22] observed a decrease of somatomedin axis hormones (anabolic effect) after an international rugby match in more fatigued players (TSF; 21.0 ± 3.5). The latter authors suggested that low levels of this hormone are linked to a state of fatigue. The association of increased CL and CN levels as well as CL/CN ratio with decreased performance standards at T1 is in agreement with previous conclusions indicating catabolic state-related training [3, 9, 13]. This catabolic state was more pronounced in G1 > 20 compared to G2 < 20.

The training programme also induced lowered urinary AD and NAD levels as well as AD/NAD ratio compared to pre-training values in both groups (especially in G1 > 20). The decreased catecholamine with IT is in agreement with previous research on swimmers, tennis players and rugby sevens players [3, 9, 12, 13] but inconsistent with those reported in 18 semi-professional rugby league players [28, 29]. A possible reason for the differences between Coutts's findings and the present results is that the training load and strain increased steeply during the last two weeks of IT in our study, whereas in the studies by Coutts et al. [28, 29], the athletes were intentionally overloaded with a progressive increase of training load and strain. It has been pointed out that repeated exposure to stressful conditions related to exercise training, such as the rugby training performed in the present study, is frequent but not always accompanied by a reduction of stress-induced catecholamine secretion [9, 12, 13]. Because NAD is mostly affected by physical stress while AD rather more by mental stress [33], we believe that the magnitude of

decrease of AD in G1 > 20 is due to mental stress related to training. Accordingly, the decrease of AD/NAD ratio reported in G1 > 20 after the initial 6-week IT can partly be explained by the reduction of sympatho-adrenomedullary activity with intensified training [10, 12]. However, the phenomenon of homeostasis disturbance was transient since the study's participants showed an ability to improve their performance standards following a short-term regeneration period (i.e. 2-week TAP). Concurrently with these performance's positive responses, CL/CN and AD/NAD ratios returned to their baseline values. It has been pointed out that exercise training sessions cause transient changes in physiological function that, when repeated over time, predispose the exercising organism to beneficial adaptations [34]. The short-term step taper completed in this study allowed for overcompensation in the majority of the measured physical performances, along with a return to a homeostasis environment especially in G2 < 20. Indeed, another salient finding of the present study was that G1 > 20 did not exhibit complete homeostasis compared with G2 < 20, resulting in a higher value of AD and a smaller improvement in 1MRBP after TAP. Overall, these data showed that 2-week tapering, suggested as the most efficient strategy to maximize performance gains [35], generates physiological and psychological complete recovery. These results are also in agreement with previous studies in team-sport athletes [3, 28, 29, 36]. Therefore, we suggest that a value of 20 units for TSF could be considered as a cut-off level above which performance could be decreased, potentially resulting in overreaching if the training load is not adjusted. To confirm or to complement these results, further research is needed in larger cohorts and/or other team sports. Importantly, the individual variations in the TSF should be examined in relation to changes in performance and biological markers throughout an extensive follow-up where fatigue occurs. The present study has some limitations that should be recognized. Despite the use of TSF and sRPE procedures which have been used to quantify training load and fatigue in high level rugby sevens players [3], we did not assess other variables such as heart rate, self-reporting of stress, fatigue, muscle soreness and quality of sleep in addition to other biochemical/hormonal and immunological variables, which are all considered as internal training load indices that could have increased the value of our study. These should be considered by future investigations in the field.

CONCLUSIONS

The findings support the suitability of the TSF in identifying rugby sevens players with high training-related levels of fatigue that are associated with negative physiological responses. A cut-off threshold higher than or equal to 20 appears to be an alarming signal of high fatigue condition and potentially an overload to be considered for training adjustments. Two weeks of tapering allowed the homeostasis state to revert back to pre-training levels. This suggests that this level of fatigue is easily detectable and still rapidly revertible. Further studies are required to either reinforce the effectiveness of this score value, or to adjust it according to high-level athletes' adaptations.

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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

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ABSTRACT: Flywheel resistance training devices (FRTD) is shown effective in improving strength, sprinting, jumping and changes of direction (COD) performance in male soccer players, however, this is not elucidated in female soccer players. We aimed to assess the effect of FRTD on these physical abilities in females soccer players. 24 professional female soccer players (age: 20.4 ± 2.6 years) were randomly assigned to a flywheel training group (FWTG) that trained twice a week for 6 weeks on a rotary inertia device with an initial volume of 3 sets of 6 repetitions and an inertia of 0,025 $kg \cdot m^{-2}$, increasing intensity and volume or a control group (CG) that did not performed any additional resistance training program. Concentric peak torque of the knee extensors (CONEXT) and flexors (CONFLEX), eccentric peak torque of the knee extensors (ECCEXT) and flexors (ECCFLEX) at $60° \cdot s^{-1}$ on an isokinetic dynamometer, countermovement jump (CMJ) height, COD and 30-metres sprint were assessed. Significant time by group interactions were found in CONEXT ($p = 0.002$; $\eta^2p = 0.425$), CONFLEX ($p = 0.037$; $\eta^2p = 0.22$), ECCEXT ($p = 0.002$; $\eta^2p = 0.43$) and ECCFLEX ($p = 0.008$; $\eta^2p = 0.334$). No time by group effect was found in CMJ ($p = 0.061$; $\eta^2p = 0.182$), COD ($p = 0.067$; $\eta^2p = 0.184$) or sprint ($p = 0.926$; $\eta^2p = 4.979 \cdot e^{-4}$). In conclusion, 6 weeks of flywheel squat training improved strength (especially eccentric strength) but not soccer-specific abilities such as jumping, changing of direction or sprinting in professional soccer players.

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INTRODUCTION

High-intensity actions, such as sprinting, jumping or changes of direction (COD) are decisive both in men's and women's soccer [1, 2]. These actions are becoming even more important in recent years, with the subsequent increment in the distance covered at high-intensities and the total number of sprints performed by soccer players [3, 4].

Women performance in high-intensity actions, such as sprinting or COD are differential factors in the competitive level, especially in high-speed running and sprinting due to its strong link to scoring chances [5]. These high-intensity actions (i.e. sprinting and COD), together with the countermovement jump (CMJ) were described as discriminatory variables of the competitive level in female soccer players, differentiating elite female soccer players from those of a lower level [5, 6]. Therefore, sprinting, COD and jump height are considered crucial skills in women's soccer performance and in the game demands.

Lower-limb strengthening has been described as one of the main strategies to improve jump performance, COD and sprint time in soccer players [7, 8]. Moreover, and despite COD being a multifactorial ability [9], its performance is also related to strength development [10]. Consequently, due to the relevance of the strength levels in women's soccer [11] and its aforementioned importance in sprint, COD and jump performance, improving these might be one of the main goals of a strength and conditioning (S&C) coach in women's soccer.

In female athletes, physical performance was also significantly enhanced after resistance training [12], and especially in soccer [13]. These studies are usually based on traditional methods employing free weights (e.g., barbell) [14], weight stacks (e.g., pulley guided weight machine) [15] and/or the athletes' body mass [16], which usually represent a constant external load that does not suit the athlete [17] (i.e., do not provide maximal resistance load during both movement phases). To overcome this issue, flywheel resistance training devices (FRTD) allows athletes to adapt the intensity to their effort due to the accommodated resistance from the flywheel [17], providing a nearly maximal resistance load during the concentric (CON) and eccentric (ECC) phase of the movement [17] due to their mechanical properties.

Interest in the use of FRTD has increased considerably [18]. FRTD consist of one or more disks connected to a shaft with a tether or a rope wrapped around [19]. Flywheel systems use kinetic energy

generated during the CON phase of the movement to transfer it to ECC phase [17, 18]. Due to the greater force that ECC actions can produce with a reduced cost of energy [20] and the larger adaptations produced by resistance training based on ECC exercise such as in hypertrophy, strength and power [21], FRTD have been commonly used to develop specific and determinant abilities in team sport players, such as sprinting, COD or jumping [19, 22].

Longitudinal studies (i.e., 6–8 weeks resistance training programs) using FRTD have shown significant improvements in strength, COD, jump height or sprint performance in male soccer players [13, 22, 23]. Further, a recent systematic review [24] reported that a wide variety of training programs based on flywheel devices can improve strength, power, jump, and COD time in male soccer players of different competitive levels. However, it seems that 6–11 weeks are enough to significantly enhance these abilities.

Nevertheless, only three studies have analyzed the effects of resistance training with FRTD on female team sport players. One was focused on the effects of unilateral exercises on unilateral jump height, COD and sprint in volleyball and basketball players [25]. Another analyzed strength, speed, power and COD changes after flywheel squat resistance training on basketball players [26]. Only one has analyzed the effects of a training program based on FRTD in female soccer players [27], reporting significant improvements in the intensity of maximum accelerations and decelerations during soccer matches as well as the distance performed accelerating and decelerating at 3 m/s^2. Therefore, previous studies performed different exercises and/or in different populations [25, 26] or analyzed very different variables from those assessed in the present study [27]. Despite the aforementioned importance of FRTD on strength and soccer-specific abilities in this population, to our knowledge, there are no studies assessing the effects of this training paradigm on these abilities in female soccer players following basic exercises such as squat. Evidence is needed for S&C coaches on the effects of training with FRTD in female soccer players to implement them in strength training programs. Consequently, the aim of this study was to analyze the effects of a 6 weeks in-season training program on lower-limb strength, sprint, COD and jump performance using a FRTD in professional female soccer players. It was hypothesised that 6 weeks of complementary flywheel squat resistance training would significantly improve strength levels, vertical jump height, COD and sprint time.

MATERIALS AND METHODS

Subjects

Twenty-four professional female soccer players (age: 20.4 ± 2.6 years; height: 1.62 ± 0.05 m; body mass: 58.7 ± 7.2 kg; body-mass index: 22.2 ± 2.4 $kg \cdot m^{-2}$; competition experience: 8.86 ± 3.36 years) belonging to the same club competing in the First National Division voluntarily participated in the study. During the season, the usual training volume was three training sessions per week on the soccer field of 90 to 120 minutes in addition to a competitive match throughout the weekend. Players were already familiar with traditional resistance training, but not FRTD. The study was conducted according to the Declaration of Helsinki, and the experimental protocol was approved by a local research ethics committee (CEI de los Hospitales Universitarios Virgen Macarena y Virgen del Rocío, Seville, Spain. Approval number: 2471-N-20). All players were required to sign an informed consent in which the entire evaluative and experimental process was detailed.

Players were excluded from the study prior to the initial evaluations if I) has suffered any joint or bone injury in the last six months, II) had programmed a change in her lifestyle during the evaluative or experimental phase of the study that could alter the results of the tests proposed for the evaluation or III) was pregnant.

TABLE 1. Descriptive data of the players. Mean ± SD.

	FWTG (n = 12)	CG (n = 12)
Age (years)	20.8 ± 2.6	20.1 ± 2.6
Height (m)	1.61 ± 0.04	1.64 ± 5.6
Body mass (kg)	57.5 ± 7.3	59.9 ± 6.9
Body-mass index ($kg \cdot m^{-2}$)	22.15 ± 2.8	22.3 ± 2
Field position		
Goalkeeper (n)	1	2
Central back (n)	3	2
Full back (n)	2	2
Central midfielder (n)	3	2
Lateral midfielder (n)	2	2
Forward (n)	1	2

Design

The current study followed a randomized controlled trial model. Players were randomly assigned to a flywheel training group (FWTG; n = 12) or a control group (CG; n = 12). FWTG underwent a resistance training intervention in addition to the usual training on the soccer field, while CG continued their usual training sessions without performing flywheel resistance training or any complementary resistance training. Both groups performed the same training sessions on the soccer field. Players who did not complete at least 75% of the training program or who were unable to complete posttests (i.e. due to injury) were not included in the final analysis. Two FWTG players (i.e., one due to injury and another due to not having completed 75% of the training sessions) and two CG players (i.e., due to injury) were not included in the final analysis, resulting in a reduced sample size both in FWTG (FWTG; n = 10) and CG (CG; n = 10). Besides, one participant had very extreme scores on her COD data and was removed from the analyses as an outlier. The descriptive data of each group are shown in Table 1.

TABLE 2. Evaluation and experimental intervention schedule

	Week 1	Week 2–7	Week 8
Day 1	Body composition Isokinetic measurements Field tests familiarization	Experimental intervention	Isokinetic measurements
Day 2	Field tests: CMJ, COD and sprint	Experimental intervention	Field tests

Methodology

The testing protocol is shown in Table 2. Players were instructed to avoid vigorous exercise the day before testing. Field tests were carried out in the following order: CMJ, COD and sprint. Between tests, the players were allowed a 3-minute rest time. All players were previously familiarized with the evaluation protocol procedures due to their inexperience with the tests performed. During the execution of the tests, the players received strong verbal encouragement.

Isokinetic measurements. A Biodex dynamometer (Biodex Medical System, Shirley, New York, USA) was used for the isokinetic measurements. The players were seated on the dynamometer with a hip angle of 85°. The lateral epicondyle of the femur was aligned with the axis of rotation of the dynamometer. A warm-up consisting of 3 sets of 10 body-weight squat repetitions was performed [23]. Concentric peak torque of the knee extensors (CONEXT) and flexors (CONFLEX) as well as eccentric peak torque of the knee extensors (ECCEXT) and flexors (ECCFLEX) were measured at $60° \cdot s^{-1}$ [23].

Following two warm-up repetitions, each player executed 1 set of 5 repetitions at maximal intended effort, evaluating the extension and the flexion movements in pairs (concentric-concentric and eccentric-eccentric), with a 2-minute rest of passive recovery. Only the dominant leg, defined as the preferred leg to kick the ball [23] was evaluated.

Field tests. Before testing, the players conducted a warm-up consisting of 5 minutes of jogging at a self-selected pace, 2–3 minutes of lower-limbs mobilizations and 2 sets of 10 body-weight squats. Following, they conducted a specific warm-up: 1 set of 5 submaximal jumps (CMJ) and 2 submaximal efforts (COD and sprint). All the tests were carried out on the players' usual training surface (artificial turf), except for the vertical jump due to the equipment used. The tests were performed with specific footwear for soccer practice.

Countermovement jump test (CMJ). Vertical jump height isolating the lower-limbs action was used as a representative measure of lower-limb impulsive strength [19]. Contact cells (Optogait, Microgate, Bolzano, Italy) were used to determine flight (t), with jump height determined from the formula: jump height = $G*t^2/8$. Players were instructed to jump for maximum height with hands placed in their hips and without flexing the knees during the flight phase, as well as on landing. Each player performed three jumps, separated by a 2-minute passive recovery rest time. The best of the three trials was entered into the analysis. Results showed an *excellent* reliability in this test (Intraclass correlation coefficient -ICC- (3,1) = 0.951) from the three attempts performed.

5+5 meters shuttle run-sprint test (COD test). Players performed two maximum efforts, with 2 minutes of passive recovery between trials. One single beam timing gate (Microgate, Bolzano, Italy) was placed at the beginning to record the time to complete the test. The players had to sprint from the start, located 30 centimeters behind the timing gate to a line marked 5 meters apart and return to the starting position as quickly as possible, stepping beyond the line freely with the preferred foot of the player [9]. The best of the two trials was introduced in the final analysis. Results showed *excellent* reliability (ICC (3,1) = 0.911) from the two attempts performed.

30-metres linear sprint test. The evaluation of the linear sprint was carried out with the same photocells (Microgate, Bolzano, Italy), located both at the start and 30 meters away. The players had three attempts, separated by 3-minutes of passive recovery between them. The best of the three attempts was used for data analyses. Players were placed 30 centimeters behind the first photocell for the start of the sprint, with the preferred foot in a forward position and the toe of the foot on the line marked on the ground [23]. *Excellent* reliability was found for this test (ICC (3,1) = 0.945) from the three attempts performed.

Experimental intervention

Figure 1 represents the intervention protocol. Prior to the intervention, three familiarization sessions were provided during week 1 to ensure squatting correct technique in parallel with the evaluation protocol. A FRTD with a horizontal cylinder-shaped shaft (Kbox 3, Exxentrix AB, Stockholm, Sweden) and a harness fixed to the shaft through a strap were used for the intervention. We used two different moments of inertia (inertia #1: 0,025 $kg \cdot m^{-2}$, #2: 0,050 $kg \cdot m^{-2}$) commonly used with female populations [28] that showed a significant loading using the same FRTD [29]. This allows to progressively increase the external load along the resistance training program, following the progression training principle [30]. Players were instructed to execute the CON phase as fast as possible, and consequently to decelerate the disk at the end of the ECC phase (e.g., thighs parallel to the ground). Players performed two resistance training sessions per week. The training sessions were separated by a minimum of 48 hours, coinciding with the usual on-field training days and prior to the main training soccer field session. At the beginning, players performed a 5-minute warm-up consisting of lower-limbs mobilizations and 1 submaximal set of 8 repetitions with inertia #1. During the experimental intervention, progression in training load was followed (see Figure 1). Players performed 2 submaximal repetitions prior to each set to speed up the disk. Rest time was 2 to 3 minutes between sets. During the training sessions, power was recorded using

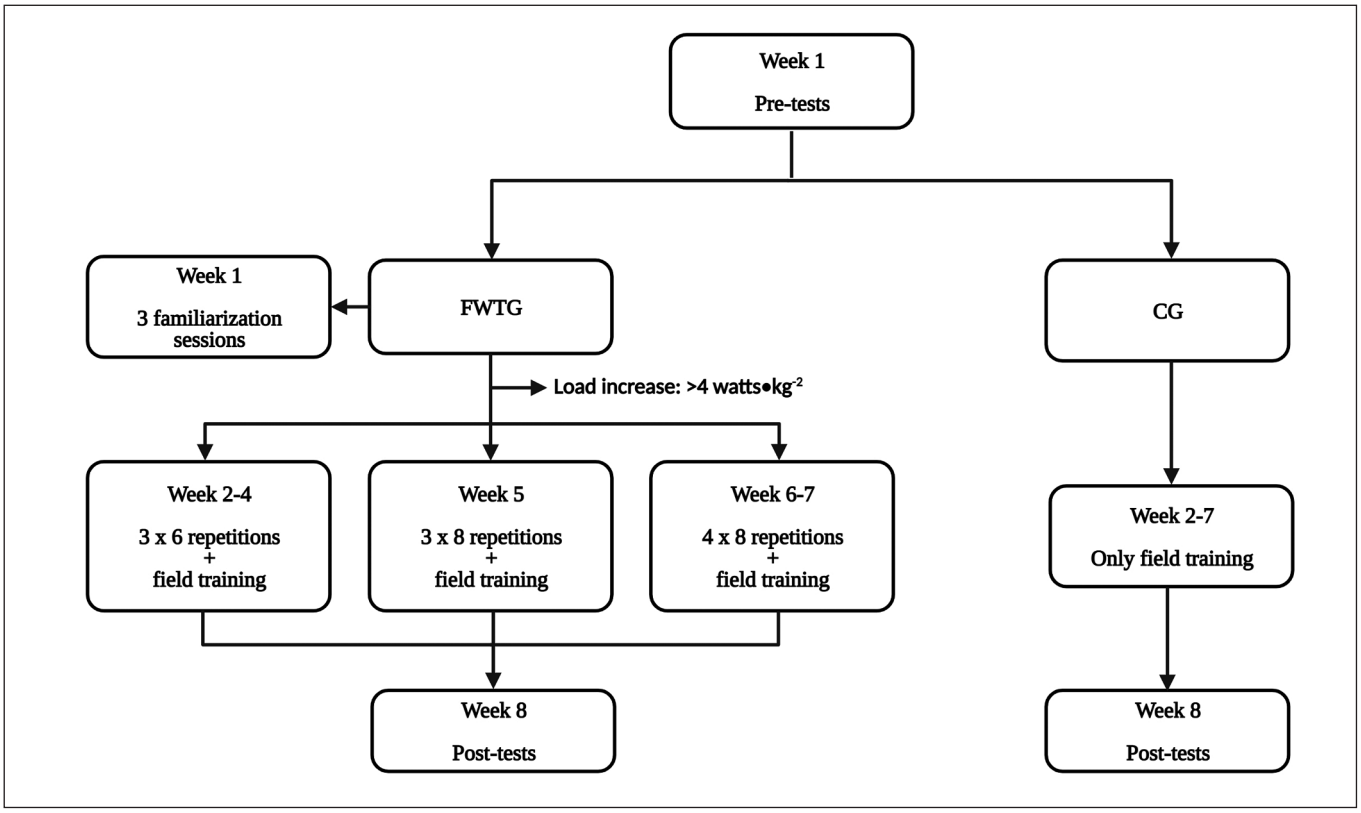


FIG. 1. Resistance training program for the experimental intervention.

TABLE 3. Changes in field tests.

Test	Group	Pre (mean ± SD)	Post (mean ± SD)	Change (Δ %)	Changes in Time		Changes in Group		Changes in Time X Group	
					p	η^2 p	p	η^2 p	p	η^2 p
CMJ (cm)	FWTG	26.08 ± 5.76	27.87 ± 7.78	5.61 ± 7.3	0.098	0.145	0.568	0.018	0.061	0.182
	CG	28.4 ± 3.02	28.28 ± 3.48	-0.38 ± 6.61						
COD (s)	FWTG	2.95 ± 0.18	2.91 ± 0.16	-1.46 ± 2.3	< 0.001	0.527	0.236	0.082	0.067	0.184
	CG	2.91 ± 0.13	2.79 ± 0.11	-3.98 ± 2.89						
Sprint (s)	FWTG	5.07 ± 0.32	5.04 ± 0.38	-0.55 ± 1.81	0.388	0.042	0.580	0.017	0.926	0.001
	CG	5 ± 0.26	4.96 ± 0.29	-0.59 ± 3.53						

CMJ = countermovement jump test. COD = change of direction test. FWTG = flywheel training group. CG = control group.

a rotary encoder (SmartCoach™, SmartCoach Europe AB, Stockholm, Sweden). All players started with inertia #1, progressing to inertia #2 if they were able to generate a mean CON power > 4 watts · kg^{-1} in all repetitions of a set [13].

Statistical analysis

Data is shown in the text as percentage of change (%) ± standard deviation (SD). First, we test the data normality using the Shapiro-Wilk normality test. Then, we compared the changes in Time (Pre vs Post) by Group (FWTG vs CG) using a two-way mixed ANOVA repeated measures test. In addition, we tested changes in Time and Group as main factors. If a significant interaction was observed, we performed an exploratory simple main effects analysis for Time factor, using Group as moderator (between-groups differences). We used the eta-partial squared (η^2p) as a measure of the effect size. For statistical differences, we considered an alpha level of 0.05. We carried out all the analyses using the JASP software (JASP Team -2020, Version 0.14.1).

Our power analysis, based on the test performed (two-way mixed ANOVA repeated measures test), revealed a minimum of

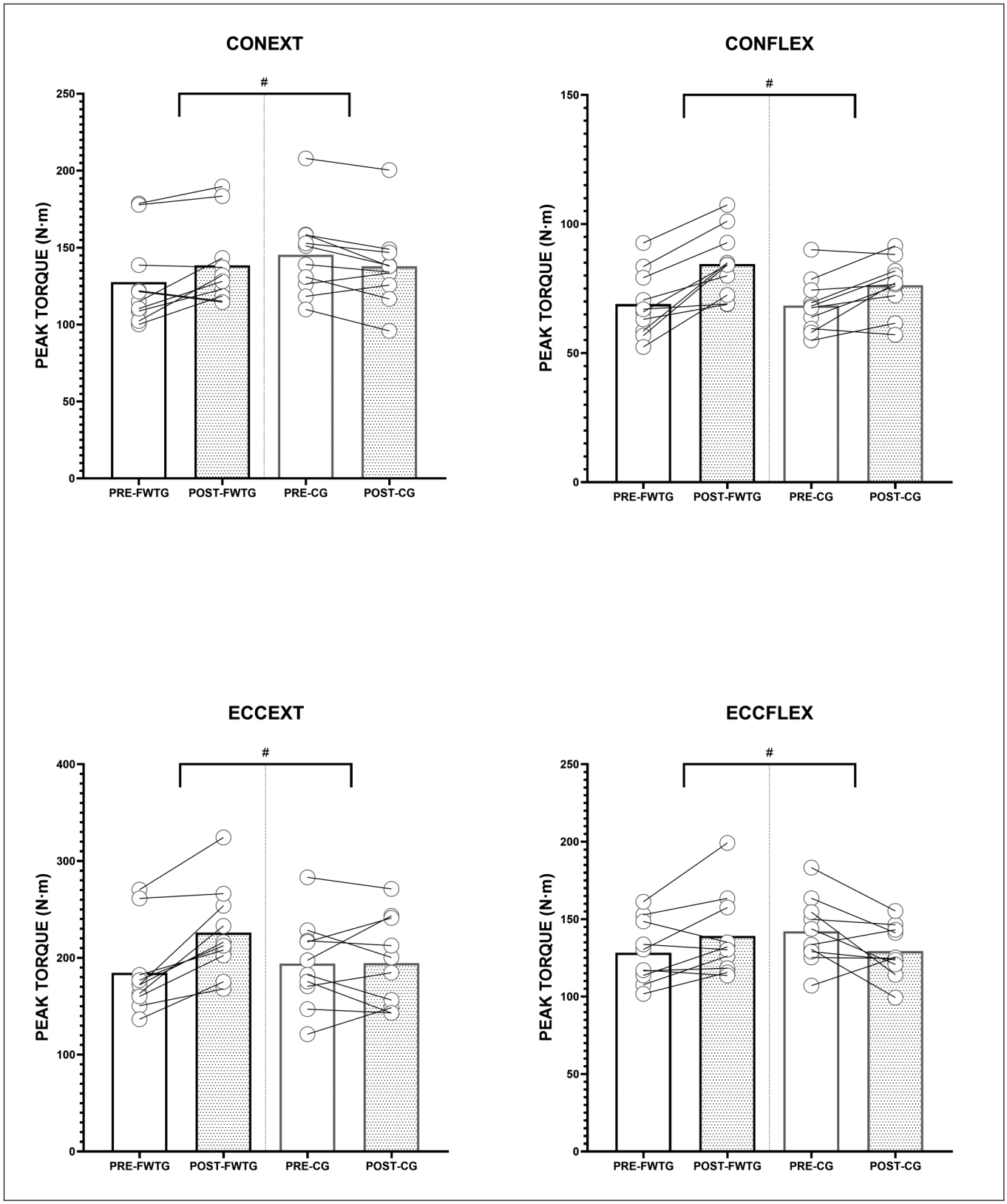


FIG. 2. Pre-post changes in isokinetic measurements. CONEXT = Concentric peak torque of the knee extensors. CONFLEX = Concentric peak torque of the knee flexors. ECCEXT = Eccentric peak torque of the knee extensors. ECCFLEX = Eccentric peak torque of the knee flexors. FWTG = Flywheel training group. CG = Control group. # = Significant time by group interactions ($p < 0.05$).

16 participants in total to reach a statistical power of 80% with an alpha error of 0.05 and an effect size of 0.40 (corresponding to a large η^2_p).

RESULTS

FWTG showed an increase in CONEXT (+9.84% ± 12.32), CONFLEX (+23.91% ± 15.42), ECCEXT (+23.81% ± 13.71) and ECCFLEX (+8.51% ± 11.31) mean values. CG showed an increase in CONFLEX (+12% ± 11.27) and ECCEXT (+1.12% ± 14.77) mean values, with a reduction in CONEXT (-5.02% ± 6.77) and ECCFLEX (-7.78% ± 13.70) mean values. Time by group interactions were found in CONEXT ($p = 0.002$; $\eta^2p = 0.425$), CONFLEX ($p = 0.037$; $\eta^2p = 0.22$), ECCEXT ($p = 0.002$; $\eta^2p = 0.43$) and ECCFLEX ($p = 0.008$; $\eta^2p = 0.334$). Descriptive data of isokinetic measurements and individual changes are shown in figure 2.

The results of the field tests are shown on Table 3.

DISCUSSION

Our results showed that 6 weeks of flywheel squat training significantly improved strength (CONEXT, CONFLEX, ECCEXT, ECCFLEX), but not CMJ, COD or sprint compared to traditional soccer field training.

Recently, Coratella et al. [23] evaluated the effects of 10 weeks of flywheel squat training in male soccer players and reported significant improvements in all isokinetic peak torque parameters in knee extensors and flexors. Further, Nuñez et al. [19] reported significant improvements in lower-limbs power in an all-out 8 repetitions test after 6 weeks of flywheel squat training in male soccer players using the same FRTD. Our results, although in female players, are in agreement with these findings, showing that 6 weeks of flywheel squat added to the usual on-field training are enough to induce significant and superior improvements in CONEXT, ECCEXT, CONFLEX and ECCFLEX. Therefore, we attribute the improvements and the differences reported in FWTG compared to CG to adaptations derived from the 6 weeks of flywheel squat training. It should be noted that greater effects were found in ECCEXT and ECCFLEX rather than CONEXT and CONFLEX, respectively. This finding could be attributable to the marked ECC component presented by FRTD, which showed greater muscle activation in the ECC phase of the movement than free weights [14].

Contrary to our hypothesis, our results have also shown that 6 weeks of flywheel squat training using a FRTD was not effective in significantly improving jump performance in female soccer players. Our results in CMJ changes are not in agreement with those reported by Coratella et al. [23], which reported a significant 8-week training effect in CMJ height, but not a significant inter-group change compared to the CG. Nonetheless, it is important to note that the CG performed a traditional back squat program as a part of the training protocol in the aforementioned study. In our study, CG did not perform any complementary resistance training, since our objective was not to compare this type of training (i.e., flywheel squat training) with other resistance training methodologies. Besides, these authors also showed a greater effect size in experimental group, suggesting that flywheel squat training programs produce superior adaptations in jump performance than traditional field soccer training alone. Similarly, De Hoyo et al. [22] showed substantial improvements in CMJ performance following a FRTD training program performing both half-squat and leg curl exercise in male soccer players. This study was carried out with a control group that did not perform any type of complementary resistance training, as in the present study. Nuñez et al. [19] also found that 6 weeks of flywheel squat was effective in improving jump performance. Thus, our results in CMJ performance in female soccer players are not in agreement with those previously reported in male soccer players [19, 22, 23]. This fact could be explained, as exposed by Pedersen et al. [32], due to the lack of high-intensity jumpings during field training sessions usually experienced in female soccer players. In this line, these authors argued that improving jumping or sprinting requires players to apply high levels of force at high velocities in addition to strength training. Men do get these stimuli with field training, but women do not, so it would be necessary to implement an additional jumping program to observe improvements in the CMJ in female soccer players.

Also contrary to our hypothesis, FWTG did not reach significant pre-post improvements in COD or sprint. Despite having improved ECC strength to a greater extent and its importance in deceleration and COD abilities [33], our results did not show a superior effect in the players that performed the flywheel squat exercise. Jones et al. [33] demonstrated that greater ECC strength levels are associated with a better 180º COD performance in high level female soccer players, due to being able to handle the greater loads experienced with faster approach velocities. These authors also highlighted the importance of developing several abilities such as strength, speed and technique for improving COD, so this fact could explain the lack of improvements in COD performance in the present study. The lack of improvements in COD, based on the *theory of specificity*, can also be attributed to non-specific stimulus of the flywheel squat in the sagittal plane and the horizontal vector. De Hoyo et al. [31], in line with our results, found no significant improvements in COD in the group that performed the squat exercise in the frontal plane. Nuñez et al. [19] also showed unclear changes in COD 180 degrees following a 6 weeks flywheel squat training program, reporting greater improvements in COD through unilateral exercises better than bilateral exercises (e.g., squat). Hence, unilateral exercises in FRTD could lead to greater improvements in COD ability rather than solely bilateral exercises as in the present study. Thus, due to the importance of determinants to improve the COD (i.e., strength, speed, COD technique and performing unilateral exercises), we suggest that these factors could explain the lack of improvements in COD after the flywheel squat training program in the present study, but more research is necessary. Therefore, S&C coaches as well as future research should take into account the specificity as well as the characteristics of the exercise for the periodization of training and thus be able to

determine if these factors could result in a substantial increase in COD performance.

We also hypothesized that 6 weeks of flywheel squat could improve 30-metres sprint time. Vertical force production is directly associated with sprint performance, especially with the ability to sprint over longer distances (> 20 metres) [34]. Thus, performing vertically-directed exercises such as squat could result in significant improvements in sprint performance [34, 35]. In addition, higher levels of lower-limbs strength are strongly associated with better sprint performance [7, 36, 37]. Nonetheless, despite having improved strength levels on knee extensors and flexors, FWTG did not significantly improve 30-metres sprint time. The lack of improvements could be explained through the *theory of specificity* due to the non-specific stimulus of the flywheel squat in the sagittal plane and the horizontal vector. In this line, Loturco et al. [35] highlighted that vertically-directed exercises would be more associated with top-speed phases, which often reached in > 40-metres sprints. Our results in 30-metres sprint, although in females, are in agreement with those reported by Coratella et al. [23], which did not show significant pre-post changes after 8 weeks of flywheel squat training in male soccer players.

The only study carried out with female soccer players [27] analyzed very different variables from those evaluated in the present study. It showed significant improvements in accelerations and decelerations, thus, it is possible that FWTG had a better performance in these actions at the end of the training program, especially in the last minutes of the game as reported in the aforementioned study. Nonetheless, possible improvements in the acceleration ability does not translate into improvements in 30-meter sprint and in the COD at maximal velocity as shown by the results of the present study.

However, more studies with female soccer players are needed to corroborate the effects of training using FRTD. Moreover, it is necessary to assess training programs based on FRTD in a more holistic sprint and COD development programme (i.e. including sprint/COD technique training, plyometrics, etc.).

Several practical applications should be highlighted from this study: 1) Strength (especially ECC strength) can significantly improve using FRTD in professional female soccer players, 2) 6 weeks of flywheel squat was not enough to improve soccer-specific abilities such as jumping, COD or sprinting and 3) to improve CMJ, COD or sprint other stimulus are necessary.

It should be noted that this paper has some limitations. The first limitation is the criteria to increase inertia (i.e., load). This criteria was used in male soccer players [13], consequently it is necessary to evaluate and establish specific criteria for selection of initial training load and load increase in females. The present training program progression was mainly focused on volume increase, whereas inertia only progressed if the player was able to overcome the aforementioned threshold. Different training programs with load increase based on inertia increments could potentially have greater strength adaptations [12]. Hence, the lack of improvement in high-velocity movements as those evaluated in the present study. Finally, the higher training volume in FWTG as a consequence of supplemental resistance training added to the usual on-field training means that the two compared groups have not been subjected to the same training volume. However, the purpose of the present study is not to compare the effects induced by resistance training based on flywheel devices with respect to other devices used in strength training.

In contrast, this study has several strengths that should be highlighted. The first strength is the evaluation of high-intensity and soccer-specific actions such as vertical jump, change of direction and sprint after a resistance training program based on a FRTD for the first time. Another strength is sample homogeneity, all belonging to the same club and undergoing the same field training. The results of the present study could be also considered a strength, since it provides important information for S&C coaches such as flywheel squat could improve strength levels but not soccer-specific abilities, so the implementation of flywheel squat in the resistance training program for female soccer players should consider these limitations.

CONCLUSIONS

Results of the present study show that 6 weeks of in-season bi-weekly flywheel squat training significantly improved CON and ECC strength of the knee extensors and flexors in professional female soccer players, highlighting the improvement in ECC strength, but not jump height, COD or sprint time. These results suggest that resistance training performing flywheel squat improve professional female soccer players strength, with interesting adaptations in ECC strength, but not soccer-specific abilities. Thus, coaches could benefit from the improvements that training programs based on FRTD produce, leading to superior adaptations than traditional soccer field training alone in strength levels.

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Conflicts of interests

The authors declare no conflict of interests. No funding was provided for this study.

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On-court throwing activity of male handball players during the European Championship 2020

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ABSTRACT: The aim of this study was to investigate the on-court throwing activity in regards to playing positions, throwing zones on the court and throwing velocity category during the male European Championship 2020. A local positioning system with microsensors placed both in the shirts of the players and inside the ball itself was used. In total, 6568 throws were retrieved for analysis from the entire tournament. Results showed that first-line players (wings and line players) used their natural zone more to throw (65% left wing, 60% right wing, and 97% line player), showing higher effectiveness from there ($p < 0.05$). Second lines players distributed more of their throws (45% left back, 50% right back and 32% center back in their natural zones) giving priority to the throws in 6 m, where they showed higher effectiveness ($p < 0.05$), or between the lines. Considering all players, shots from nearby and intermediate areas corresponded to 83% of the shots showing higher efficiency ($p < 0.05$) than shots performed from the areas furthest from the goal (14.9%. from zones 6-7-8). Back players mainly performed the highest velocity throws (Category 4 > ~100 km/h) from these furthest areas. Throwing velocity and effectiveness by throwing zones and positions was not significantly modified over the three rounds of the tournament ($p > 0.05$), indicating no effect of possible fatigue. A higher team ranking was associated with higher throwing efficiency but only for wing players. The results of this research could help handball coaches to better adjust training programs for the improvement of throwing velocity and its transfer to the competition.

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INTRODUCTION

Team handball is a fast-paced Olympic sport characterized by intermittent actions performed at maximal or near-maximal effort, interspersed with short recovery intervals [1, 2]. Among the fundamental movement skills in handball, such as running, blocking, jumping and throwing [3], the latter is of at most importance in goal actions [4]. Hence, throwing performance in handball is an essential factor to win a match [5].

Traditionally, handball analysis consisted of human observation during the matches, but results were constrained by visual observation and information processing limitations [6]. With the advent of audiovisual technology and the widespread low-cost and portable computers, data acquisition and analysis dramatically increased in accuracy and reliability [7]. Motion analysis of handball players has been acquired with optical systems, either single- [8, 9] or multiple-camera tracking systems installed on top of the court [10] for indoor venues, or with Global positioning systems (GPS) [11] for outdoor settings. Most studies using these tracking systems have been conducted either in controlled training conditions [4, 12, 13] or in national league games [14], providing limited information on the performance demands of handball at an elite level. In regards to the analysis of throwing velocity, several studies have attempted to measure this key variable in handball by using radar guns, photoelectric cells, and cinematography [13, 15–19]. However, most of these studies have been conducted without opposition or even a goalkeeper, in controlled training contexts. Only a few studies have analysed throwing velocity in real competition but without considering the position of the players or the court throwing zones [20].

More recently, local positioning systems (LPS) [21] have been introduced to give continuous positional tracking of both players and the ball in indoor venues. LPS is a radio-frequency based technology with high temporal and 3D spatial accuracy compared to error-free criteria [22]. This instrument allows for a comprehensive analysis of the throwing action and positional data of both players and the ball in real competitions. The on-court activity of elite handball players in high-level championships is necessary for a better understanding of the game dynamics, especially concerning the throwing performance for playing positions and court throwing zones. To the knowledge of the authors, there is no available data defining the throwing activity on a court during an entire high-level tournament. Furthermore, the introduction of a microsensor inside the ball allows

for obtaining higher precision data in regards to the speed of the ball, its location in the goal, the place from where it has been shot and the player who performed it.

Therefore, this study aimed to investigate the on-court throwing activity throughout the tournament in regards to playing positions, throwing zones on the court, throwing velocity categories, and according to the final ranking for top-level male handball players. To that end, an LPS system was used to acquire continuous positional tracking information of the players and the ball in the latest European Handball Federation (EHF) EURO 2020, held in Austria/Norway/Sweden. This LPS system has been used in the Velux EHF Final4 and the first division of the German handball national league since the 2019/2020 season [23].

MATERIALS AND METHODS

Subjects

A total of 337 male players (age 27.8 ± 4.7 y, height 192.3 ± 6.7 cm, body mass 93.9 ± 11.8 kg and body mass index 52.3 ± 2.2 kg/m^2) enrolled in 24 national teams taking part in the European Handball Federation (EHF) EURO 2020, held in Austria/Norway/Sweden, were included in this study. Player's positions were identified according to the handball nomenclature: Left wing, LW (n = 49); Left back, LB (n = 66); Centre back, CB (n = 51); Right back, RB (n = 50); Right wing, RW (n = 44); and Line player, LP (n = 77). Goalkeepers were excluded from the analysis because their performance is not affected by the throwing characteristics. In total, the teams played 65 matches, from which 6568 throws were retrieved for analysis. The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Ethics Committee of the University of Alicante (UA-2020-09-10).

Instrumentation

The time-motion characteristics of players and the ball were collected through a LPS (Kinexon Precision Technologies, Munich, Germany), which has recently been validated against well-known systems such as GPS, showing proper between-device reliability (coefficient of variation around 5%) [22]. A complete description of the system can be found elsewhere [23]. The LPS can determine the real-time position and motion data of the player through a lightweight position chip (tag) positioned between shoulder blades using the manufacturer's harness, whereas, for the ball, the same tag is incorporated in its centre. The sensor calculates 3D data (x,y,z) with position accuracy < 10 cm at a sampling frequency of 20 Hz for players and 50 Hz for the ball [22]. The position is determined using the time-of-flight (TOF) of ultra-wide-band radio signals travelling from the transmitter to the base stations, which calculate the actual 2D position of the tags within the playing field. Subsequently, instantaneous speed is derived by calculating the difference between two consecutive positions, i.e., approximating the derivative of the player or ball position. The raw position and speed data are filtered and smoothed using a Kalman filter for position data and an exponential moving average filter with a window length of 1 s for speed and position data. All data were analyzed using the system software (Kinexon Web Application, version 3.2.6, Munich, Germany).

Procedures

This was a descriptive observational cross-sectional study to examine on-court throwing activity in regards to playing positions and throwing zones during elite competitive matches. The players were informed of the purposes, procedures, and risks and provided informed consent before the beginning of the study in a contract with the EHF. Personal data were anonymized for the purpose of this study. All the procedures were conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the University of Alicante (registration number UA-2020-09-10).

The following variables were extracted from the positional data of players and ball tags for each throw event. The absolute throwing velocity and categorized in velocity zones C1 (< 17 m/s), C2 (17–22 m/s), C3 (22–28 m/s), and C4 (> 28 m/s) were computed [24]. These zones correspond to approximately < 60, 60–80, 80–100, and < 100 km/h, respectively. The throwing position in the court was also categorized into eight zones within the court, [24]. In turn, these zones were also aggregated to account for the areas in which players perform throws to the goal as LW (1+2), LB (2+6), CB (3+7), RB (4+8), RW (4+5) and LP (2+3+4).

Likewise, effectiveness was calculated as the percentage relation between the number of throws that scored a goal and the number of throws, in accordance with similar handball studies [25, 26]. In order to check for differences in throwing velocity and effectiveness within a match, four equally timed periods of 15 min were categorized. Similarly, in order to study possible fatigue in the championship, the six finalist teams were compared in preliminary, main, and final rounds. Finally, the six finalist teams were compared to the teams ranked last in order to check for differences between ranked teams.

Statistical Analyses

Descriptive data are presented as mean and standard deviation. The normality distribution of the data in all subgroups was checked through a Kolmogorov-Smirnov test. ANOVA tests were used to check differences between playing positions, throwing position zones, or velocity categories in regards to throwing velocity and effectiveness for the four periods within each match, the four stages of the tournament and the teams ranked first and last, followed by Games–Howell post hoc testing. Finally, a z-test was used to compare the proportion of goal, no goal and total throws when contrasted by each of the aforementioned groups. The alpha level of significance was set at $p < 0.05$. Statistical analysis was performed using the Statistical Package for Social Sciences (SPSS V22.0 for Windows, SPSS Inc, Chicago, USA).

RESULTS

The distribution of throws in court for the six playing positions shows a marked difference in throwing activity for wing players, performing

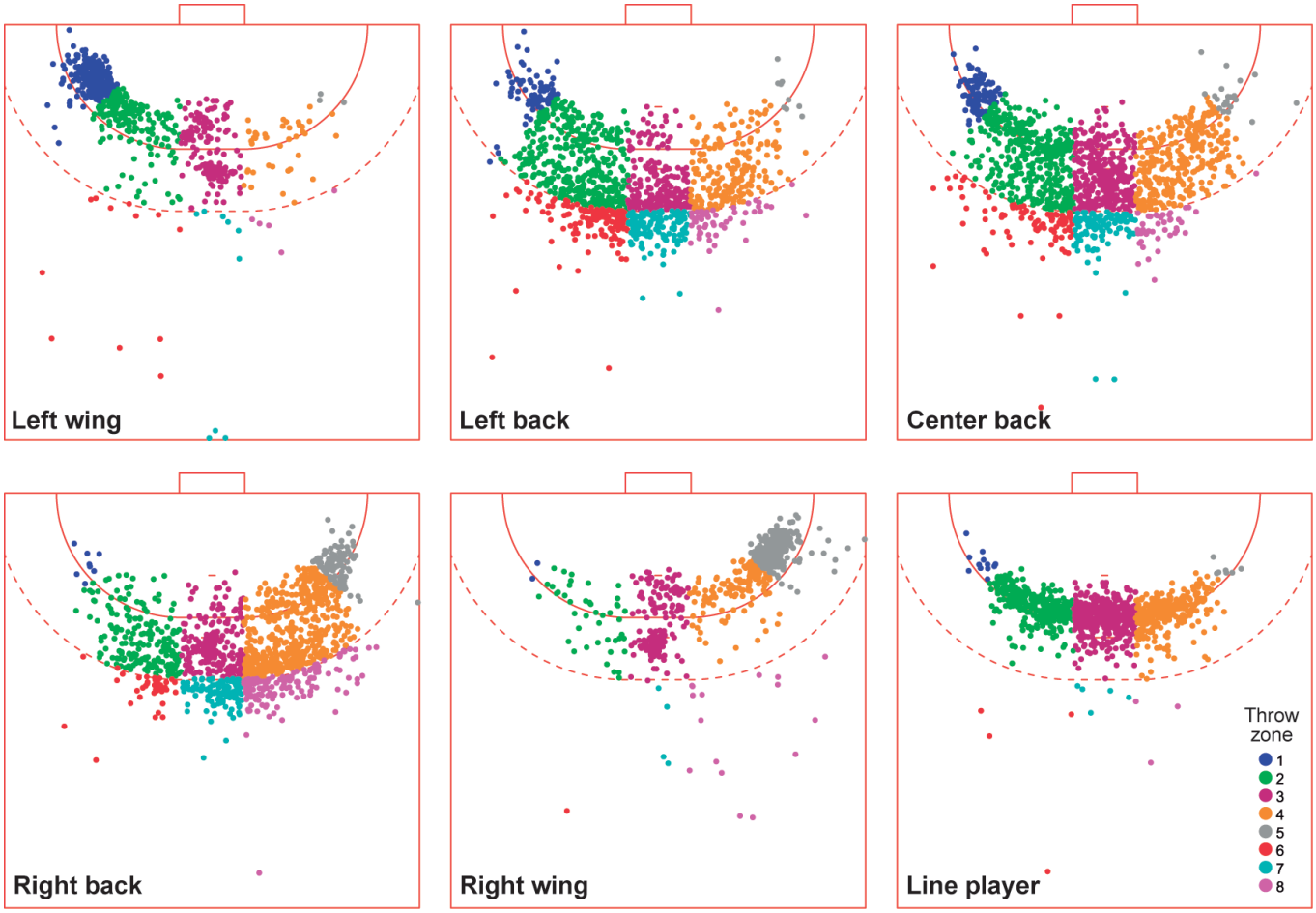


FIG. 1. Heatmaps of throwing activity for different playing positions by throwing zone.

most actions inside zones 1, 2 for LW and 4, 5 for RW, as depicted in Figure 1. Contrastingly, back players execute more throws from adjacent positions than from their natural zones: LB and CB from zone 2 and RB from zone 4. Finally, CB shows a scattered distribution across central and side zones, whereas LP concentrates their throwing activity in the three central zones 2, 3 and 4.

Table 1 shows the throwing frequency activity split for throws resulting in a goal, no goal and total throws, calculated as the number of throws in a zone concerning the total for each playing position. LW showed high activity in zones 1 and 2 with more than 60% of all throws for the three results, where zone 1 was the most populated ($z = 4.3–17.6$, $p < 0.05$), followed by Zone 2 ($z = 10.7–14.3$, $p < 0.05$). Zone 3 was also very active, with one-quarter of the total throws ($z = 10.0–13.7$, $p < 0.05$). A similar trend can be observed for RW with zones 3, 4 and 5 ($z = 4.2–14.8$, 7.3–11.4, and 18.7–17.4, respectively, all $p < 0.05$). The activity of CB and LP is mostly performed in central zones 2, 3 and 4, with differences within zones ($z = 2.4–4.2$, $p < 0.05$) and between these zones and less populated ones ($z = 2.4–18.0$, $p < 0.05$). Finally, high throwing proportions in zones 2, 3 for LB and 3, 4 for RB were observed, with significant differences between them and the rest of the zones ($z = 2.4–21.5$, and 3.8–19.3, $p < 0.05$). As with wing players, LB and RB players perform in adjacent zones (4 and 2, respectively).

The throwing activity for goal situations is depicted in Figure 2 for playing zones, together with zones aggregated according to the natural playing zones of players in a court (black) and the rest of the zones (grey). Significant differences were observed between aggregated zones for each playing position and the rest of the zones combined ($z = 8.0$, -3.9, -10.7, 3.4, and 32.6 for LW, LB, CB, RW, and LP, respectively, all $p < 0.01$), except for RB ($z = -0.7$, $p = 0.45$), which showed an overall throwing activity of 51.1% in zones other than 4 and 8. The other two playing positions with remarkable activity out of their natural playing zones were back players, which activity was 51.9% in zones 2 and 4 (CB), and 33.8% in zones 3 and 4 (LB).

A similar trend can be found for no goal and total throwing activity, as shown in Table 2. Differences were consistent both in percentage and significance for all positions ($z = 3.4–32.6$ for LW, RW, LP, and $z = -3.3 – -18.9$, $p < 0.01$), regardless of the throw result (goal, no goal and total), except for RB.

TABLE 1. Throw frequency (%) by playing positions and court throwing zones for goal, no goal and total throws.

		Throwing zones							
Pos.	**Result**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
LW	Goal	35.0%*(2,4–8) [152/434]	28.6%*(1,4–8) [124/434]	29.3%*(4–8) [127/434]	3.7%* [16/434]	0.5%*(1–4) [2/434]	1.4%*(1–4) [6/434]	1.4%*(1–4) [6/434]	0.2%*(1–4) [1/434]
	No goal	42.4%*(2,4–8) [114/269]	24.5%*(1,3–8) [66/269]	18.6%*(2,4–8) [50/269]	9.3%* [25/269]	0.4%*(1–4) [1/269]	2.2%*(1–4) [6/269]	1.1%*(1–4) [3/269]	1.5%*(1–4) [4/269]
	Total	37.8%* [266/703]	27.0%*(1,4–8) [190/703]	25.2%*(1,4–8) [177/703]	5.8%* [41/703]	0.4%*(1,4–6) [3/703]	1.7%*(1–5) [12/703]	1.3%*(1–4) [9/703]	0.7%*(1–4) [5/703]
LB	Goal	6.0%*(2–7) [34/565]	33.1%* [187/565]	18.2%*(1,2,5–8) [103/565]	15.6%*(1,2,5–8) [88/565]	0.4%* [2/565]	11.2%*(1–5,8) [63/565]	11.5%*(1–5,8) [65/565]	4.1%*(2–7) [23/565]
	No goal	6.7%*(2–7) [47/700]	32.3%* [226/700]	15.4%*(1,2,5,7,8) [108/700]	15.7%*(1,2,5,7,8) [110/700]	1.1%* [8/700]	13.3%*(1,2,5,8) [93/700]	11.0%*(1–5,8) [77/700]	4.4%*(2–7) [31/700]
	Total	6.4%* [81/1265]	32.6%* [413/1265]	16.7%*(1,2,5–8) [211/1265]	15.7%*(1,2,5–8) [198/1265]	0.8%* [10/1265]	12.3%*(1–5,8) [156/1265]	11.2%*(1–5,8) [142/1265]	4.3%* [54/1265]
CB	Goal	4.5%*(2–5,8) [29/641]	31.5%*(1,4–8) [202/641]	28.4%*(1,4–8) [182/641]	20.4%* [131/641]	0.9%*(1–4,6,7) [6/641]	5.3%*(2–5,8) [34/641]	6.7%*(2–5,8) [43/641]	2.2%*(1–4,6,7) [14/641]
	No goal	8.6%*(2–5,8) [66/766]	26.0%*(1,3,5–8) [199/766]	21.3%*(1,2,5–8) [163/766]	22.5%*(1,6–8) [172/766]	2.2%*(1–4,6,7) [17/766]	7.4%*(2–5,8) [57/766]	8.4%*(2–5,8) [64/766]	3.7%*(1–4,6,7) [28/766]
	Total	6.8%*(2–5,8) [95/1407]	28.5%* [401/1407]	24.5%*(1,2,5–8) [345/1407]	21.5%*(1,2,5–8) [303/1407]	1.6%* [23/1407]	6.5%*(2–5,8) [91/1407]	7.6%*(2,5–8) [107/1407]	3.0%* [42/1407]
RB	Goal	0.7%*(2–5,7,8) [4/603]	13.8%* [83/603]	20.2%* [122/603]	39.6%* [239/603]	6.1%*(1–4,6,8) [37/603]	1.7%*(2–5,7,8) [10/603]	8.6%*(1–4,6) [52/603]	9.3%*(1–6) [56/603]
	No goal	0.5%* [4/743]	14.7%*(1,4–7) [109/743]	12.7%*(1,4–6) [94/743]	37.8%* [281/743]	8.2%*(1–4,6,8) [61/743]	3.9%* [29/743]	9.8%*(1,2,4,6,8) [73/743]	12.4%*(1,4–7) [92/743]
	Total	0.6%* [8/1346]	14.3%*(1,4–8) [192/1346]	16.0%*(1,4–8) [216/1346]	38.6%* [520/1346]	7.3%*(1–4,6,8) [98/1346]	2.9%* [39/1346]	9.3%*(1–4,6) [125/1346]	11.0%*(1–6) [148/1346]
RW	Goal	0.2%*(2–5,8) [1/470]	5.7%* [27/470]	36.2%*(1,2,4,6–8) [170/470]	21.1%* [99/470]	34.5%*(1,2,4,6–8) [162/470]	0.0%*(2–5,8) [0/470]	0.2%*(2–5,8) [1/470]	2.1%* [10/470]
	No goal	0.4%*(2–5) [1/265]	6.8%* [18/265]	21.1%*(1,2,5–8) [56/265]	21.5%*(1,2,5–8) [57/265]	46.4%* [123/265]	0.4%*(2–5) [1/265]	1.1%*(2–5) [3/265]	2.3%*(2–5) [6/265]
	Total	0.3%*(2–5,8) [2/735]	6.1%* [45/735]	30.7%* [226/735]	21.2%* [156/735]	38.8%* [285/735]	0.1%*(2–5,8) [1/735]	0.5%*(2–5,8) [4/735]	2.2%* [16/735]
LP	Goal	0.7%*(2–5) [4/572]	31.1%* [178/572]	41.1%* [237/572]	25.7%* [147/572]	0.0%*(1–4) [0/572]	0.5%*(2–4) [3/572]	0.2%*(2–4) [1/572]	0.3%*(2–4) [2/572]
	No goal	1.8%*(2–4,6,8) [8/452]	30.1%*(1,5–8) [136/452]	36.1%*(1,4–8) [163/452]	29.2%*(1,5–8) [132/452]	1.5%*(2–4,6,8) [7/452]	0.2%*(1–6) [1/452]	0.9%*(2–4) [4/452]	0.2%*(1–6) [1/452]
	Total	1.2%*(2–4,6,8) [12/1025]	30.7%*(1,3,5–8) [314/1025]	39.1%* [400/1025]	27.2%*(1,3,5–8) [279/1025]	0.7%*(2–4) [7/1025]	0.4%*(1–4) [4/1025]	0.5%*(2–4) [5/1025]	0.3%*(1–4) [3/1025]

Note: * Significance between zones for each position indicated by zone numbers in parenthesis. A number of throws for each zone out of the total for the position is indicated between brackets.

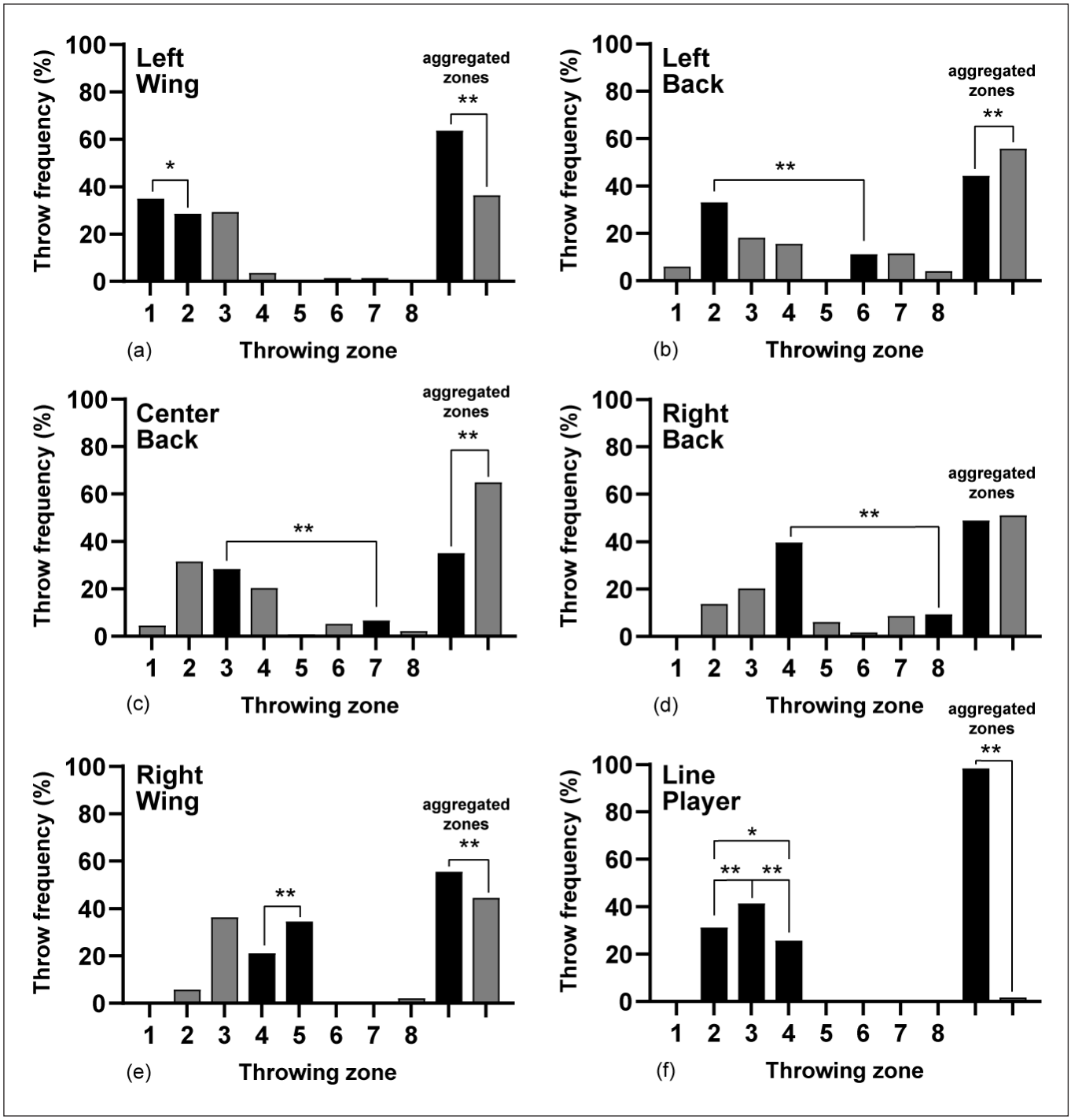


FIG. 2. Throw frequency (%) by playing positions, court throwing zones and aggregated zones for throws resulting in goal.
Note: * $p<0.05$, ** $p<0.01$: For clarity, significance is only indicated within zones in an aggregated zone and between aggregated zones.

TABLE 2. Throw frequency (%) by playing positions and aggregated court throwing zones for goal, no goal and total throws.

Position (zones)	Left wing (1+2)	Left back (2+6)	Center back (3+7)	Right back (4+8)	Right wing (4+5)	Line player (2+3+4)
Goal	63.6%** [276/434]	44.2%** [250/565]	35.1%** [225/641]	48.9% [295/603]	55.5%** [261/470]	98.3%** [562/572]
No goal	66.9%** [180/269]	45.6%** [319/700]	29.6%** [227/766]	50.2% [373/743]	67.9%** [180/265]	95.4%** [431/452]
Total	64.9%** [456/703]	45.0%** [569/1265]	32.1%** [452/1407]	49.6% [668/1346]	60.0%** [441/735]	97.0%** [993/1024]

** $p < 0.01$: Significance between aggregated zones and the rest of the zones combined. A number of throws for each aggregated zone out of the total for the position indicated between brackets.

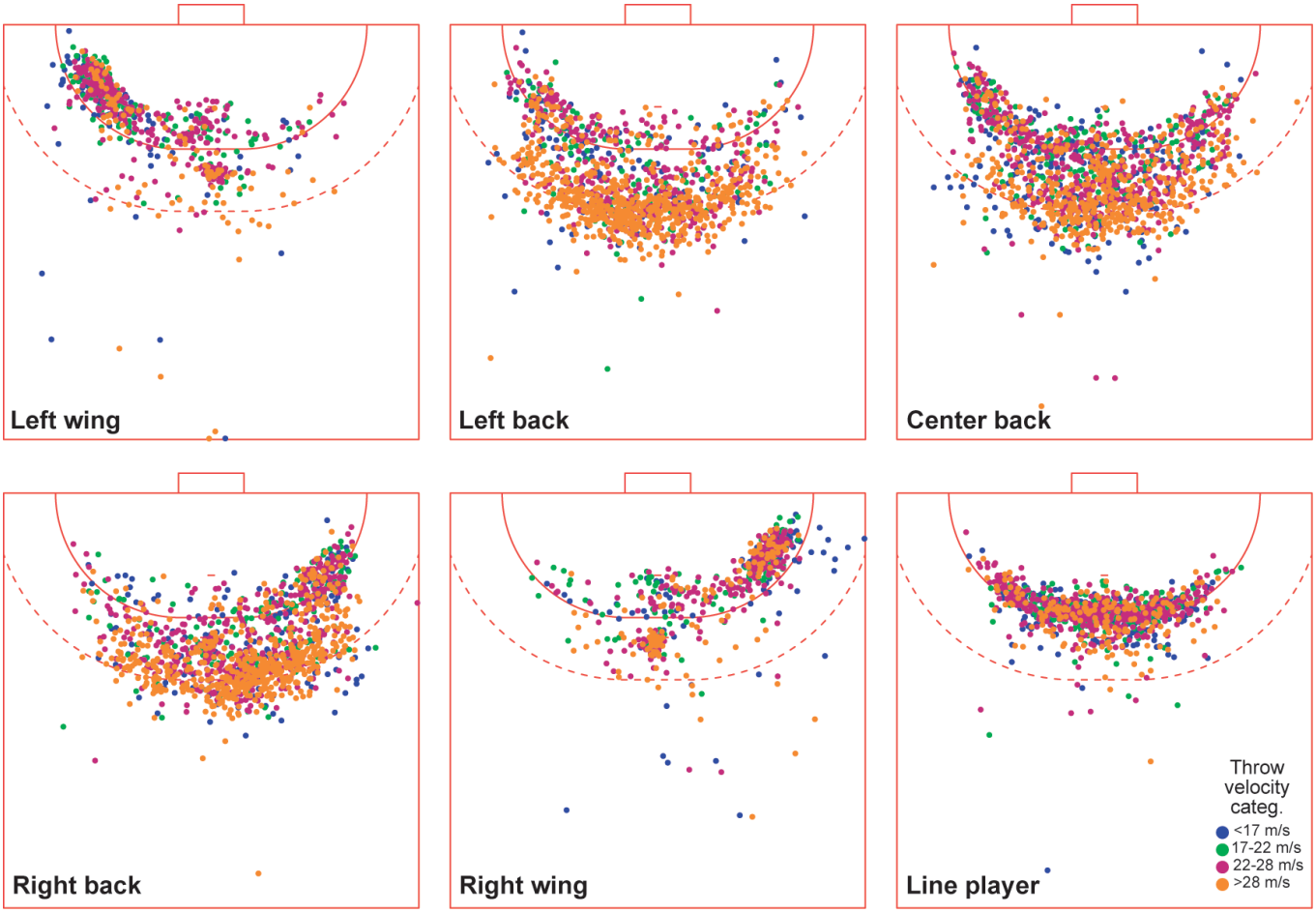


FIG. 3. Heatmaps of throwing activity for different playing positions by velocity category.

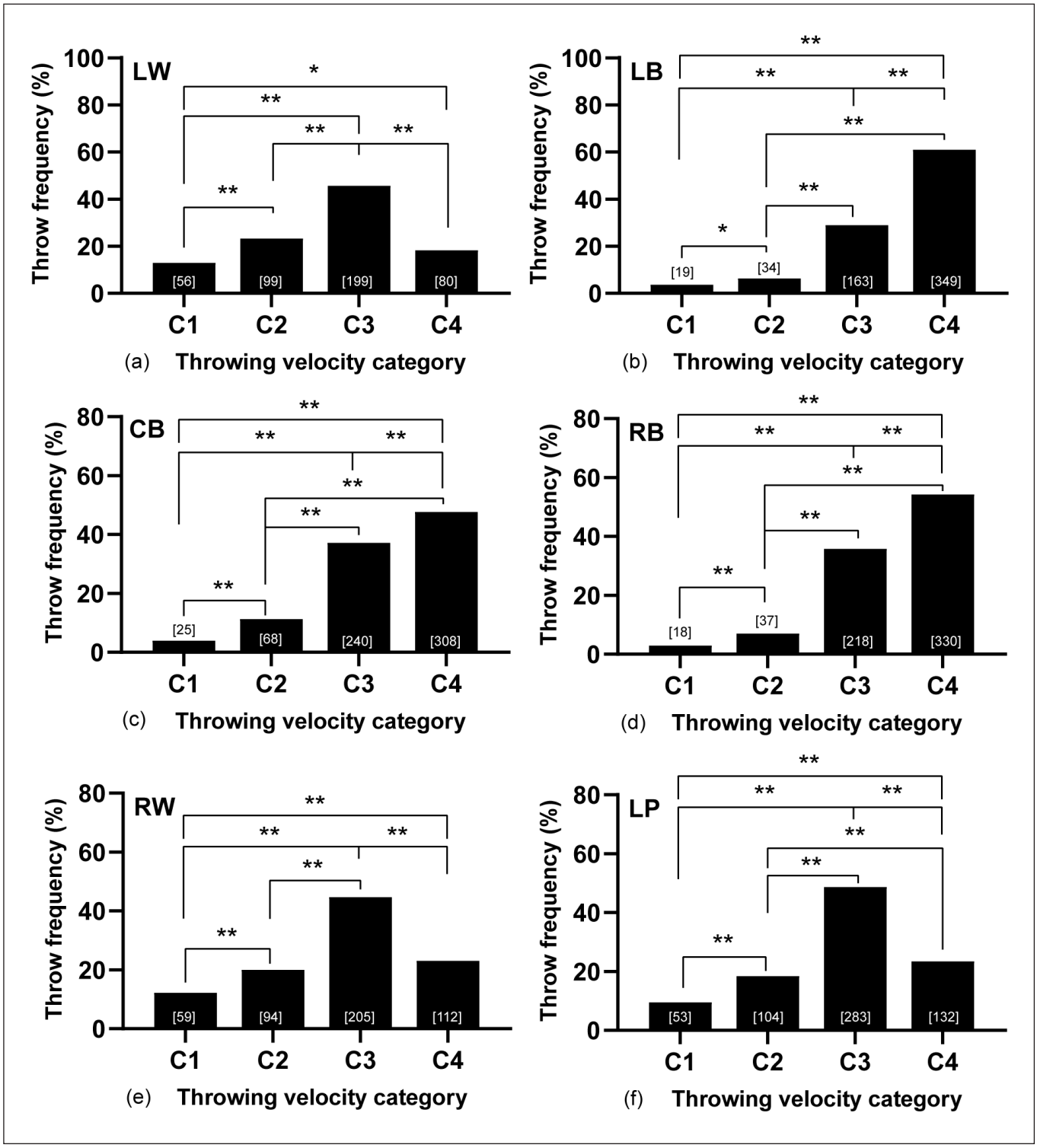


FIG. 4. Throw frequency (%) by playing positions and velocity categories for throws resulting in goal. Number of throws indicated between brackets for each group. * $p<0.05$, ** $p<0.01$.

TABLE 3. Throwing velocity (m/s) and effectiveness (%) by playing positions and court throwing zones according to four periods in a match, the three rounds in the championship and two rank-level teams.

	Position						Throwing zones							
	LW	**LB**	**CB**	**RB**	**RW**	**LP**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Match														
Period 1	23.1 ± 5.9 62 ± 49% [182]	26.7 ± 7.0 41 ± 49% [357]	24.4 ± 7.2 47 ± 50% [352]	25.7 ± 7.3 43 ± 50% [324]	22.8 ± 6.5 69 ± 46% [172]	22.0 ± 7.2 54 ± 50% [241]	22.0 ± 6.5 53 ± 50% [138]	23.7 ± 7.5 45 ± 50% [354]	24.5 ± 6.1 61 ± 49% [395]	25.1 ± 7.2 48 ± 50% [361]	21.7 ± 6.4 54 ± 50% [113]	27.9 ± 8.6 39 ± 49% [83]	27.7 ± 6.3 42 ± 49% [109]	25.6 ± 8.7 39 ± 49% [75]
Period 2	23.0 ± 5.6 55 ± 50% [184]	26.7 ± 7.1 44 ± 50% [329]	24.6 ± 7.3 45 ± 50% [390]	26.7 ± 6.7 46 ± 50% [350]	22.6 ± 5.9 64 ± 48% [212]	21.4 ± 6.6 55 ± 49% [262]	21.5 ± 5.8 42 ± 49% [124]	24.7 ± 6.8 50 ± 50% [440]	23.6 ± 6.6 58 ± 50% [402]	24.9 ± 7.1 51 ± 50% [399]	22.3 ± 5.9 47 ± 50% [119]	26.5 ± 7.8 37 ± 49% [83]	28.4 ± 7.1 46 ± 50% [94]	28.3 ± 7.6 42 ± 50% [66]
Period 3	21.6 ± 6.0 62 ± 49% [145]	26.3 ± 7.0 45 ± 50% [269]	24.5 ± 7.8 48 ± 50% [291]	26.1 ± 7.0 50 ± 50% [322]	22.6 ± 6.1 64 ± 48% [162]	22.5 ± 6.8 56 ± 50% [250]	21.3 ± 6.5 46 ± 50% [86]	24.1 ± 7.1 56 ± 50% [354]	24.2 ± 6.5 60 ± 49% [370]	24.6 ± 7.0 50 ± 50% [343]	20.2 ± 6.6 52 ± 50% [92]	27.1 ± 7.8 41 ± 50% [54]	29.2 ± 6.2 40 ± 49% [89]	25.9 ± 8.9 37 ± 49% [51]
Period 4	22.1 ± 6.0 67 ± 47% [192]	26.6 ± 6.8 49 ± 50% [310]	23.7 ± 7.8 42 ± 49% [374]	25.4 ± 7.6 41 ± 49% [350]	22.3 ± 6.1 59 ± 49% [189]	23.0 ± 6.2 58 ± 49% [271]	20.9 ± 6.6 51 ± 50% [116]	23.7 ± 7.3 55 ± 50% [407]	24.1 ± 6.3 61 ± 49% [408]	24.5 ± 6.9 44 ± 50% [394]	21.8 ± 6.3 43 ± 50% [102]	26.2 ± 8.6 37 ± 49% [83]	26.9 ± 7.5 43 ± 50% [100]	26.8 ± 7.7 40 ± 49% [76]
Championship														
Preliminary	22.7 ± 6.0 64 ± 48% [77]	26.4 ± 6.6 47 ± 50% [139]	24.8 ± 7.2 44 ± 50% [158]	25.7 ± 7.6 42 ± 50% [160]	23.3 ± 6.0 65 ± 48% [115]	21.8 ± 6.3 59 ± 50% [121]	21.6 ± 7.1 52 ± 51% [40]	24.8 ± 6.7 56 ± 50% [187]	23.5 ± 6.7 59 ± 49% [208]	25.0 ± 6.5 47 ± 50% [185]	22.4 ± 6.2 40 ± 49% [57]	24.9 ± 9.9 26 ± 44% [27]	26.2 ± 6.4 43 ± 50% [37]	28.6 ± 7.4 55 ± 50% [29]
Main	22.2 ± 5.9 71 ± 46% [85]	26.2 ± 7.4 47 ± 50% [180]	23.9 ± 7.6 46 ± 50% [232]	25.3 ± 7.6 49 ± 50% [244]	23.6 ± 5.9 73 ± 44% [132]	22.5 ± 7.4 56 ± 50% [172]	20.7 ± 7.0 55 ± 50% [56]	23.8 ± 7.6 50 ± 50% [273]	24.7 ± 6.5 60 ± 49% [269]	24.6 ± 7.4 56 ± 50% [260]	21.8 ± 6.9 56 ± 50% [75]	25.8 ± 9.4 33 ± 48% [36]	27.0 ± 8.4 42 ± 50% [47]	27.0 ± 7.3 48 ± 50% [29]
Finals	22.9 ± 6.1 65 ± 49% [23]	26.2 ± 6.8 51 ± 50% [47]	23.8 ± 8.2 36 ± 49% [104]	25.8 ± 7.1 38 ± 49% [94]	24.1 ± 5.2 57 ± 50% [44]	21.0 ± 7.8 58 ± 50% [67]	22.8 ± 6.0 50 ± 51% [18]	22.8 ± 7.3 43 ± 50% [82]	22.7 ± 6.6 57 ± 50% [98]	24.9 ± 6.8 43 ± 50% [90]	19.4 ± 6.0 50 ± 51% [24]	27.6 ± 8.1 44 ± 50% [25]	30.0 ± 6.2 36 ± 49% [28]	24.5 ± 11.1 36 ± 50% [14]
Rank														
Top	22.0 ± 5.9 65 ± 48%* [242]	26.7 ± 7.1 47 ± 50% [422]	24.4 ± 7.7 44 ± 50% [627]	25.7 ± 7.3 45 ± 50% [608]	22.4 ± 6.6 68 ± 47%* [328]	22.1 ± 6.5 57 ± 50% [433]	20.8 ± 6.9 52 ± 50%* [158]	23.8 ± 7.3 51 ± 50% [640]	24.0 ± 6.5 59 ± 49% [703]	24.9 ± 6.9 50 ± 50%* [629]	21.4 ± 6.7 49 ± 50% [181]	26.3 ± 9.0 37 ± 48% [109]	28.1 ± 6.6 42 ± 50% [144]	27.3 ± 8.2 48 ± 50% [96]
Low	22.9 ± 6.1 51 ± 50%* [222]	26.1 ± 7.0 43 ± 50% [426]	23.1 ± 7.0 40 ± 49% [304]	25.5 ± 7.1 44 ± 49% [316]	21.9 ± 6.1 57 ± 50%* [193]	21.5 ± 7.1 51 ± 50% [288]	21.7 ± 5.7 40 ± 49%* [145]	23.8 ± 7.4 49 ± 50% [430]	23.8 ± 6.4 55 ± 50% [405]	23.9 ± 7.1 42 ± 49%* [405]	21.0 ± 5.9 46 ± 50% [120]	25.1 ± 8.5 39 ± 49% [71]	27.2 ± 7.0 44 ± 50% [99]	26.8 ± 8.0 42 ± 50% [74]

*$p < 0.05$: Significance between top- and low-ranked groups. A number of throws for each group is indicated between brackets.

Concerning throwing velocity, Figure 3 shows that most high-velocity throws in the C4 zone (> ~100 km/h) occur at large distances from the goal for the three back playing positions. Contrastingly, wing and line players use a variety of velocity zones regardless of throw distance.

To study the influence of throwing velocity on playing positions for successful throws, Figure 4 depicts the differences in the four-velocity categories. The throwing activity for back players is very similar in terms of throw frequency and significant differences between the two lowest categories and C3 and C4 (z = 2.1–20.9, 4.6–18.0, and 2.6–19.8 for LB, CB and RB, respectively, all $p < 0.05$). For these playing positions, most of the throws are performed above ~80 km/h: 90.6% for LB, 85.4% for CB, and 90.9% for RB. Conversely, wing and LP showed a similar profile, by which around half of the throws are executed in the C3 zone: 45.9%, 43.6%, and 49.5% for LW, RW and LP, respectively. There were significant differences in successfully throwing activity in these playing positions between the lowest velocity category C1 and the rest (z = 2.2–14.9, $p < 0.05$), between C2 and C3 (z = 7.1–11.2, $p < 0.05$) and between C3 and C4 (z = 6.4–9.2, $p < 0.05$).

The throwing velocity and effectiveness by playing positions and court throwing zones according to four periods in a match are shown in Table 3. Consistent throwing velocity and effectiveness are observed across playing positions and therefore, ANOVA revealed no significant differences between periods in a match for throwing velocity (F = 0.81, p = 0.49), and for effectiveness (F = 0.53,

$p = 0.66$). Similarly, ANOVA also indicated no differences for throwing zones between the four-match periods ($F = 1.70$, $p = 0.16$ for throwing velocity and $F = 0.12$, $p = 0.95$ for effectiveness).

The throwing velocity and effectiveness of playing positions and court throwing zones are also shown in Table 3 for the three rounds of the tournament. Results indicated that both variables maintain little variations for playing positions across the tournament, and therefore, no statistical change is present, according to ANOVA ($F = 0.89$, $p = 0.41$ for throwing velocity and $F = 2.0$, $p = 0.13$ for effectiveness). In the same way, no differences were observed for throwing velocity ($F = 0.13$, $p = 0.89$) and effectiveness ($F = 1.0$, $p = 0.37$) in the activity performed in the court throwing zones.

Finally, the throwing velocity and effectiveness by playing positions and court throwing zones for the two rank-level teams are given in Table 3. While no differences were observed in throwing velocity by playing positions between top- and down-ranked teams ($F = 3.15$, $p = 0.08$), ANOVA showed significant differences in effectiveness ($F = 16.27$, $p < 0.01$, $\eta^2 = 0.04$). Post hoc revealed that wing players were more efficient in top-ranked teams than in down-ranked teams: +13.6% for LW ($p < 0.01$), and +9.9% for RW ($p < 0.05$). Conversely, both throwing velocity and effectiveness showed consistency across the tournament when analyzed by throwing zones ($F = 2.12$, $p = 0.15$ and $F = 3.72$, $p = 0.06$, respectively).

DISCUSSION

This study aimed to investigate the on-court throwing activity in regards to playing positions, throwing zones in the court and throwing velocity category in the matches played during the Men's EHF EURO 2020. The introduction of a microsensor inside the ball itself has allowed analyzing in an ecological way variables related to the shots that had never been able to be studied directly (like combining the PP with the throwing zone) and even less in a major sporting event such as the EHF EURO 2020.

The most relevant data showed that first-line players (wings and LP) use their natural zone more to throw. A 65% of the LW, a 60% of the RW and a 97% of the LP's throws were carried out from what is considered their playing position. Specificity is what prevails in these players. In the case of the second lines (LB-CB-RB) the throwing distribution from their playing position is not so high (45% for LB, 50% for RB and 32% for the CB) giving priority to the throws in 6 m or between the lines. The CB is the one that makes the closest throws to the 6 m line, almost 83% of its throws compared to 73% and 77% of the LB and RB respectively. The CB shows more diversity, with a slight tendency to finish in zone 2 and 3. The central player has a spatial advantage due to his position, to move in a variety of ways either in parallel or vertical to the defence and thus has more opportunities to throw from different positions [27]. As in most teams, the CB are right-handed, and they tend to come out to their weak point. The LB is the one who throws the most from a distance of all positions (28%).

The main difficulty of this research is to find studies in which the shots by position and areas are analyzed as is our case. The only study with a similar objective is that of Hatzimanouil [27], but they do so by analyzing a lower level of play and with a different orientation, comparing natural areas and positions with other areas and positions.

The effectiveness of a handball throw can be determined, among other factors, by distance to the goal. Blanco [28] and Almeida et al. [29], observed that proximity shots had a positive relationship with success compared to remote shots, where the relationship is negative. In our study, shots from nearby and intermediate areas correspond to 83% of the total of 6568 shots analyzed. The shots made from the areas furthest from the goal (zones 6-7-8) correspond to 14.9% of the total. Even back players, that are supposed to throw from long distances, showed a frequency of just 22.5%. The results are similar to those obtained by other studies [28, 30, 31], very far from the data provided by Eftene et al. [32] that estimate remote shots to be around 45.66%. These differences may be due to the registration system based on direct observation, compared to the registration through technological resources used in the present study.

Concerning effectiveness, first-line players (Wings and LP) showed higher effectiveness when throwing from their playing position than from aggregated zones. Curiously, LP's effectiveness is slightly higher from zone 4 than 2, which is usually the weak side of right-handed players. Although second-line players are supposed to score from long distances, they showed higher effectiveness when throwing from aggregated zones close to the 6 m line, with exception of the RB who showed similar values, meaning a greater specialization than the LB.

One of the most relevant results of this study is that most of the shots that are made at high speed (zone C4) are executed from long distances from the goal (zone 6-7-8) and are mainly undertaken by the back players. In this sense, Tuquet et al. [31] indicate that a throw, when made from the middle distance (9 m) and between the lines (6–9 m), must be strong and powerful so that it can surprise the defence.

The differences in throwing velocity between the first and second lines could also be explained by anthropometric factors [33]. Studies in this regard show that second-line players are typically taller and larger [34], with a longer arm span that favours greater application of force, showing higher levels of muscle mass, strength and power [4].

Another relevant issue of this study is to verify that more than 80% of the throws in all positions are made at high or very high speeds (categories 3 and 4). In the same line, Tuquet et al. [31], who analyzed 1049 throws of a high-level men's championship, found that more than 95% of the throws were made at the highest possible speed compared to only 5% that were ability shots. Regarding effectiveness, the wings are the most effective players with 62% and 64% (LW and RW respectively). The shots volume is over 50% lower than the back players, which are over 45% effective, with the CB being the one that

makes a greater volume of throws. The data are similar to those obtained by Blanco [28], 66% for the wings and 49% for the RB and LB and much lower concerning the CB with 58%.

Analyzing throwing velocity, the first line players (wings and LP) showed greater efficiency in the shots category 3, while the second line players (backs) showed it in category 4. This fact could indicate that the backs should be lavished more on external shots, executed at maximum speed. This lower throwing velocity of the wings and LPS may be because many of the shots are close to goal, without opposition and contact. As this is an optimal condition for the shot, the effectiveness increases threefold [33]. Another of the aims of this study was to know if the throwing activity in terms of playing positions, throwing zones on the court and the speed category would be affected by the moment of the match, differentiating four quarters. The results showed that the time does not influence the variables analyzed. When analyzing if the fatigue accumulated throughout the championship could influence any of the variables analyzed, it was found that throwing velocity and effectiveness by throwing zones and positions did not show significant differences throughout the three rounds of the tournament. Possibly this result is because being a high-level event in which the best players from each country play, the coaches can rotate their players, allowing the variables analyzed not to be affected by fatigue.

Finally, regarding the study of situational variables analyzed in this study, such as the effect of ranking, it was observed that the wings of the best-classified teams were more efficient than those of the lower-ranked teams, coinciding with one of the predictive variables proposed by Almeida et al.[35].

These data are difficult to be compared with other research. The studies that have more similarities are those that compare winning teams with losers [36–39]. Their results showed that high-level teams were more efficient in all analyzed throwing related capabilities [37]. In our case, this only happens with the wings. The method of data collection may be an explanatory factor for the differences, together with the heterogeneity of the studies. The remarkable thing is that thanks to the LPS in this research, the data collection has been direct and automatic compared to the indirect methods of other studies. In this sense, the way to obtain data indirectly raises serious doubts about the reliability and validity of the registration [40].

The results of this research suggest that for the improvement of throwing performance, coaches should adjust training programs and loads to the conditions that will later be found in competition (zones, distance, opposition, etc.). This would probably allow minimizing the gap that exists between the improvement of the throwing velocity under training conditions and its transfer to the competition. We agree with Vila et al [25] that a study that analyzes the effect of increased throwing velocity in training on the throwing performance in matches should be carried out. For this, the use of microsensors inside the ball used in this research could be useful.

Limitations

Although with LPS devices we can immediately measure the throwing activity of a championship, considering playing position, throwing zone, throwing velocity and location of the ball in the goal, the degree of opposition is not known automatically.

CONCLUSIONS

The findings of this study revealed different throwing activities for playing positions in regards to the throwing zones and effectiveness on the court. First-line players showed a balanced throw distribution among zones, with scattered ball velocity and higher effectiveness in distances close to the goal, whereas second-line players used their natural zone more to throw with higher velocities. There was also no effect of fatigue in throwing activity throughout the tournament, which could be due to being elite players than can be changed on demand. Finally, only wing players showed higher throwing efficiency in higher ranking teams.

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Conflict of interests

The authors have no conflicts of interest to declare.

Author contribution

Research concept and study design (B. Pueo, J. Tortosa-Martínez, L.J. Chirosa-Rios, C. Manchado), literature review (J. Tortosa-Martínez, L.J. Chirosa-Rios, C. Manchado), data collection (B.Pueo), data analysis and interpretation (B.Pueo, J. Tortosa-Martínez, L.J. Chirosa-Rios, C. Manchado), statistical analyses (B.Pueo), writing of the manuscript (B.Pueo, J. Tortosa-Martínez, L.J. Chirosa-Rios, C. Manchado), or reviewing/editing a draft of the manuscript (B. Pueo, J. Tortosa-Martínez, L.J. Chirosa-Rios, C. Manchado).

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Predicting the unpredictable: analysing the entropy and spatial distribution of ball movement patterns in field hockey

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ABSTRACT: Analysing the ball movement patterns of team invasion sports provides practical insight into successful strategies by identifying how and where to move the ball to create goal scoring opportunities. The aim of this study was to analyse the entropy and spatial distribution of ball movement patterns in international field hockey teams. A notational analysis system was developed in SportsCode to analyse 131 matches (n = 57 men, n = 74 women) from the 2019 Pro League tournament. The start and end location of each ball movement and the outcome of each play was recorded. Calculated variables included game possession (%), entropy, possession per zone (%) and progression rates. Decision trees identified that higher circle possession and direct movements to goal from deep attack, and lower build attack and build defence entropy, were the strategies most likely to lead to goal shots. However, teams should be unpredictable when the opposition are organised to maintain possession and unbalance the defence. Match context only had small effects on ball movement strategies highlighting there is more than one way to be successful. Executing strategies that exploit these factors should lead to greater attacking opportunities and success. Analysing the dynamic, complexity of international hockey allows coaches to prepare specific strategies for individual teams.

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INTRODUCTION

Identifying the ball movement patterns of team invasion sports is a key part of performance analysis. Performance analysis is used to provide objective insight into tactics and strategy to understand how teams are successful. Strategies are plans developed pre-game by a coach on how a team intends to attack and defend, while tactics are plans developed in-game in response to the opposition's strategy and the evolving game situation [1]. In international women's field hockey, transferring the ball through the wider channels (or edges) of the field and through the side of the circle, before moving the ball to the top of the circle, was identified as the most likely play leading to a goal scoring opportunity [2–3]. The most likely way to score a goal from a penalty corner was via a drag flick from the top of the circle for males, and using a pass to generate a deflection close to goal for females [4]. This type of information is critical for coaches to understand so they may implement and execute effective strategies that increase the chance of team success.

In team invasion sports, there is a delicate balance between being organised and consistent, and being disorganised and creative in ball movement patterns [5]. Unpredictability is linked to success as it creates uncertainty in the defence, whereas consistently utilising the same tactics allows the opposition to prepare counter strategies to impede this movement [5]. For example, higher values of entropy (a measure of unpredictability) were observed in basketball matches with a large deficit win compared to small deficit wins and large deficit losses [6]. This outcome implies that the degree of unpredictability can positively influence a match outcome [6]. Identifying ball movement patterns and the consistency or unpredictability of these patterns, provides insight into a team's game style and their adaptability to match context. Game styles are defined as the consistent attacking and defensive strategies implemented by a team [7]. Game styles have previously been developed in soccer, Australian Football, Rugby Union, and field hockey by studying in-game events and describing the game actions used, strength in attack types or speed of play [8–12]. For example, Lord et al., [12] identified game styles in international field hockey teams based on whether a team typically used passing or dribbling actions, were strong or poor in established and counter attacks, created high or low set pieces per game and employed a possession or direct tempo. This analysis method identified ways a team was successful by focusing on what actions and events were occurring in a game in relation to the opposition. A similar approach can be taken to develop game styles from ball movement patterns, but instead placing greater focus on the spatio-temporal variables to understand how and where a team moves the ball to be successful. Associating the

tempo and control of a team with the areas they typically play in provides critical information for developing strategies, styles and tactics. A coach can use these insights to determine which areas of the field their team needs to control, and the type of defensive structure to implement based on the consistent or unpredictable nature of the opposition.

Research investigating movement patterns in team invasion sports has increased in recent years given improvements in technology. Player and ball tracking can occur in real time using semi-automated vision-based tracking systems, or a local (LPS) and global positioning system (GPS). However, tracking technology can be expensive, and access to one team's GPS data only provides "half the story". Therefore, these techniques are largely restricted to professional teams. Alternatively, Stockl and Morgan [3] tracked the ball movements of hockey teams manually to identify the most likely pattern leading to a goal scoring opportunity. However, they only focused on the spatial distribution of possession, and consequently two teams may have similar profiles, but achieve different outcomes. Analysing spatial distribution alone does not provide insight into how a team moved across the field, how quickly they progressed the ball, nor how predictable they were in their movements. The combination of these variables provides a holistic perspective of strategy, and can differentiate the attacking abilities of teams.

There is an opportunity to develop new methods of analysing ball movement patterns with the resources available in field hockey that provides practical insight into performance. The primary aim of this study was to analyse the entropy and spatial distribution of ball movement patterns of international hockey teams. The secondary aims were to assess the influence of match context on these movement patterns, and identify the most common attacking movement patterns related to play outcomes.

MATERIALS AND METHODS

Video footage of matches from the 2019 International Hockey Federation (Fédération Internationale de Hockey, FIH) Pro League (n = 57 men, n = 74 women) were accessed and analysed for this study. The tournament was an invitational competition played in a home and away season by 8 (men) and 9 (women) teams ranked in the top 12 FIH teams. Teams included Argentina, Australia, Belgium, China (women only), Great Britain, Germany, Netherlands, New Zealand, Spain (men only) and United States of America (women only). Ethical approval was granted by the Universities Human Research Ethics Committee.

Computerised performance analysis software, SportsCode (Version 11, Hudl, https://www.hudl.com), was used to retrospectively analyse the match video footage. Variables related to the team in possession, ball movement in general play (i.e. not set pieces), the outcome of the play, and the match context, were annotated using a specifically designed code window (Figure 1). To track ball movement, the field was divided into 5×8 cells (i.e. 40 field zones in total). Each cell on the field that a player had control of the ball was annotated. If a player dribbled the ball through multiple cells each individual cell the ball was controlled through was notated. However, when passing, only the cells where the ball was passed from, and received, were notated.

The outcome was also recorded at the end of the possession and included a goal shot, penalty corner, restart (long corner or ball played from within the circle to outside the circle and possession retained), or turnover. Only the initial outcome was recorded; for example, if a goal shot resulted in a turnover only a goal shot was recorded, to ensure the pattern of play was analysed rather than execution of the goal shot. If a goal shot from general play or a penalty corner resulted in a rebound for the attacking team, a ball movement would not be recorded to limit movement patterns to the creation of goal scoring opportunities. A new movement pattern was only initiated if a team retained possession after a goal shot or penalty corner once the ball had left the attacking circle.

Contextual variables were recorded for each game including match status at the time of possession (winning, losing or drawing) and team ranking at the end of the tournament (1st – 8th/9th). Relative team quality was calculated retrospectively by subtracting the reference team rank from the opposition team rank. For example, a relative team quality of +7 or -3 indicated a team was ranked 7 places higher and 3 places lower than the opposition.

A pilot study was completed on a randomly selected game from the database to ensure all necessary variables were recorded and the size of the cells in the code window were appropriate. Intra- and inter-coder reliability tests were also conducted on one random game to ensure coding was completed consistently and accurately. The intra- and inter-coder Kappa values were calculated as 0.92 and 0.91 for start locations, 0.91 and 0.87 for end locations and 1.0 and 1.0 for outcomes, respectively. These values indicate "very good" levels of agreement between observers [13] and the notational analysis process was deemed reliable.

Data Analysis

The XML file for each game, which contained all the variables recorded in chronological order, was exported from SportsCode™ (Version 11, Hudl, https://www.hudl.com) and converted to CSV using Microsoft Excel™. These CSV files were then imported into RStudio 1.3.1093 (RStudio Inc, https://www.rstudio.com) for data analysis using R (version 4.03) [14]. Each team per match per match status (winning, losing or drawing) was analysed individually to identify how and where they moved the ball under different match situations. The 40 cells were grouped into 7 attacking zones based on the different phases of attack occurring in each zone. Table 1 describes the definitions for each attacking zone and their respective phases of attack, and Figure 2 illustrates these zones on the field.

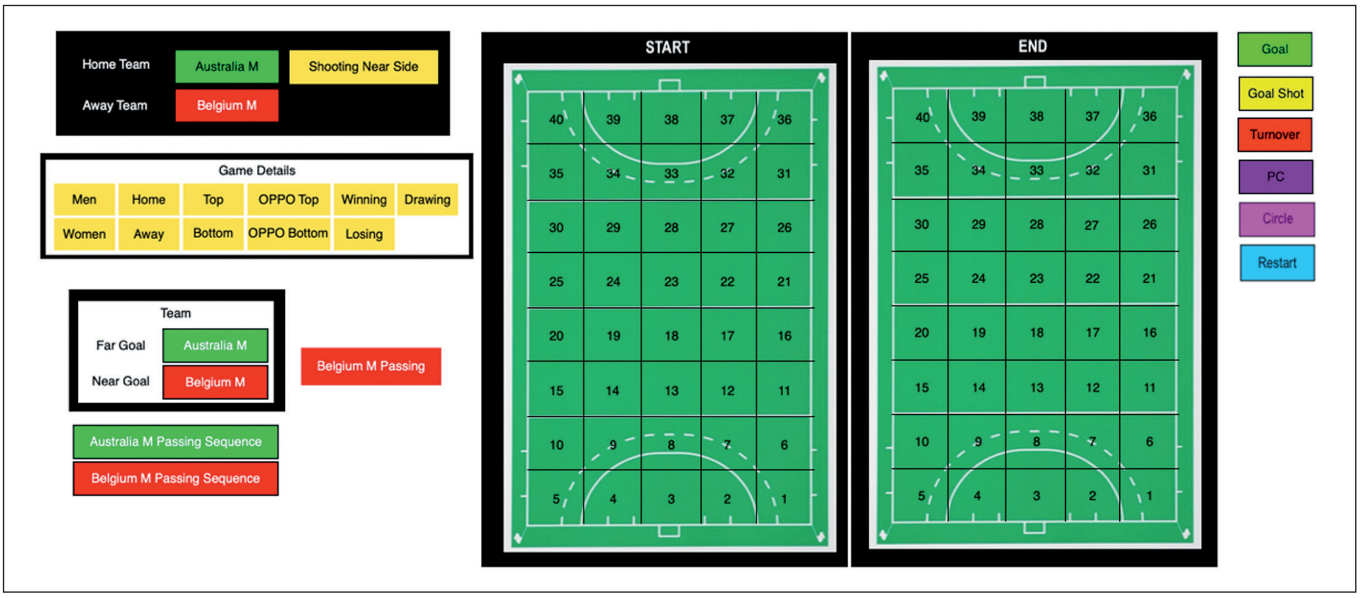


FIG. 1. Notational analysis system used to capture ball movement patterns in SportsCode showing an example game between Australia and Belgium men's teams. An analyst would choose the team in possession, the start and end location of each ball movement followed by the outcome at the end of a play. The field orientation would switch direction depending on which team was in possession so cell 1 always corresponded to the attacking 25 left corner and cell 40 to the defensive 25 right corner of the field

TABLE 1. Attacking zone definitions relating areas on the field to phase of attack

Attacking Zone	Location	Aim	Players and ball movement
Circle	Areas closest goal encompassing the majority of the circle	Create goal scoring opportunities	Attackers attempt to move the ball along the baseline to the centre of circle as this is the best goal scoring position given the angle and proximity to goal.
Corners	Two corners of the attacking 25 bordered by the baseline and sideline	Create circle entry	Safer path into the circle as the offence look to move the ball around the edge of the defence along the baseline into the circle. However, the longer route into the circle provides greater opportunities for the defence to get numbers to better goal scoring positions.
Deep Attack	Centre of the attacking half and top of the circle	Create circle entry and/or goal scoring opportunity	Attackers attempt to move directly to the top of the circle for a goal shot or pass closer to goal, providing the more direct route to goal and best angle for a goal shot. However, it is also a riskier option as a team must play through the defenders clustered around the circle, increasing the chances of a turnover and counter attack.
Build Attack	Edges of the attacking half and across the attacking side of the half way line	Manipulate defence to create space for an attacking opportunity	Attack look to manipulate the defence by passing back and around the midfield. Defence condense into their defensive half, protecting the direct routes to goal. The depth and width of this shape reflects the spread of the attackers in an attempt to maintain possession by transferring the ball backwards or across the field.
Build Defence	Defensive side of the half way line and centre of the defensive 50	Gain ground, manipulate defence	Until ground can be gained defenders transfer the ball from side to side to attempt to generate holes in the opposition's structure. Generally, a team will have one or two central defenders and two wide defenders reflecting the shape of this zone.
Outlet	Areas used to take free hits from the defensive 25 and the likely path out from defence	Gain ground	Defence are set up in front of the ball, protecting the centre but allowing the player to move to the sideline. Attackers generally have two central defenders and two higher wider defenders for moving the ball up the sideline.
Deep Defence	Area along the baseline of the defensive 25	Protect goal	Danger zone for attacking team, turnover in this area could lead to a goal shot or restart of play for the opposition. Attackers look to move wide towards the space near the sideline to remove ball from circle and away from the defence.

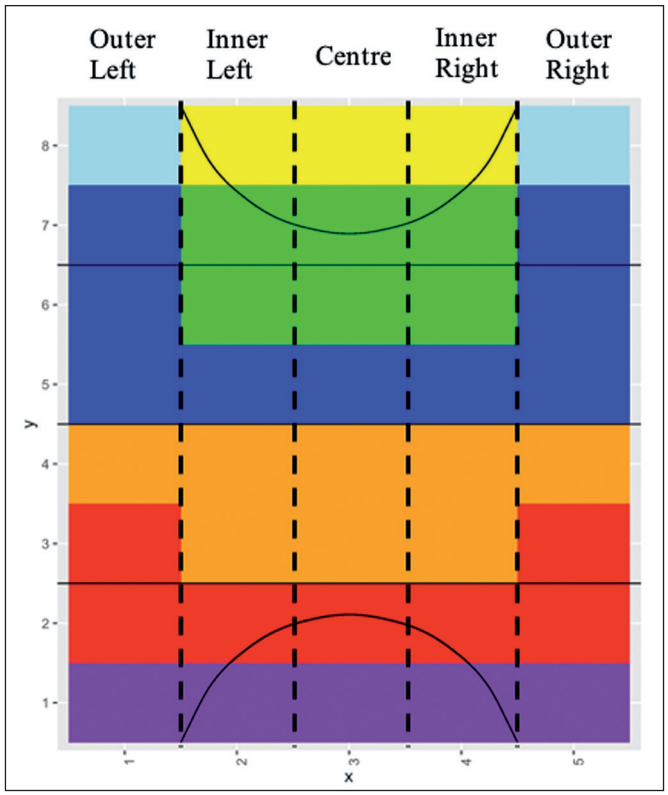


FIG. 2. Field split into seven attacking zones; yellow = circle, light blue = corners, green = deep attack, dark blue = build attack, orange = build defence, red = outlet, purple = deep defence

Data were analysed for entropy and spatial distribution which included game possession, possession per zone, and progression rates (i.e. the percentage of ball movements in different directions). Time in possession was calculated by summing the total time of all actions completed per cell location by calculating the difference between start and end times for each movement. The percentage of game possession for a team in a single match was calculated by dividing the total time for the reference team's game actions by the total time for both team's game actions per match. This metric reflected how much control a team had per match. Possession per zone was calculated by dividing the time for all game actions in one attacking zone by the total time in possession for all attacking zones for a team. This metric indicated the offensive opportunities of a team.

Shannon's entropy (*H*) was calculated to determine the unpredictability of ball movement for each cell location [6], which reflects the passing range of a team and the variety of ways they may attack. The equation for Shannon's entropy is shown in Equation 1 where p_i is the probability of the ball entering a certain location, and *n* is the total number of locations the ball can enter [15]. The minimum entropy value of 0 indicates a highly predictable movement pattern. The maximum entropy value is determined by taking the natural logarithm of the number of locations included in the calculation. If the ball is transferred from one cell to every other location on the field, then *n* is equal to 40. Therefore, the theoretical maximum entropy for this analysis was 3.69 ($\log_e(40)$). The mean was then calculated for each attacking zone. Entropy values were normalised by dividing by the theoretical maximum (3.69) entropy, so the theoretical minimum normalised entropy value was 0 and the theoretical maximum normalised entropy was 1.

$$\text{Equation 1: } H(X) = H(p_{1,}, \ldots, p_n) = -\sum_{i=1}^{n} p_i log_e p_i$$

Progression rates were calculated to determine the intent of teams to attack directly and progress the ball towards goal, or maintain possession. A novel method was developed to assess progression rates. Progression rates were calculated for each of the 40 cells by calculating the percentage of ball movements that ended in each cell. Cells were then grouped into the 7 attacking zones, for start and end locations, and averages calculated for each zone. Movements were simplified to four direction categories so they could be compared between zones. Direction categories included:

- Back: ball movement was received in a zone behind the starting zone
- Stay: ball movement started and ended within the same zone
- Forward: ball movement was received in the adjacent zone in front of the starting zone
- Goal: ball movement ended in a zone 2 or 3 ahead from a starting zone in the defensive half, or ended in a zone more direct to goal through the centre of the field from the attacking half

Table 2 shows the description of categories for each attacking zone. Attacking team profiles were developed by analysing when a team was in attack, and defensive team profiles by calculating opposition values for each team.

Statistical Analysis

Statistical analysis was completed in RStudio separately on male and female data. Data were transformed to a z-score to ensure equal weighting in the analysis. Linear mixed models, using the '*lmer*' function from the *'lme4'* R package [16], were used to analyse the effect of contextual variables and attacking zones on game possession, entropy, possession per zone and progression rates. In the first model, match status and attacking zones were identified as fixed factors, and team and game number included as nested random factors, and relative team quality as a random factor. In the second model, relative team quality and attacking zones were identified as fixed factors and team, game number and match status included as nested random variables. The interaction between fixed factors was analysed in both models. Assumptions of normality and homoscedasticity were checked via visual inspection of residual plots and histograms.

Likelihood ratio tests, using the *'anova'* function, were used to determine the statistical significance of a fixed or random factor by comparing models with and without the variable in question. To identify significant pairwise comparisons in a model assessing match status, the '*emmeans*' function with false discovery rate correction [17] from

TABLE 2. Movement progression categories for each attacking zone representing the least to most direct attacking options to take from left to right. For example, a team that has possession in the Circle (first row below), if they move into the Corners or Build Attack zones it is considered a movement back, if they dribble or pass within the circle the team has not changed zones so it is considered as a stay movement, and if the team moves the ball to the Deep Attack zone it is considered to be movement in the forward direction as the ball remains in an attacking position for a goal shot, even though the initial ball movement is away from goal.

Directness Start Zone	Least Back	Stay	Forward	Most Goal
Circle	Corners Build Attack	Circle	Deep Attack	NA
Corners	Build Attack Build Defence	Corners	Deep Attack	Circle
Deep Attack	Build Attack Build Defence	Deep Attack	Corners	Circle
Build Attack	Build Defence Outlet	Build Attack	Corners	Deep Attack Circle
Build Defence	Outlet Deep Defence	Build Defence	Build Attack Corners	Deep Attack Circle
Outlet	Deep Defence	Outlet	Build Defence	Build Attack Deep Attack
Deep Defence	NA	Deep Defence	Outlet	Build Defence Build Attack

the *'emmeans'* R package [18] was employed. To assess relative team quality, the *'emtrends'* function from the *'emmeans'* R package [18] was used. Results are presented as unstandardised estimated marginal mean ± 95% confidence limits (CL) and considered significant when $p < 0.05$. Practical differences were identified by considering the aim of the attacking zone, and the minimal difference in possession, entropy or progression rates needed to achieve this aim.

Decision trees were developed, using the '*rpart*' function from the '*rpart'* R package [19], to assess the variables determining the outcome of a play – goal shot, positive (penalty corner or restart), or turnover. Forty predictor variables were included in the model including entropy, possession, and movements back, stay, forward and goal for each attacking zone. The prediction accuracy of the model was assessed by splitting the data into train (70%) and test (30%) data sets and using the *'predict'* function from the *'caret'* R package [20]. The overall accuracy was 86% for men and 91% for women with sensitivity (true positives) > 79% and specificity (true negatives) > 88%. The decision tree model was deemed able to accurately distinguish play outcomes. The *'varImp'* function from the *'caret'* R package [20] was used to identify which variables distinguished play outcomes.

RESULTS

Match Status

The total number of ball movements recorded for men in 57 games when winning was 18406, losing 18799, and drawing 22680. The mean number of ball movements completed per team per game when winning was 301 (± 398) (mean ± standard deviation), losing 261(± 143) and drawing 201 (± 122). The mean length of time in seconds of each ball movement when winning was 2.16 s (± 1.30 s), losing 2.14 s (± 1.24 s) and drawing 2.14 s (± 1.23 s). For women, the total number of ball movements recorded in 74 games when winning was 20147, losing 19818 and drawing 26621. The mean number of ball movements completed per team per game when winning was 221 (± 143), losing 218 (± 129) and drawing 180 (± 112). The mean length of time in seconds of each ball movement when winning was 2.12 s (± 1.24 s), losing 2.09 s (± 1.15 s) and drawing 2.08 s (± 1.16 s).

Men's and women's profiles when winning, losing and drawing and pairwise comparisons are presented in Figure 3. For both men and women, practical differences were observed between teams for game possession and possession per zone. For men, losing teams had greater game possession (8.1 ± 1.7%; mean ± 95% CL) and greater possession (3.3 ± 3.0%) in deep attack than winning teams. Winning teams had greater possession (5.9 ± 5.2%) in outlet than losing teams. For women, losing teams had greater game possession (6.1 ± 1.1%) and greater possession in build attack (5.0 ± 4.5%) than winning teams. Winning teams had greater possession in deep defence (4.1 ± 3.9%) and outlet (7.3 ± 6.0%) than losing teams.

Team Quality

For men, the total number of ball movements recorded when relative team quality was -7 was 893 (2 games), +1 was 8683 (16 games)



FIG. 3. A comparison of ball movement patterns when winning, losing and drawing for men's (left) and women's (right) teams in the 2019 Pro League tournament. Results are presented as average of ball movement variable on the x axis per match status per attacking zone on the y axis. Z-score indicates above (green) and below (red) average performance compared to the league average. D = significant difference compared to drawing, L = significant difference compared to losing, and W = significant difference compared to winning teams. For example, game possession for men, losing teams have greater possession than drawing and winning teams and drawing teams have greater game possession than winning teams.



FIG. 4. A comparison of ball movement patterns when relative team quality is +7, +1 and -7 for men's (left) and +8, +1 and -8 for women's (right) teams in the 2019 Pro League tournament. Results are presented as average of ball movement variable on the x axis per match status per attacking zone on the y axis. Z-score indicates above (green) and below (red) average performance compared to the league average. * indicates significant trend in relative quality of teams. For example, game possession for men decreases with ranking from teams ranked 7 places higher than their opposition to teams ranked 7 places lower



FIG. 5. A comparison of plays ending in a goal shot, positive or turnover for men's (left) and women's (right) teams in the 2019 Pro League tournament. Results are presented as average of ball movement variable on the x axis per play outcome per attacking zone on the y axis. Z-score indicates above (green) and below (red) average performance compared to the league average. Superscripted numbers indicate variables important in distinguishing play outcomes in order of importance. For example, circle possession was the most important variable for men, with plays ending in a goal shot having greater circle possession than positive outcomes and positive outcomes having greater circle possession than turnovers.

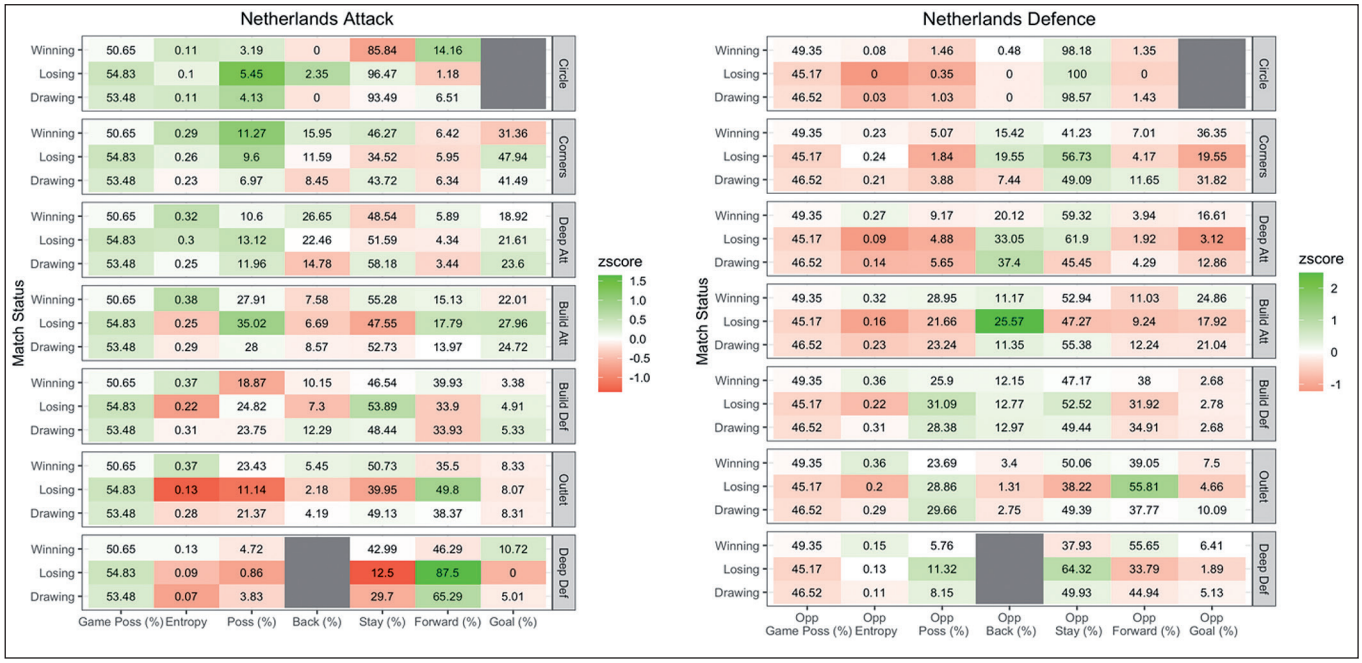


FIG. 6. Attacking (left) and defensive (right) ball movement variables for Netherlands women's team when winning, losing or drawing. Results are presented as average of ball movement variable on the x axis per match status per attacking zone on the y axis. Z-score indicates variables used more (green) and less (red) often than the league average.

and +7 was 1255 (2 games). The mean number of ball movements per team per game when relative quality was -7 was 447 (± 8), +1 was 548 (± 88) and +7 was 628 (± 43). The mean length of time in seconds of each ball movement when relative quality was -7 was 2.05 s (± 1.18 s), +1 was 2.06 s (± 1.17 s) and +7 was 2.08 s (± 1.17 s). For women, the total number of ball movements recorded when relative team quality was -8 was 774 (2 games), +1 was 7702 (17 games) and +8 was 1291 (2 games). The mean number of ball movements per team per game when relative quality was -8 was 387 (± 23), +1 was 453 (± 50) and +8 was 646 (± 15). The mean length of time in seconds of each ball movement when relative quality was -8 was 1.98 s (± 1.06 s), +1 was 2.08 s (± 1.19 s) and +8 was 1.89 s (± 1.05 s).

Men's and women's profiles are shown for lower, similar and higher ranked teams (relative to the reference team) in Figure 4. For men, game possession increased by 1.4% (± 0.6%) with an increase in team quality by one ranking (place). Entropy increased by 0.0057 (± 0.0053) in deep attack and by 0.0062 (± 0.005) in build attack with an increase in ranking. Possession increased by 0.4% (± 0.3%) in build attack, and decreased by 0.8% (± 0.3%) in outlet with an increase in ranking by one.

For women, practical differences were observed in game possession, an increase of 0.9% (± 0.4%) was seen with an increase in one ranking (place). As ranking increased, entropy in deep attack increased by 0.0065 (± 0.0041). Ball movements that stayed in the corners were higher for lower ranked teams. Movements directed towards goal were higher for relatively higher ranked teams from corners and deep attack.

Play Outcomes

The total number of ball movements recorded in 57 games for men during phases of play leading to a goal shot was 6401, a positive outcome 8808 and a turnover 44255. The mean number of ball movements completed per team per game resulting in a goal shot was 56 (± 30), a positive outcome 78 (± 36) and a turnover 388 (± 58). The mean length of time in seconds of each ball movement in plays resulting in a goal shot was 1.98 s (± 1.18 s), a positive outcome 2.08 s (± 1.22 s) and a turnover 2.18 s (± 1.27 s). The total number of ball movements for women in 74 games resulting in a goal shot was 5657, a positive outcome 7993 and a turnover 52309. The mean number of ball movements per team per game for plays resulting in a goal shot was 38 (± 24), a positive outcome 54 (± 24) and a turnover 353 (± 44). The mean length of time in seconds of each ball movement for plays resulting in a goal shot was 1.87 s (± 1.06 s), a positive outcome 2.08 s (± 1.16 s) and turnover 2.12 s (± 1.19 s).

Men's and women's profiles when a play ends in a goal shot, positive outcome, or a turnover, and the variables important in distinguishing play outcomes are shown in Figure 5. A total of 16 variables were considered important for men, with the three highest-ranked variables including Circle Possession, Build Defence Entropy and Build Attack Entropy. For women, a total of 13 variables were considered important, and the three most important variables were Deep Attack Goal, Build Defence Entropy and Build Attack Entropy.

Team Profiles

An example profile for Netherlands women is displayed in Figure 6 for attacking and defensive variables when winning, losing and drawing. Additional supplementary files showing all individual team profiles are available from the corresponding author.

DISCUSSION

This study analysed the entropy and spatial distribution of ball movement patterns in international field hockey. Ball movement profiles were developed by analysing the interaction of these spatio-temporal variables. This novel method of data capture and analysis provides more practical insights into performance as it accounts for the multitude of factors influencing ball movement patterns. To be successful, teams need to be both predictable when direct opportunities to attack arise, but also unpredictable when trying to maintain possession in attacking positions and unbalance the defence. The results of this study highlight the importance of analysing the critical factors influencing strategy. This approach ensures that coaches have the level of detail needed to develop specific strategies for success in different match situations.

Differences in ball movement variables were evident between play outcomes in the FIH Pro League, and similar trends were observed between genders highlighting several basic principles of hockey. A turnover was likely to occur when a play had greater entropy, higher possession in the defensive half, and a greater proportion of actions staying in defence or moving back in attacking positions. In contrast, a positive outcome resulted from plays with lower entropy, but higher possession in corner zones as teams had a greater proportion of actions moving forward. Goal shots, also resulted from plays with lower entropy, but higher possession in deep attack and the circle, and a greater proportion of actions moving more directly to goal. The ability to progress the ball quickly and more directly through the centre of the field provides greater opportunities for goal shots before the opposition can organise their defence. An inability to penetrate the defence and progress directly to goal allows greater time for the defence to protect the direct lines to goal, subsequently more likely resulting in a turnover when a team is held up in the defensive half and a positive outcome in attacking positions. This outcome reflects earlier research indicating a goal scoring opportunity was more likely if the ball was possessed near, or at the top of the circle [3], and a goal scored the further up the pitch the ball was regained [2]. Understanding differences between these play outcomes, assists both the analyst and coach interpret team profiles and assess the attacking ability of a team.

Hockey is a low scoring game and our results show > 75% of game possession were related to plays ending in a turnover. Thus, goal scoring opportunities are likely to result from a sequence of plays

that aim to disorganise the defence by building pressure in attacking positions, while restricting the opposition doing the same. For both men and women, teams ranked relatively higher had greater game possession, and entropy and possession in zones in the attacking half. Although these effects were small, they reflect the trend for greater differences in attacking opportunities as the relative team difference increased given the ability of higher ranked teams to control the ball in the attacking half. A limitation of this study was that all teams were ranked within the top 12 international teams in 2019 which may have masked the impact of relative team quality on ball movement patterns. A larger effect may have been seen if there were teams competing from a greater range in rankings. Nonetheless, this outcome is consistent with analysis in soccer where the top-ranked teams completed greater actions related to ball possession and ending actions [21], had the greatest mean values of entropy [22], and greater width and length in attack against weaker opposition [23]. This pattern of play makes higher ranked teams more unpredictable and harder to defend against as the opposition has to protect a larger portion of the field. Consequently, higher ranked teams are more likely to create greater attacking opportunities per game.

When analysing the effect of match status on ball movement variables for both men and women, compared to teams that are drawing, losing teams have more game possession, greater entropy and possession in the attacking half. While winning teams have less game possession, but greater entropy and possession in the defensive half as they are more likely to move backwards. Although these effects may be small, they reflect a tendency for teams to change strategy when there is a change in match status. A larger effect may be observed if score differences and interaction with relative team quality are assessed. Nonetheless, winning teams are more likely to retreat to their defensive half to protect their goal, while losing teams are likely to increase their defensive pressure higher up the ground. This pattern is observed in soccer, with losing teams having greater possession in the attacking half, and more likely to increase their use of build-up and sustained threats plays which increased a team's level of game possession, and winning teams having greater possession in the defensive half, and increased use of direct attacks [24, 25]. The relationship between entropy and possession reflects the change in strategy with match status that increases the attacking opportunities of losing teams, while reducing those of winning teams.

It appears there are two key factors related to success which a coach can use to develop effective strategies. First, it is the ability of a team to get the ball to the build attack zone quickly, and secondly maintaining possession in the attacking half using a variety of movement patterns, that increases the chance of the play being successful. We have showed that successful hockey teams and plays revolve around possession in the attacking half, utilising the length and width of the attacking half to disorganise the defence and create space to attack the direct routes to goal. This is reflected in research identifying soccer teams were more likely to create a goal scoring opportunity from a counter attack or regaining the ball in the attacking third [26]. In basketball only front (attacking) court entropy, as opposed to full court entropy was related to success [6], and entropy was positively correlated to generating future high probability shots [27]. Therefore, teams may be predictable when the opposition is disorganised, and immediate scoring opportunities present themselves, but unpredictable when the opposition are organised to maintain possession while attempting to unbalance the defence.

The relatively small effect of match status and team quality on ball movement patterns may reflect the different strategies individual teams use in different situations to be successful. For example, Netherlands (women) are a dominant team as they have high game possession, and entropy and possession in the attacking half while limiting their oppositions attacking possession by forcing them backwards. In contrast, Australia (women) have lower game possession, lower entropy in the attacking half and lower circle possession, and concede high opposition possession in their attacking half. However, Australia's ability to absorb pressure and counter attack led them to the final of the 2019 Pro League tournament against Netherlands. The opposing strategies reflects the need to analyse teams individually as there is more than one way to win a game of hockey and teams must develop strategies that reflect the abilities of their players.

CONCLUSIONS

We developed attacking and defensive ball movement profiles in international field hockey using video and notational analysis of the 2019 FIH Pro League men's and women's tournaments. These profiles were developed by analysing the entropy, possession and progression rates of ball movement patterns and assessing the interaction of these spatio-temporal variables across seven attacking zones. These profiles highlight the direction and unpredictability of a team's ball movements and the attacking opportunities that arise. The ability to quickly get the ball to and then maintain possession in the attacking half using a variety of patterns are key factors in developing effective strategies. This novel approach provides important evidence for coaches to develop strategies that utilises their team's strengths and exploits the opposition's weaknesses.

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Monitoring physical match performance relative to peak locomotor demands: implications for training professional soccer players

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ABSTRACT: This study aimed to analyse physical performance relative to peak locomotor demands of match play. Data were collected during 13 professional soccer matches. Initially, the 1-minute peak values were registered in each match, including the percentage of the total distance (TD), high-speed running distance (HSRD), sprinting distance (SPD), and high-metabolic load distance (HMLD), and a total of high-intensity accelerations and decelerations (Acc+Dec). Secondly, the time (measured in minutes) spent at different percentage ranges for the 1-minute peak values registered in each match was calculated. Thirdly, the physical performance required in the different percentage ranges for the 1-minute peak values were obtained. Finally, the time and physical performance required above the 90-minute average demands were calculated. The 90-minute average for all playing positions represented ~53% of the total distance (TD), ~23.4% of high-metabolic load distance (HMLD), ~16% of high-speed running distance (HSRD), ~11% of the total of high-intensity accelerations and decelerations (Acc+Dec), and ~6% of sprinting distance (SPD) for the 1-minute peak values. Likewise, statistically significant differences ($p < 0.05$) in the physical performance and time spent between specific percentage ranges for the 1-minute peak locomotor demands were also noted. In addition, all the variables reported that the physical performance required for above 90-minute average demands were significantly greater ($p < 0.05$) than the 90-minute average demands. Therefore, these findings may guide the prescription of training intensity by considering the physical performance relative to the peak locomotor demands of match play.

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Game Analysis
Team Sport
Worst Case Scenario

INTRODUCTION

The application of electronic performance and tracking systems to soccer has increased our understanding of the physical demands of the game [1]. Soccer is characterized by intermittent activity and high-intensity actions, which have increased significantly over the past several years [2], are interspersed with periods of lower intensity [3, 4]. Tracking systems provide objective data about players' performance, and thus, tracking performance has become a common tool used by strength and conditioning coaches [5].

The management of the data can guide coaches in their decision-making process regarding training schedules [6]. Several studies have concluded that professional soccer players should be trained based on the physical demands of match play to prevent injury and ensure successful match performance [3, 7, 8]. For example, a previous study suggested that if the players covered 115 m/min during the match (with an average of 29 m/min at high-speed running), they ought to be trained for similar demands [3]. Hence, coaches may design their training drills (e.g., modifying area per player in small-sided games) to meet such demands [9].

However, recent studies have concluded that the training drills should also consider the periods of peak locomotor demands experienced by the players during match play because 90-minute average demands may be lower than the physical demands experienced in match play [10–12]. Specifically, these periods of peak locomotor demands, which have been interpreted as the most demanding passages of play or worst-case scenarios by previous studies, are duration-specific periods of the match (e.g., 1-minute periods) in which the players are required to perform at very high intensity [4, 11, 13, 14]. For instance, a recent study reported that professional players could cover ~200 m (with ~61 m considered to be high-speed running and ~30 m to be sprinting speed) or perform ~4 high-intensity accelerations or decelerations in one minute [4]. Additionally, the 1-minute periods have been recently

described across team formation, ball in play, and ball possession to help practitioners contextualize the maximal technical-tactical match demands during practice [15].

Nevertheless, it should be noted that these peak locomotor demands only occur once throughout a match, and this approach, therefore, does not reflect overall physical demands (especially when it comes to the volume completed at or close to such peak demands) [12, 16]. In this regard, the peak locomotor demands of match play may guide training intensity prescription, although little is known about the distribution of this intensity in professional soccer [12]. For instance, strength and conditioning coaches might wonder which percentage range (for the 1-minute peak locomotor demands) corresponds to the 90-minute average demands and how long the players must train above this intensity [12]. Given that research on the topic is scarce, this study aims to analyse physical performance relative to peak locomotor demands of match play.

MATERIALS AND METHODS

Study design

A longitudinal study was conducted in LaLiga123. Data were collected using electronic performance and tracking systems during 13 official 2018–2019 season matches (7 away matches and 6 home matches). These matches were played on a non-congested calendar (i.e., only one match per week) with 4-4-2 as the standard playing formation. This study was conducted in accordance with the principles of the Declaration of Helsinki (1975), and the university's Bioethics Committee authorized the data collection.

Participants

Seventeen professional soccer players (26.79 ± 3.72 years old; body mass index, 23.30 ± 0.21) participated in the study. The players were classified according to the following playing positions: fullbacks (FB, $n = 5$), forwards (FW, $n = 2$), central defenders (CD, $n = 3$), wide midfielders (WMF, $n = 3$), and central midfielders (MF, $n = 4$). Only players who played for the full duration of the match were included. Specifically, a total of 109 match observations were registered with an average of 6.4 ± 4.1 matches per player. In addition, goalkeepers were excluded as this playing position is characterized by a different activity profile [17].

Procedures

WIMU Pro (RealTrack Systems, Almería, Spain) electronic performance and tracking systems were placed in the back pocket of players' vests (Rasán, Valencia, Spain). These tracking systems are valid and reliable instruments for tracking physical performance in soccer [18] and have been certified by the FIFA Quality Program to collect physical performance variables based on position and speed accuracy [19]. Each device was turned on 30 minutes before each match and calibrated on a Smart Station (RealTrack Systems, Almería, Spain) following the manufacturer's instructions [20]. Furthermore, each player wore the same device in every match to reduce inter-unit error [4].

Once the match had concluded, the data were transferred to SPro (RealTrack Systems, Almería, Spain). Match data were split into two halves of match play (first and second half), and then, these halves were divided into 1-minute periods. The Intervals Pro performance report (RealTrack Systems, Almería, Spain) was then downloaded. Also, the 1-minute peak locomotor demands were obtained through the worst-case scenario report (RealTrack Systems, Almería, Spain) based on rolling averages techniques [21]. Specifically, the following physical performance variables were analysed: total distance (TD) covered, high-speed running distance (HSRD, above 19.8 km/h), sprinting distance (SPD, above 25.2 km/h), high-metabolic load distance (HMLD, above 25.5 W/kg), and the sum of high-intensity accelerations and decelerations (Acc+Dec, above 3 m/s^2) per minute.

Statistical analysis

Once the data was exported, the physical performance analysis relative to the peak locomotor demands of match play was conducted following the procedures used in a previous study [12]. Firstly, the percentage of TD, HSRD, SPD, HMLD, and Acc+Dec for the 1-minute peak values registered in each match was calculated. Secondly, the time (in minutes) spent at different percentage ranges for the 1-minute peak values registered in each match (e.g., time spent between 0% and 10% of the TD covered in the 1-minute peak) was calculated. Thirdly, the volume of physical performance required by a percentage range for the 1-minute peak values was obtained (e.g., TD covered per minute between 90% and 100% of the TD covered in the 1-minute peak multiplied by the time spent within the same range). Finally, to represent the total volume of physical performance at intensities above the 90-minute average demands, a sum of the total volume of physical performance required by a range of percentages for the 1-minute peak values above the 90-minute average demands was calculated.

This study used a linear mixed model analysis to compare the effects of playing position by percentage ranges for the 1-minute peak locomotor demands on each variable related to the physical demands [12]. The model considered each variable representing physical performance parameters (i.e., TD, HSRD, SPD, HMLD, and Acc+Dec), the playing position, and the different percentage ranges for the 1-minute peak locomotor demands as independent fixed factors while the players were set as random intercepts. A log-likelihood ratio test was used to analyse the quality of fit of the models. Multiple comparison analysis was determined using Bonferroni's correction. Cohen's *d* effect size (ES) with 95% confidence intervals (CI) calculated and categorized them as trivial (< 0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (≥ 2.00) [22]. The level of statistical significance was set at $\alpha < 0.05$. The statistical analysis was performed on SPSS (version 26, Armonk, NY, USA).

RESULTS

Figure 1 shows the 90-minute average demands represented as the percentage of TD (53.3 ± 0.3%), HSRD (15.7 ± 2.0%), SPD (6.2 ± 1.7%), HMLD (23.4 ± 1.1%), and Acc+Dec (10.9 ± 0.5%) for the 1-minute peak values registered in each match for all playing positions. In this regard, substantial differences between variables ($p < 0.001$; ES: 2.07 to 38.4) were observed for all playing positions. However, no significant differences between playing positions ($p > 0.05$) were found.

Figure 2 shows the time (in minutes) spent at different percentage ranges for each playing position's 1-minute peak locomotor demands. There were significant differences in time spent between specific ranges ($p < 0.001$). In addition, although the main effect of playing position on the time spent at different percentage ranges for the 1-minute peak locomotor demands was not significant ($p > 0.05$), some differences between playing positions were observed. In this regard, trivial to small differences between positions (ES: 0.04 to 0.37) in TD and Acc+Dec as well as a moderate difference in forwards compared to midfielders at the 20–30% range for SPD were found (Figure 2).

Specifically, Table 1 shows the volume of physical performance required for each percentage range (e.g., TD covered per minute at each range multiplied by the time spent at the same range) for the 1-minute peak locomotor demands. Significant differences in physical performance were required between specific ranges ($p < 0.001$) for all variables.

The results reported that the physical performance required above 90-minute average demands was significantly greater ($p < 0.001$; ES: 2.35 to 13.33) than the 90-minute average demands in TD (125.9 ± 6.2 m/min vs 107.2 ± 9.3 m/min), HSRD (29.3 ± 3.8 m/min vs 9.1 ± 2.9 m/min), SPD (20.2 ± 1.5 m/min vs 2.0 ± 1.2 m/min), HMLD (34.4 ± 3.68 m/min vs 21.4 ± 3.9 m/min), and Acc+Dec (1.3 ± 0.1 actions/min vs 0.9 ± 0.2 actions/min). In this regard, Table 2 shows the total volume of physical performance at intensities above the 90-minute average demands. Specifically, the 78.7 ± 1.8%, 84.5 ± 1.5%, 99.9 ± 0.2%, 85.8 ± 1.9% and 100.0 ± 0.0% of total volume for TD, HSRD, SPD, HMLD and

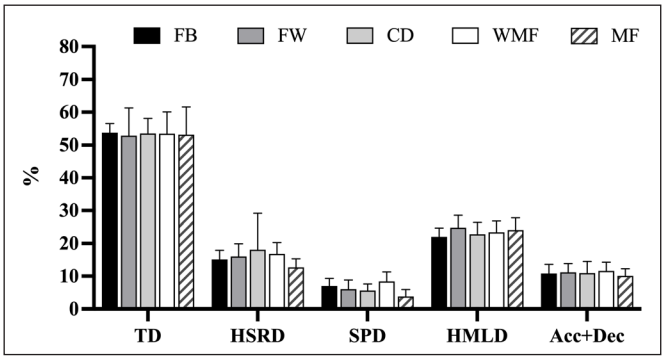


FIG. 1. 90-minute average demands represented as the percentage of the total distance (TD), high-speed running distance (HSRD), sprinting distance (SPD), high-metabolic load distance (HMLD), and the total number of accelerations and decelerations (Acc+Dec) for the 1-minute peak values registered for all playing positions. Note: FB: fullbacks; FW: forwards; CD: central defenders; WMF: wide midfielders; MF: central midfielders.

TABLE 1. The volume of physical performance required for each percentage range (e.g., TD covered per minute at each range × the time spent at the same range) for the 1-minute peak locomotor demands

Ranges	TD (m)	HSRD (m)	SPD (m)	HMLD (m)	Acc+Dec (count)
0–10%	16.5 ± 8.5	30.2 ± 10.7	0.1 ± 0.1	75.1 ± ± 12.5	0.0 ± 0.0
10–20%	77.9 ± 22.7	104.3 ± 26.4	**8.3 ± 7.2**	212.2 ± 28.8	**1.5 ± 1.2**
20–30%	261.9 ± 55.5	**136.4 ± 45.1**	**18.3 ± 11.1**	**290.1 ± 32.9**	**6.2 ± 3.8**
30–40%	572.4 ± 82.6	**126.6 ± 29.5**	**27.5 ± 13.7**	**319.4 ± 45.2**	**26.8 ± 6.2**
40–50%	1192.3 ± 51.9	**109.3 ± 33.3**	**21.7 ± 13.6**	**318.1 ± 41.3**	**22.0 ± 4.4**
50–60%	**1886.7 ± 164.8**	**93.4 ± 24.8**	**19.8 ± 9.1**	**258.3 ± 43.5**	**0.2 ± 0.3**
60–70%	**2252.2 ± 163.2**	**66.3 ± 18.6**	**16.7 ± 7.1**	**187.9 ± 28.1**	**12.9 ± 3.6**
70–80%	**1902.8 ± 177.7**	**58.4 ± 25.1**	**16.9 ± 11.6**	**130.2 ± 22.7**	**1.4 ± 1.1**
80–90%	**1100.7 ± 143.2**	**47.9 ± 19.9**	**11.5 ± 6.8**	**103.6 ± 23.3**	**0.0 ± 0.0**
90–100%	**654.0 ± 100.0**	**94.0 ± 20.5**	**48.3 ± 12.9**	**127.3 ± 24.9**	**12.4 ± 1.4**

Note: TD = total distance; HSRD = high-speed running distance; HMLD = high-metabolic load distance; Acc+Dec = total of high-intensity accelerations and decelerations. Bold text highlights the physical performance required above the average percentage corresponding to the 90-minute demands.

TABLE 2. The total volume of physical performance at intensities above 90-minute average demands.

	TD	HSRD	SPD	HMLD	Acc+Dec
Minutes	62.2 ± 1.1	24.9 ± 3.6	9.3 ± 3.7	50.9 ± 2.4	64.5 ± 4.0
Meters	7834.8 ± 454.4	739.6 ± 194.6	190.0 ± 89.2	1748.5 ± 213.6	n/a
Count	n/a	n/a	n/a	n/a	83.5 ± 8.3

Note: TD = total distance; HSRD = high-speed running distance; HMLD = high-metabolic load distance; Acc+Dec = total of high-intensity accelerations and decelerations; n/a = not applicable.

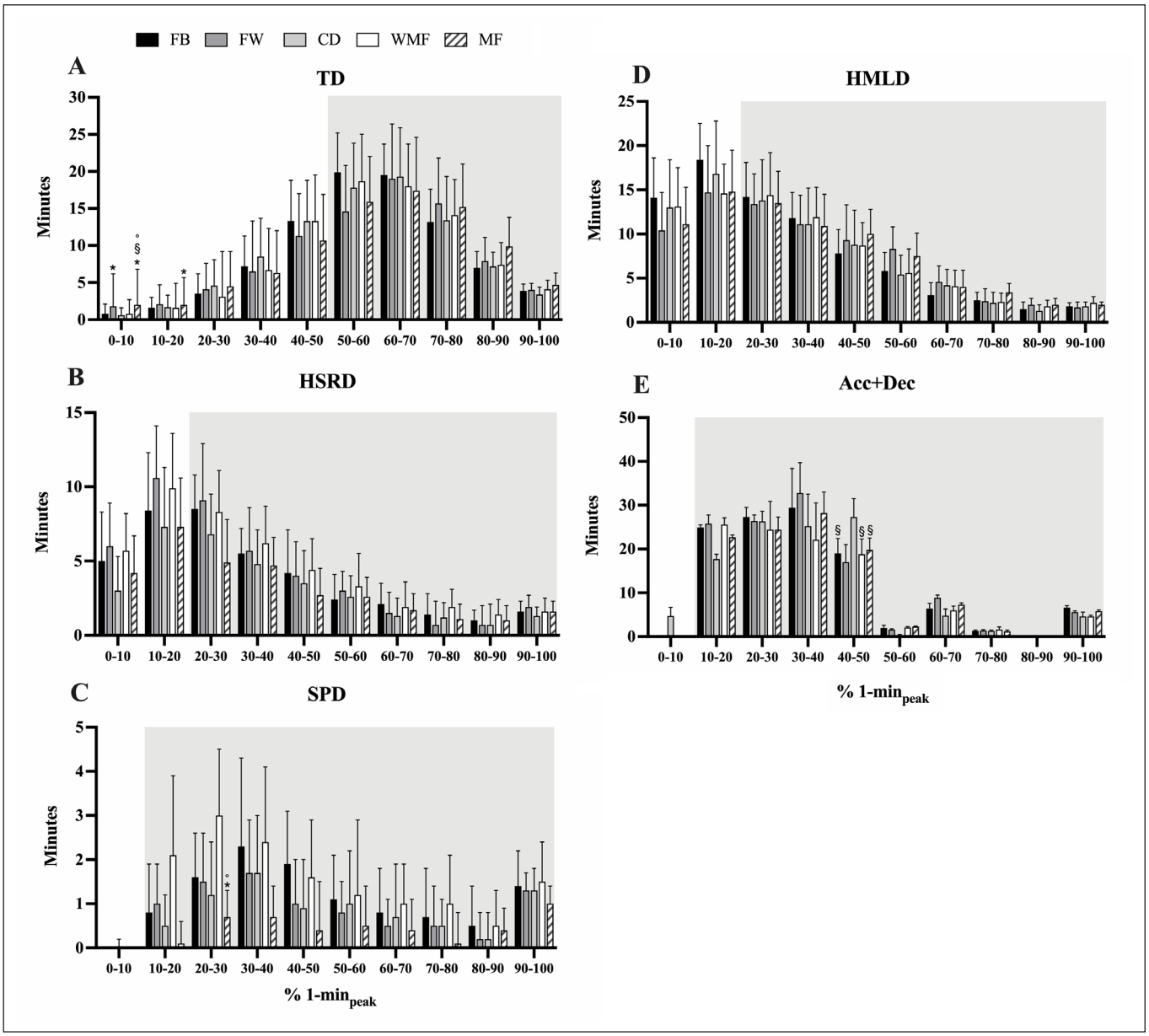


FIG. 2. Time (in minutes) spent at different `percentage ranges for each playing position's 1-minute peak locomotor demands. The grey area highlights the time required for above 90-minute average demands.
Note: TD: total distance; HSRD: high-speed running distance; SPD: sprinting distance; HMLD: high metabolic load distance; Acc+Dec: a total of high-intensity accelerations and decelerations. FB: fullbacks; FW: forwards; CD: central defenders; WMF: wide midfielders; MF: midfielders. $^{*}p < 0.05$ *vs* FB; $^{\S}p < 0.05$ *vs* CD; $^{\circ}p < 0.05$ *vs* WMF.

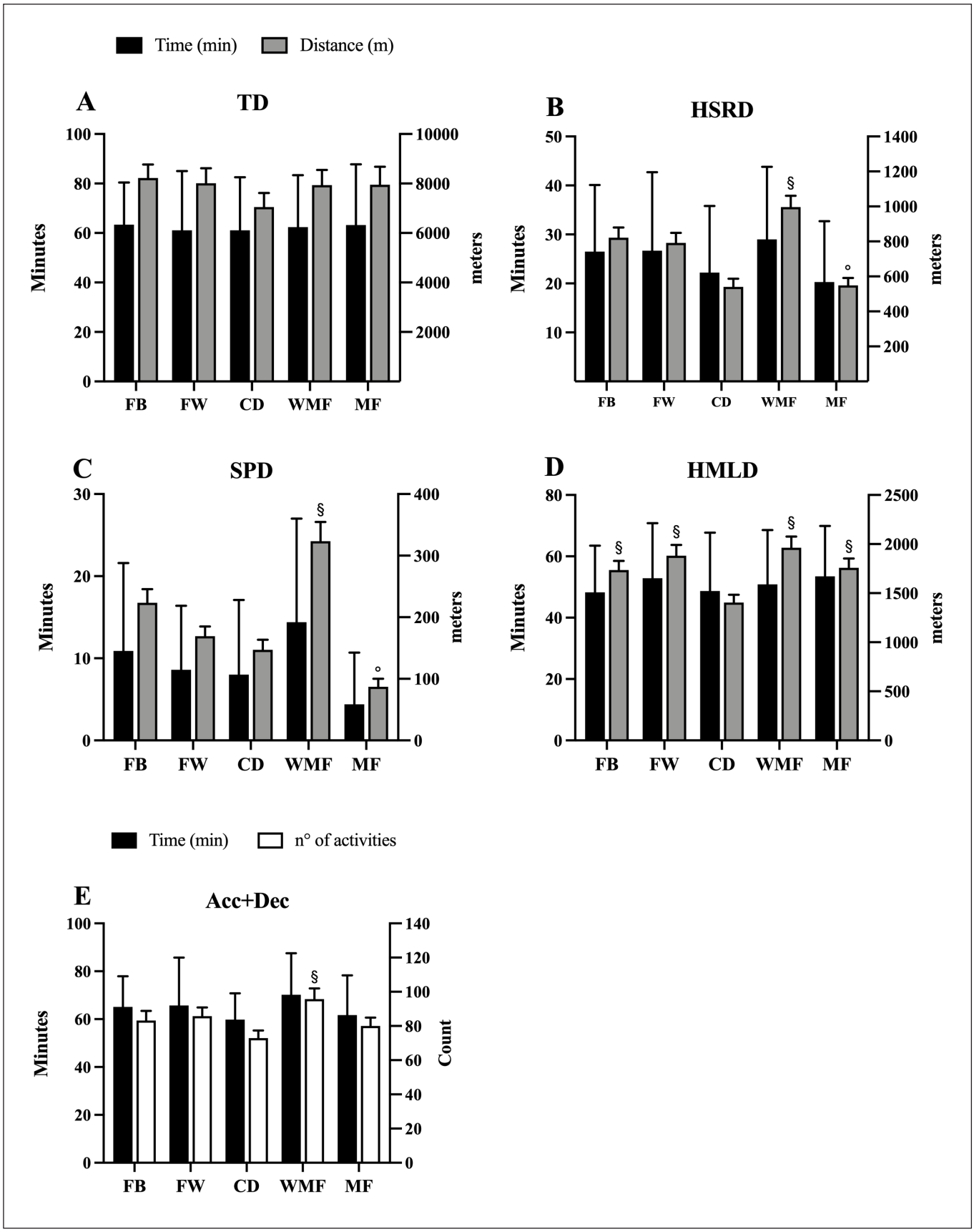


FIG. 3. Time and physical performance required above 90-minute average demands by playing position.
Note: TD: total distance; HSRD: high-speed running distance; SPD: sprinting distance; HMLD: high metabolic load distance; Acc+Dec: a total of high-intensity accelerations and decelerations. FB: fullbacks; FW: forwards; CD: central defenders; WMF: wide midfielders; MF: midfielders. $^{§}p < 0.05$ *vs* CD; $^{°}p < 0.05$ *vs* WMF.

Acc+Dec, respectively, was performed above the 90-minute average demands.

Figure 3 summarizes the time and physical performance required above the 90-minute average demands by playing position. No significant differences ($p > 0.05$) between the playing positions were found for the time spent above the 90-minute average demands. However, some differences were found between positions ($p < 0.05$) for HSRD, SPD, HMLD, and Acc+Dec required above the 90-minute average demands ($p < 0.05$; ES: -1.83 to -0.25). Specifically, CD showed significantly lower HSRD (Figure 3B), SPD (Figure 3C), and Acc+Dec (Figure 3E) than WMF. Also, CD covered the lowest HMLD compared to the rest of the playing positions (Figure 3D).

DISCUSSION

This study analysed physical performance relative to peak locomotor demands of match play. One of the main findings of this study was that 90-minute average demands represented ~53% of TD, ~23.4% of HMLD, ~16% of HSRD, ~11% of Acc+Dec, and ~6% of SPD for the 1-minute peak locomotor demands for all playing positions. Another novel finding was the differences in the volume of physical performance and time spent between specific percentage ranges for the 1-minute peak locomotor demands. In addition, the physical performance required for above 90-minute average demands was significantly greater than the 90-minute average demands in all variables, especially for the most demanding locomotor actions (i.e., SPD and Acc+Dec).

The fact that the 90-minute average represented ~53% of TD, ~23.4% of HMLD, ~16% of HSRD, ~11% of Acc+Dec, and ~6% of SPD for the 1-minute peak values implies that strength and conditioning coaches should not limit themselves to considering average demands. These findings are in line with previous studies that suggest that 90-minute average demands might under prepare players for higher intensity periods of match play [10–12, 23]. This becomes especially important for variables closely related to high-intensity actions (e.g., HMLD, HSRD, SPD, and Acc+Dec) since the 90-minute average demands represented very low values in the 1-minute peak values. In this regard, a recent study reached a similar conclusion, with the 90-minute average representing ~60% of TD and only ~9% of SPD for the 1-minute peak values, regardless of the playing position [12]. Moreover, another recent study, which focused on the analysis of the physical demands of transitions comparing them to 90-minute match demands, observed that the transitions exceeded the 90-minute average in all players and exposed players to maximal physical outputs [23].

This study also found differences in the volume of physical performance between specific percentage ranges for the 1-minute peak locomotor demands. For instance, players spent more time within the 60–70% range of peak locomotor demands compared to other ranges and covered ~2252 m within this range. This is consistent with a recent study that analysed a larger sample (n = 148). Said study showed players spent more time within the 60–70% range of peak locomotor demands in TD than in other ranges and covered ~2580 m within this range [12]. Similar to the present findings, the same study [12] found that players covered more SPD at 90–100% of peak locomotor demands. Consequently, since the distribution of this intensity in professional soccer matches was analysed [12], these findings may guide training intensity prescription.

Furthermore, this study observed that the physical performance required above 90-minute average demands was significantly greater than the 90-minute average demands in all variables. A high percentage of the total distance covered across different metrics during official matches was at a higher intensity than the 90-minute average demands. In this instance, ~79% to ~85% of the total whole match distance for TD, HSRD, and HMLD was at a higher intensity than the 90-minute average match demands. Interestingly, for the most demanding metrics (i.e., SPD and Acc+Dec), the whole (i.e., ~100%) locomotor load was covered at a higher intensity than the 90-minute average match demands. Previous findings have highlighted similar results, with ~95% of the SPD covered above the 90-minute average demands in Italian Serie A soccer players [12]. Thus, coaches and sports scientists should consider the physical performance over the 90-minute average match demand for more contextualized soccer-specific training prescriptions, especially for high-intensity activities. In this regard, having a better understanding of when and how soccer players perform high-intensity activities would be interesting too from a practical perspective [24, 25].

This study presents some limitations which need to be acknowledged. For example, only five key load indicators in professional soccer were used. Some of these variables, which included high-speed and high-intensity acceleration actions, were based on absolute thresholds (e.g., 25.2 km/h for SPD). However, the individualization of these variables (e.g., relative to a player's maximum speed) may be considered for future studies [26]. In addition, although this type of analysis is recommended to be used by each soccer team and similar results were observed in previous research [12], our sample was limited to one professional soccer team. Lastly, practitioners should acknowledge that the maximal individual locomotor, cardiovascular and metabolic capacity could exceed maximal individual match requirements. Therefore, while match-derived training prescription is critical for high-performance development, specific exercises based on individual cardiovascular and metabolic capacity at submaximal [27] and maximal intensities [28, 29] should be considered.

CONCLUSIONS

These findings may guide the prescription of training intensity. The total volume of physical performance required for above 90-minute average demands could be employed to design the whole training session load. If the 90-minute average represented ~53% of TD covered for the 1-minute peak locomotor demands, this implies that coaches should not only focus on match averages as reference values. The time and physical performance required above 90-minute

average demands should be used as a reference for designing the whole training session. In addition, the volume required at different ranges of percentages for the 1-minute peak locomotor demands may be helpful for the design of specific drills (e.g., small-, medium- and large-sided games or positional drills). For example, if the HSRD covered by the players is ~50 m in the 1-minute peak locomotor demands and matches also require ~6 minutes above 80% for the 1-minute peak locomotor demands, coaches may design positional games that take into account this time window and intensity (e.g., six repetitions of 1 minute).

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Conflict of Interest Disclosure

None of the authors have a conflict of interest to declare, and all authors were involved in the study design, data collection and interpretation, and contributed to the writing of the manuscript.

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Tier-specific contextualised high-intensity running profiles in the English Premier League: more on-ball movement at the top

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ABSTRACT: The present study aimed to determine the physical-tactical profiles of elite football teams and individual players according to final league rankings. A total of 50 English Premier League matches ($n = 100$ match and 583 player observations) were analysed by coding the player's physical-tactical actions through synchronising tracking data and video. Final league rankings were categorised into Tiers: (A) 1st–5th ranking ($n = 25$), (B) 6th–10th ranking ($n = 26$), (C) 11th–15th ranking ($n = 26$), and (D) 16th–20th ranking ($n = 23$). One-way analyses of variance were used to compare match performances between different Tiers, and effect size (ES) was determined for the meaningfulness of the difference. Tier A teams covered 39–51% more high-intensity distance for 'Move to Receive/Exploit Space' (ES: 1.3–1.6, $P < 0.01$) and 'Run with Ball' (ES: 0.9–1.0, $P < 0.05$) than Tier C and D, and 23–94% more distance for 'Over/Underlap' (ES: 1.0, $P < 0.01$), 'Run in Behind/Penetrate' (ES: 0.7, $P < 0.05$), and 'Break into Box' (ES: 0.9, $P < 0.05$) compared to Tier C. Central and Wide Defensive Players in Tier A covered 65–551% more high-intensity 'Move to Receive/Exploit Space' distance compared to other Tiers (ES: 0.6–1.0, $P < 0.01$). Moreover, the additional options within the physical-tactical actions and zonal differences unveiled more meaningful insights into 'HOW' the top Tier teams physically and tactically perform. Thus, the amalgamated physical-tactical data help improve our understanding of a team's playing style relative to their competitive standard.

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Football
Match performance
Physical-tactical data
Standard
Ranking

INTRODUCTION

The energetic demands of football (soccer) during a match can be indirectly quantified via time-motion analysis, which can provide valuable data to applied coaching staff [1]. Although a plethora of research has quantified the physical demands of elite football during match-play [2–5], limited evidence exists on the relationship between success in football and physical performance [3, 6]. This ambiguity seems to be due to limited consideration of the tactical context pertaining to the physical data as tactical scenarios during match-play are one of the factors modulating the physical actions that occur in football [7].

Previous research that has examined associations between physical data and final league rankings have demonstrated that lower-ranked clubs ran greater total distance in high-speed running during match-play with higher-ranked teams performing more when in possession of the ball [8–11]. Although success in football appears to be more likely associated with greater high-intensity in-possession actions whilst maintaining possession to create more space and attacking threats, it is unknown what types of tactical actions are performed pertaining to high-intensity efforts [10, 11]. Therefore, to improve our understanding of team success, tactical context should be tagged alongside the physical metrics. Furthermore, such limited relationships are possibly due to the methodological approach most previous research has adopted [3, 4, 10, 12]. For instance, only individual player performances rather than collective team performances are considered. As football is a team sport where physical and tactical performances of players are affected by not only opponent but also teammate's activities [13], more research is warranted to understand if team performance characteristics are informative when trying to gain insights into the determinants of success.

Technical performances, rather than physical performance per se (e.g., high-intensity running distance), seem to be better

indications to predict a team's success and to demarcate between various team standards and/or league rankings in elite football [4, 14]. Higher-ranked clubs tend to have a greater number of shots on target, ball touches, and passes, as well as a higher percentage of pass accuracy compared to lower-ranked clubs [14, 15]. However, using technical metrics in isolation is still one-dimensional and insufficient to understand a team's success and to differentiate between team standards and/or league rankings in football given the fact that players' performances are impacted by the combination of physical, tactical, technical, and psychological as well as contextual parameters [13, 16]. Some studies have attempted to integrate physical metrics with technical data, but the method they used was not an integration but an aggregation of such performances within their results [10, 12].

Currently, a systematic integrated approach that can contextualise physical metrics with key tactical purposes has been established [17]; however, this approach still does not include technical performance. This is due to this novel approach still requiring a manual coding process, which is labour intensive [18]. Hence, amalgamating high-intensity running activities with the key tactical purpose of the action could be a starting point [19]. Despite this shortcoming, the novel approach appears to be a possible solution to better understand a team's success through discriminating between team standards since various physical-tactical patterns of teams/players according to their final league ranking may be identified. Therefore, this present study aimed to determine the physical-tactical profiles of elite football teams and individual players with reference to final league rankings to identify associations between success and physical-tactical data alongside technical metrics.

MATERIALS AND METHODS

Team and player data

Match physical-tactical data were collated from the 2018–19 English Premier League (EPL) season using an integrated approach and a new filter developed for this research. Players' motions were captured by cameras placed at roof level during matches and their physical-tactical activities were coded using the integrated approach. The validity and reliability of this approach and the novel filter were previously verified [17], from which detailed methodological information can be found. Using the new filter, high-intensity activities reaching speeds > 19.8 $km \cdot h^{-1}$ for a minimal dwell time of 1 s were isolated [20].

The researcher underwent 350 hours of coding to analyse 50 competitive games. This consisted of the total number of 388 individual outfield players across 1,265 player observations within 20 different teams. All of the player's physical-tactical actions for each match were summarised to analyse team performances (those who were subbed in or out were included; $n = 100$ match observations). However, regarding an individual player's analysis, only outfield players who had completed the entire match in the same position were included (n = 583 player observations). This consisted of 179 Central Defensive players (CDP), 147 Wide Defensive players (WDP), 167 Central Midfield players (CMP), 54 Wide Offensive players (WOP), and 36 Central Offensive players (COP). All data were analysed for the duration of each half, including stoppage time. Prior to analysis, all original data were anonymised to ensure confidentiality. Research approval was given by the local Ethics Committee of the appropriate institution.

Match control and data balance

Matches were randomly chosen while concurrently controlling several contextual factors (e.g., phases of season, location, and team/opposition standard) to enhance the scientific rigor of the research design [12]. Matches were omitted if goal differential was > 3 and a player dismissal occurred since these impact match running performances [21, 22].

League ranking categorisation into tiers

The classification of final league rankings was determined using four Tiers: (A) 1st–5th ranking ($n = 25$ match observations), (B) 6th–10th ranking ($n = 26$ match observations), (C) 11th–15th ranking ($n = 26$ match observations), (D) 16th–20th ranking ($n = 23$ match observations). Categorising league ranking is challenging due to inter- and intra-season variations of team performance; however, a generic process was applied to explore the physical-tactical performances by different Tiers [10].

The integrated approach used to quantify match performance

Two main coding categories were used: tactical actions and additional options to make this approach more systematic (Table 1). Isolated high-intensity actions were synchronised with wide-angle video footage of all players throughout matches to categorise the tactical purpose of each action. All coding occurred using QuickTime Player (Apple Inc, Cupertino, California) to view video footage of high-intensity efforts and then categorise their tactical actions.

The coding process was as follows: high-intensity actions with one tactical action were classified as a single action ($n = 27{,}054$) with dual tactical actions being classified as a hybrid action ($n = 4{,}718$). High-intensity actions with more than three tactical actions were coded as 'Other' ($n = 3{,}398$). If the high-intensity effort consists of 70–90% the primary with 10–30% of the secondary action, it was classified as a hybrid action. However, if it is made up of 50–60% of the primary with 40–50% of the secondary action, then it was classified as 'Other'. Since hybrid actions are an amalgamation of the primary and the secondary actions [19], all hybrid actions were analysed with the former to simplify data outputs. Additional options were also analysed using the descriptions (Table 1). The intra-rater reliability for the additional options ($n = 241$) revealed 88% of agreement with the kappa statistic value of 0.87, interpreted as a strong intra-observer reliability [23].

TABLE 1. Physical-tactical variables and additional options (direction and/or different situational options). adapted from Ju et al. [17].

Variables	Description	Additional Options
In Possession		
Run with Ball	Player moves with the ball either dribbling with small touches or running at speed with fewer ball touches.	Drive forward/diagonal/lateral (Central) Run down/up channel (Wide) Run into channel (Central to Wide) Drive inside (Wide to Central)
Over/Underlap	Player runs from behind to in front of the player on the ball or receiving the ball.	Run down channel (Wide) Run into channel (Central to Wide)
Push up Pitch	Player moves up the pitch to play offside and/or to squeeze to a higher line.	Move forward/diagonal (Central) Run down channel (Wide) Move into channel (Central to Wide) Move inside (Wide to Central)
Break into Box	Player enters the opposition's penalty box.	Towards the central zone in the box (Central) Towards one of the wide zones in the box (Wide) Towards the central zone through a wide zone in the box (Wide to Central) Within the box
Run in Behind /Penetrate	Player attacks space behind, overtakes and/or unbalances the opposition defence.	Drive forward/diagonal (Central) Run down channel (Wide) Run into channel (Central to Wide) Drive inside (Wide to Central)
Move to Receive/ Exploit Space	Player moves to receive a pass from a teammate and/or to create/exploit space.	Move forward/diagonal (Central) Move backward/diagonal/lateral (Central) Run down/up channel (Wide) Run into channel (Central to Wide) Drive inside (Wide to Central)
Support Play	Player supports from behind/level by trying to engage in offensive/transition play.	Drive forward/diagonal (Central) Run down channel (Wide) Run into channel (Central to Wide) Drive inside (Wide to Central)
Out of Possession		
Close Down /Press	Player runs directly towards opposition player on or receiving the ball, or towards space or players that are not a viable passing option.	Towards the player on the ball (after ball touch) Towards the player receiving the ball (before ball touch) Space/a player
Interception	Player cuts out the ball during the transition of a pass.	Intercept the ball in offensive third Intercept the ball in offensive-mid third Intercept the ball in defensive-mid third Intercept the ball in defensive third
Recovery Run	Player runs back toward their own goal to be goal side of the ball when out of position.	Run back towards own goal (ball behind) Run back towards own goal from attacking/set play (ball still in front) Ball passed over top/down side (opposition closer to the ball)
Covering	Player moves to cover space or an opposition player while remaining goal side of the ball.	Space/a player Long Ball/Pass (> 25 m; not beaten by opposition)
Close Down/Press	Player runs directly towards opposition player on or receiving the ball, or towards space or players that are not a viable passing option.	Towards the player on the ball (after ball touch) Towards the player receiving the ball (before ball touch) Space/a player
Unclassifiable		
Other	All other variables that could not be classified by the above.	Each additional option also has 'Other'.

Technical data

Technical tracking data from the matches analysed were collected from an established company (OPTA Sports, London, United Kingdom). The reliability of this system has been verified [24]. Technical events such as the number of shots, shots on target, ball touches, passes, crosses, dribbles, long passes, accurate long passes, and interceptions as well as pass accuracy were analysed. All individual data for each match were summed up to represent team performances.

Statistical analyses

Data are presented as the mean ± standard deviation. All statistical analyses were conducted using IBM SPSS Statistics for Mac OS X, version 26 (IBM Corp., Armonk, N.Y., USA). Data normality was verified by Shapiro-Wilk and Kolmogorov-Smirnov tests. One-way analyses of variance were used to compare match performances by each Tier with Tukey's post hoc test used to determine localised differences. Statistical significance was set at $P < 0.05$. Effect sizes (ES) for the meaningfulness of the difference were determined as follows: 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 extremely large (>4.0) [25]. The Pearson correlation coefficient was used for correlation analyses. According to Hopkins et al. [26], the magnitudes of the correlation coefficients were regarded as trivial (r ≤ 0.1), small (r > 0.1–0.3), moderate (r > 0.3–0.5), large (r > 0.5–0.7), very large (r > 0.7–0.9), and nearly perfect (r > 0.9). The coefficients of variation (CV) were analysed for match-to-match variabilities of team performances [27].

RESULTS

Contextualised high-intensity distance according to tiers

Tier A teams covered 34% more high-intensity distance when in possession than Tier C and D (ES: 1.4–1.6, P < 0.01, Table 2) whilst covering 39–51% more high-intensity distance for 'Move to Receive/Exploit Space' (ES: 1.3–1.6, $P < 0.01$) and 'Run with Ball' (ES: 0.9–1.0, $P < 0.05$) compared to Tier C and D, and 23–94% more distance for 'Over/Underlap' (ES: 1.0, $P < 0.01$), 'Run in Behind/Penetrate' (ES: 0.7, $P < 0.05$), and 'Break into Box' (ES: 0.9, $P < 0.05$) compared to Tier C. Contextualised high-intensity distances covered across various positions in different Tiers are shown in Figure 1.

Additional options across different tiers

Figure 2 illustrates the comparison of additional options for in- (A, B, and C) and out-of-possession (D and E) variables between Tiers. In possession, teams in Tier A performed 88–118% more high-intensity actions in the central zone whilst moving backwards than other Tiers (ES: 1.0–1.1, $P < 0.01$). Clubs in Tier A also executed 54–78% and 25–43% more high-intensity actions for 'Run with Ball' and 'Run in Behind/Penetrate' in the central zone, respectively, than other Tiers (ES: 0.7–1.2, $P < 0.05$). The average numbers of physical-tactical actions produced by various Tiers across different zones are illustrated in Figure 3 (A for in-possession and B for out-of-possession variables).

Correlation matrix within physical-tactical actions

Regarding 'within' dualities (i.e., teammates performing together, Table 3), producing high-intensity actions for 'Run with Ball' was highly associated with teammates performing high-intensity 'Move to Receive/Exploit Space' ($r = 0.5$, P < 0.01). Regarding 'between' dualities (i.e., Team A vs Team B, Table 4), one team performing high-intensity actions of 'Support Play' was largely correlated to the opposition team producing high-intensity 'Recovery Run' actions ($r = 0.6$–07, P < 0.01).

Technical performances

Teams in Tier A had 36–57% more shots on target than other Tiers (ES: 0.7–1.2, $P < 0.05$) whilst also completing 24–34% more ball touches and 38–55% more passes (ES: 1.5–1.8, $P < 0.01$). Tier A teams also had a higher passing accuracy (82 ± 5%) than Tier B (78 ± 6%, ES: 0.8, $P < 0.05$) and Tiers C and D (74 ± 5% and 73 ± 7%, respectively, ES: 1.4, $P < 0.01$). The correlations between technical metrics and contextualised actions are presented in Figure 4.

TABLE 2. High-intensity distances across various tiers.

Tier	A	B	C	D	Difference and Effect Size
Total	7778 ± 1039	7242 ± 962	7078 ± 1233	7153 ± 1190	# (ES: 0.1–0.6)
IP	3277 ± 533	2914 ± 742	2439 ± 647	2447 ± 512	A > C*/D* (ES: 1.4–1.6) A > B# (ES: 0.6)
OOP	3835 ± 838	3653 ± 798	3968 ± 878	4057 ± 952	# (ES: 0.1–0.5)
Other	666 ± 195	675 ± 191	671 ± 173	649 ± 239	# (ES: 0.0–0.1)

ES: Effect sizes: 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 extremely large (>4.0) [25]. Asterisk (*) denotes differences ($P < 0.05$); Hash (#) denotes no differences ($P > 0.05$). IP: In Possession, OOP: Out of Possession. Values are represented as means and standard deviations (m).

TABLE 3. The Correlation matrix of 'within' dualities for physical-tactical actions.

'Within' Dualities

IP	BIB	RIB	MTR	RWB	SP	OVL	PUP
BIB	1.0						
RIB	0.3	1.0					
MTR	0.2	0.3	1.0				
RWB	0.4	0.2	0.5	1.0			
SP	0.1	0.3	0.3	0.2	1.0		
OVL	0.3	0.1	0.3	0.4	0.2	1.0	
PUP	0.0	-0.1	0.1	0.0	0.0	0.0	1.0

OOP	RR	COV	CD/P	IOP
RR	1.0			
COV	0.4	1.0		
CD/P	0.3	0.2	1.0	
IOP	0.1	0.1	0.3	1.0

BIB: Break into Box; RIB: Run in Behind/Penetrate; MTR: Move to Receive/Exploit Space; RWB: Run with Ball; SP: Support Play; OVL: Over/Underlap; PUP: Push up Pitch; RR: Recovery Run; COV: Covering; CD/P: Close Down/Press; IOP: Interception. The magnitudes of the correlation coefficients were regarded as trivial ($r \leq 0.1$), small ($r > 0.1$–0.3), moderate ($r > 0.3$–0.5), large ($r > 0.5$–0.7), very large ($r > 0.7$–0.9), and nearly perfect ($r > 0.9$) [26]. Moderate and large correlations are highlighted in grey ($r > 0.3$) and orange ($r > 0.5$–0.7), respectively. IP: In Possession; OOP: Out of Possession.

TABLE 4. The correlation matrix of 'between' dualities for physical-tactical actions.

'Between' Dualities

		Team A						
	IP vs OOP	**BIB**	**RIB**	**MTR**	**RWB**	**SP**	**OVL**	**PUP**
Team B	**RR**	0.1	0.3	0.0	0.0	0.7	0.1	-0.1
	COV	0.2	0.4	0.5	0.5	0.3	0.4	0.0
	CD/P	0.2	0.3	0.2	-0.2	0.4	-0.1	0.1
	IOP	0.0	-0.1	0.0	-0.3	0.0	-0.3	0.1

		Team B						
	IP vs OOP	**BIB**	**RIB**	**MTR**	**RWB**	**SP**	**OVL**	**PUP**
Team A	**RR**	0.2	0.3	0.3	0.3	0.6	0.1	0.1
	COV	0.4	0.4	0.5	0.6	0.6	0.3	0.0
	CD/P	0.1	0.3	0.5	0.4	0.3	0.2	0.0
	IOP	0.3	0.3	0.2	0.6	0.0	0.2	0.0

BIB: Break into Box; RIB: Run in Behind/Penetrate; MTR: Move to Receive/Exploit Space; RWB: Run with Ball; SP: Support Play; OVL: Over/Underlap; PUP: Push up Pitch; RR: Recovery Run; COV: Covering; CD/P: Close Down/Press; IOP: Interception. The magnitudes of the correlation coefficients were regarded as trivial ($r \leq 0.1$), small ($r > 0.1$–0.3), moderate ($r > 0.3$–0.5), large ($r > 0.5$–0.7), very large ($r > 0.7$–0.9), and nearly perfect ($r > 0.9$) [26]. Moderate and (very) large correlations are highlighted in grey ($r > 0.3$–0.5) and orange ($r > 0.5$–0.9), respectively. Team A: Home team; Team B: Away Team. IP: In Possession; OOP: Out of Possession.

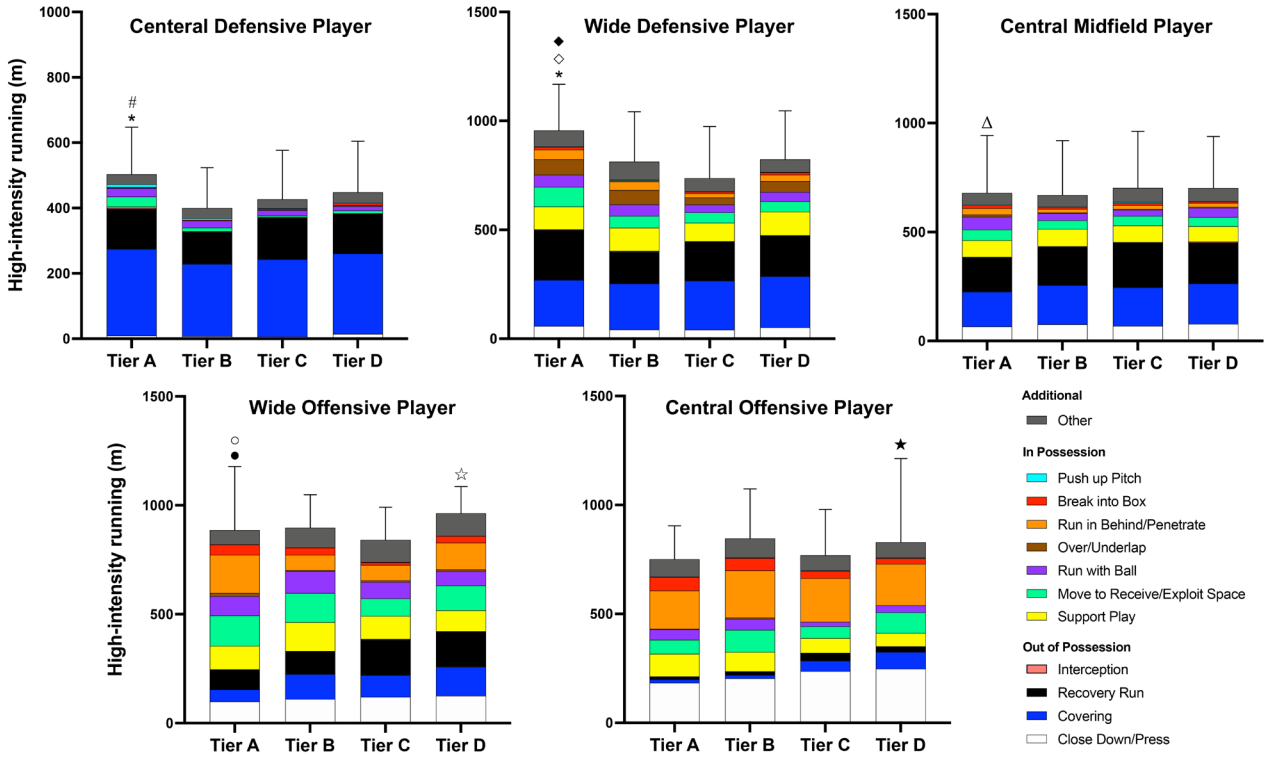


FIG. 1. Contextualised high-intensity distances covered by various positions in different Tiers. *Greater distance covered for 'Move to Receive/Exploit Space' than Tier A, B, and C ($P < 0.01$). #Greater distance covered for 'Push up Pitch' than Tier C ($P < 0.05$). ◇Greater distance covered for 'Over/Underlap' than Tier C ($P < 0.05$). ◆Greater distance covered for 'Recovery Run' than Tier B ($P < 0.05$). ΔGreater distance covered for 'Run with Ball' than Tier B and C ($P < 0.05$). ●Greater distance covered for 'Run in Behind/Penetrate' than Tier B and C ($P < 0.01$). ○Greater distance covered for 'Break into Box' than Tier C ($P < 0.01$). ☆Greater distance covered for 'Covering' than Tier A ($P < 0.05$). ★Greater distance covered for 'Covering' than Tier A and B ($P < 0.05$). The volume of 'Interception' and 'Push up Pitch' distances was relatively small; thus, they are invisible on the figure.

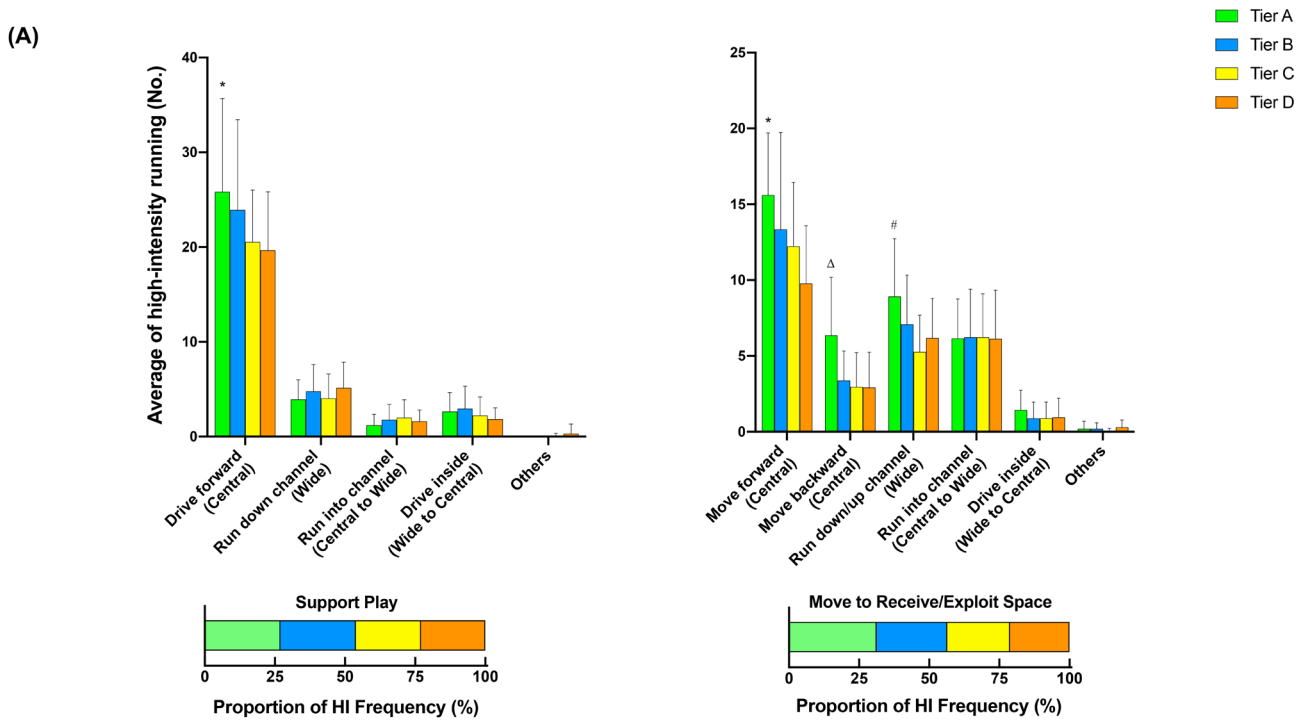


FIG. 2a. Comparison of additional options for in- (A, B and C) and out-of-possession (D and E) variables between Tiers. Symbols denote differences ($P < 0.05$). ΔMore actions performed than all other Tiers. *More actions performed than Tier D. #More actions performed than Tier C and D. ●More actions performed than Tier C. ◆More actions performed than Tier B and C.

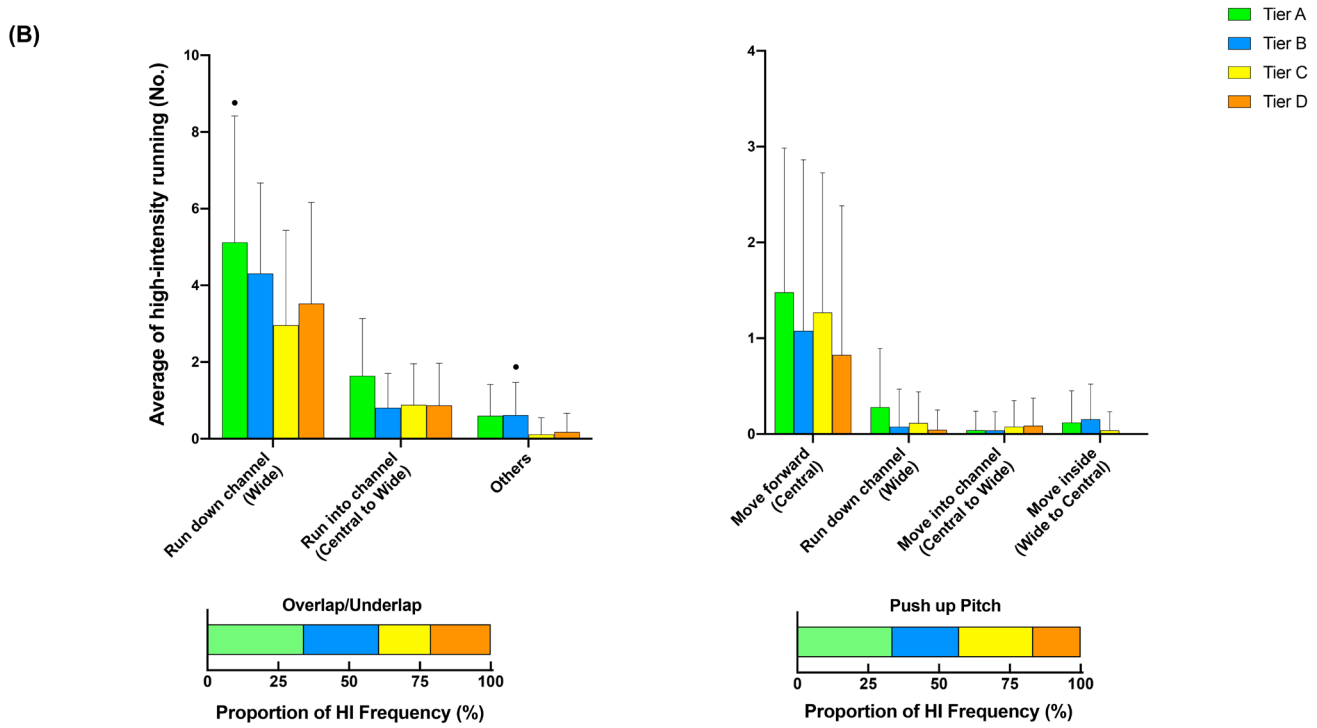


FIG. 2b. Comparison of additional options for in- (A, B and C) and out-of-possession (D and E) variables between Tiers. Symbols denote differences (P < 0.05). ΔMore actions performed than all other Tiers. *More actions performed than Tier D. #More actions performed than Tier C and D. ●More actions performed than Tier C. ◆More actions performed than Tier B and C.

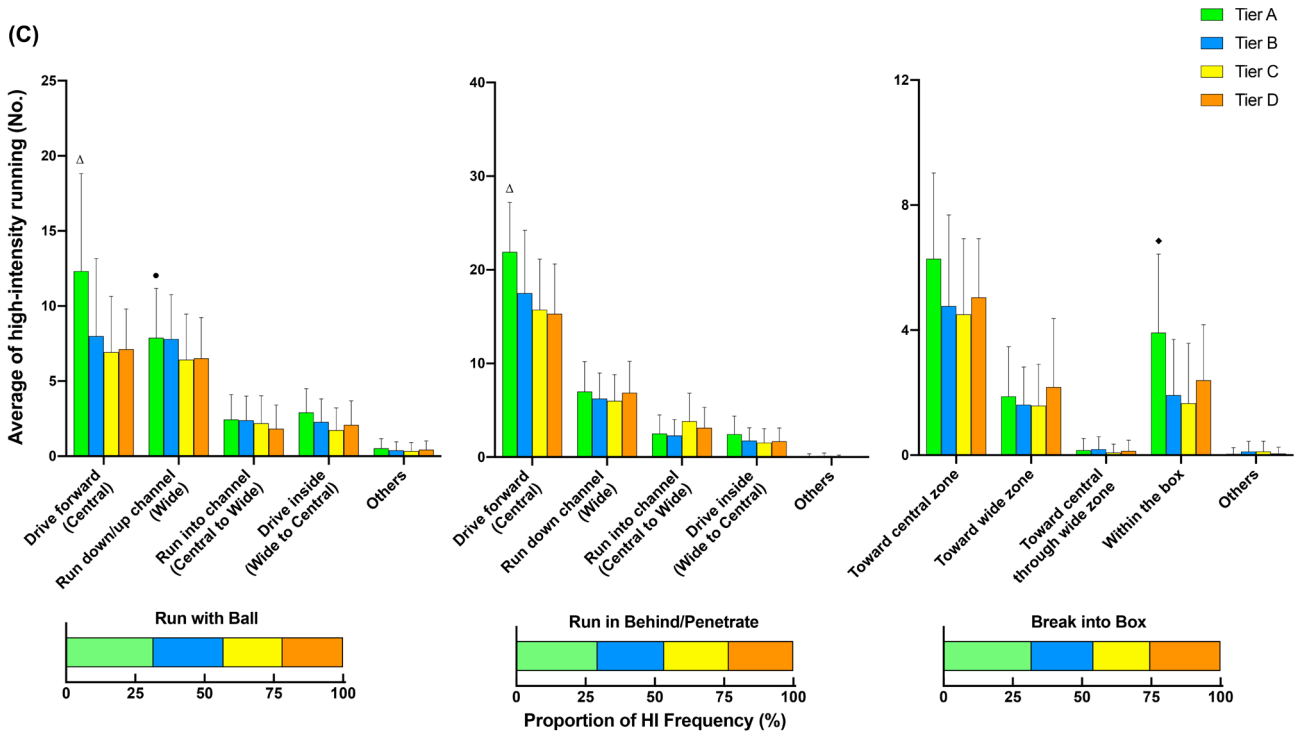


FIG. 2c. Comparison of additional options for in- (A, B and C) and out-of-possession (D and E) variables between Tiers. Symbols denote differences (P < 0.05). ΔMore actions performed than all other Tiers. *More actions performed than Tier D. #More actions performed than Tier C and D. ●More actions performed than Tier C. ◆More actions performed than Tier B and C.

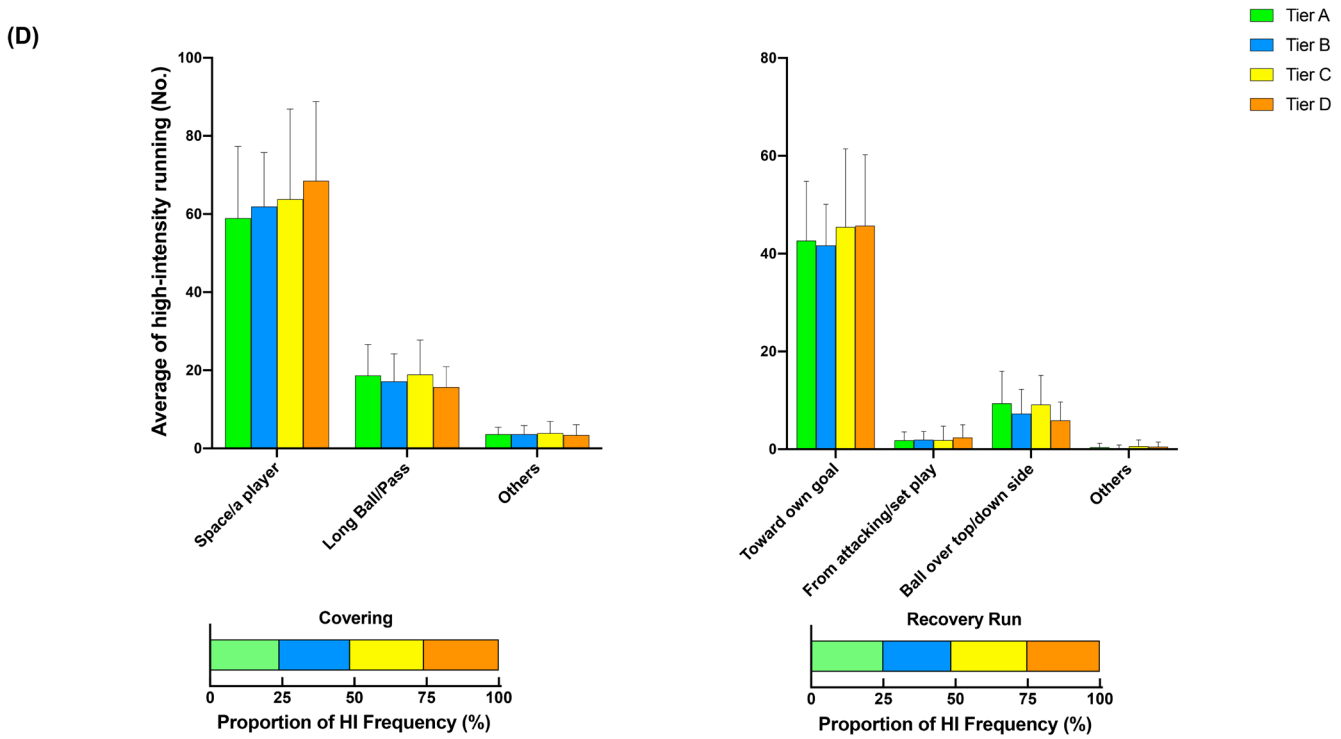


FIG. 2d. Comparison of additional options for in- (A, B and C) and out-of-possession (D and E) variables between Tiers. Symbols denote differences (P < 0.05). ΔMore actions performed than all other Tiers. *More actions performed than Tier D. #More actions performed than Tier C and D. ●More actions performed than Tier C. ◆More actions performed than Tier B and C.

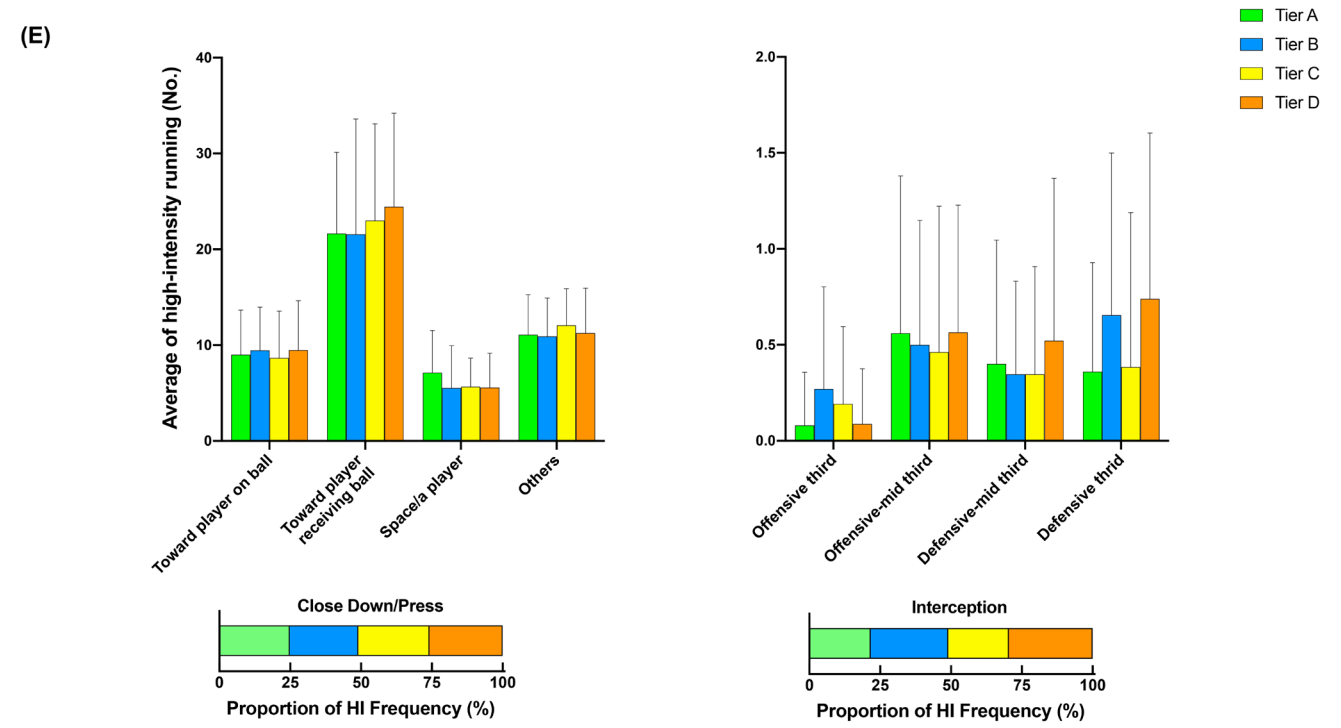


FIG. 2e. Comparison of additional options for in- (A, B and C) and out-of-possession (D and E) variables between Tiers. Symbols denote differences (P < 0.05). ΔMore actions performed than all other Tiers. *More actions performed than Tier D. #More actions performed than Tier C and D. ●More actions performed than Tier C. ◆More actions performed than Tier B and C.

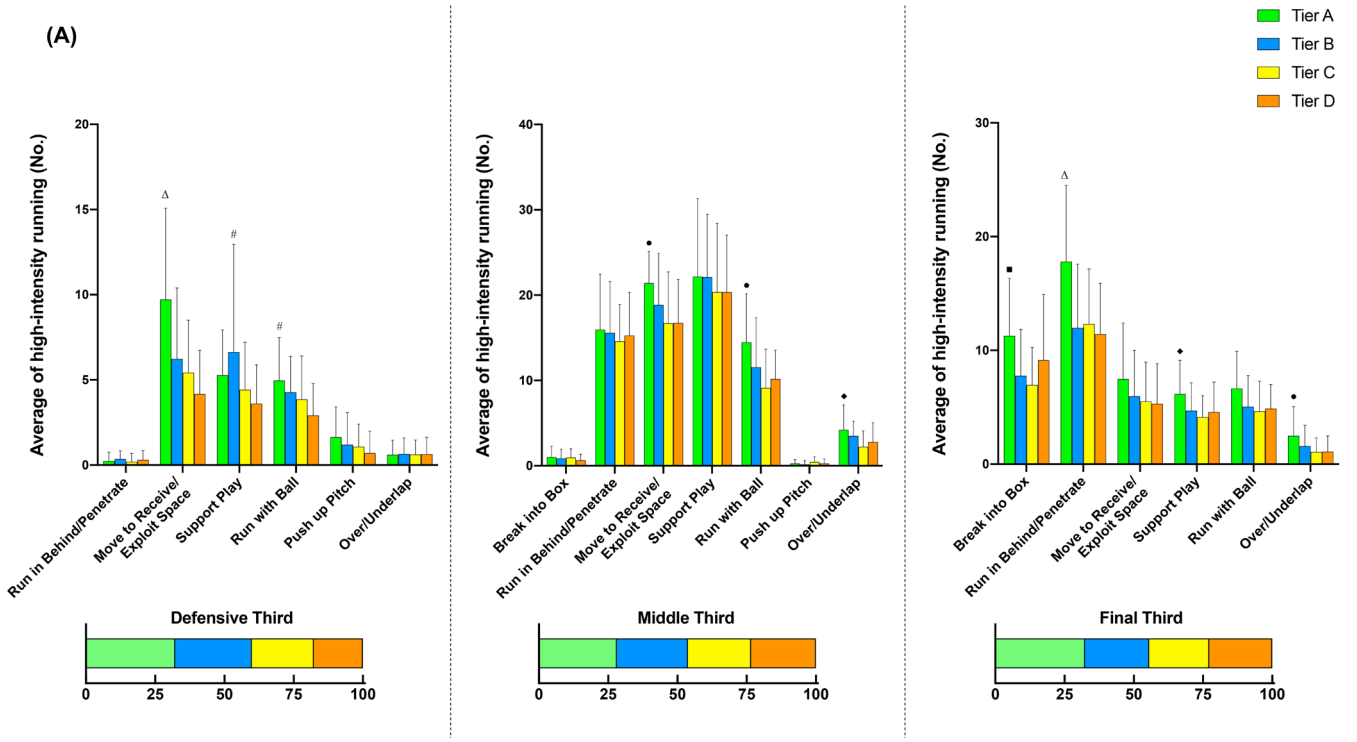


FIG. 3a. Frequency of high-intensity running in relation to (A) in-possession and (B) out-of-possession categories with special reference to different zones (defensive, middle, and final third). Symbols denote differences ($P < 0.05$). ΔMore actions performed than Tiers. #More actions performed than Tier D. *More actions performed than Tier A. ●More actions performed than Tier C and D. ◆More actions performed than Tier C. ■More actions performed than Tier B and C.

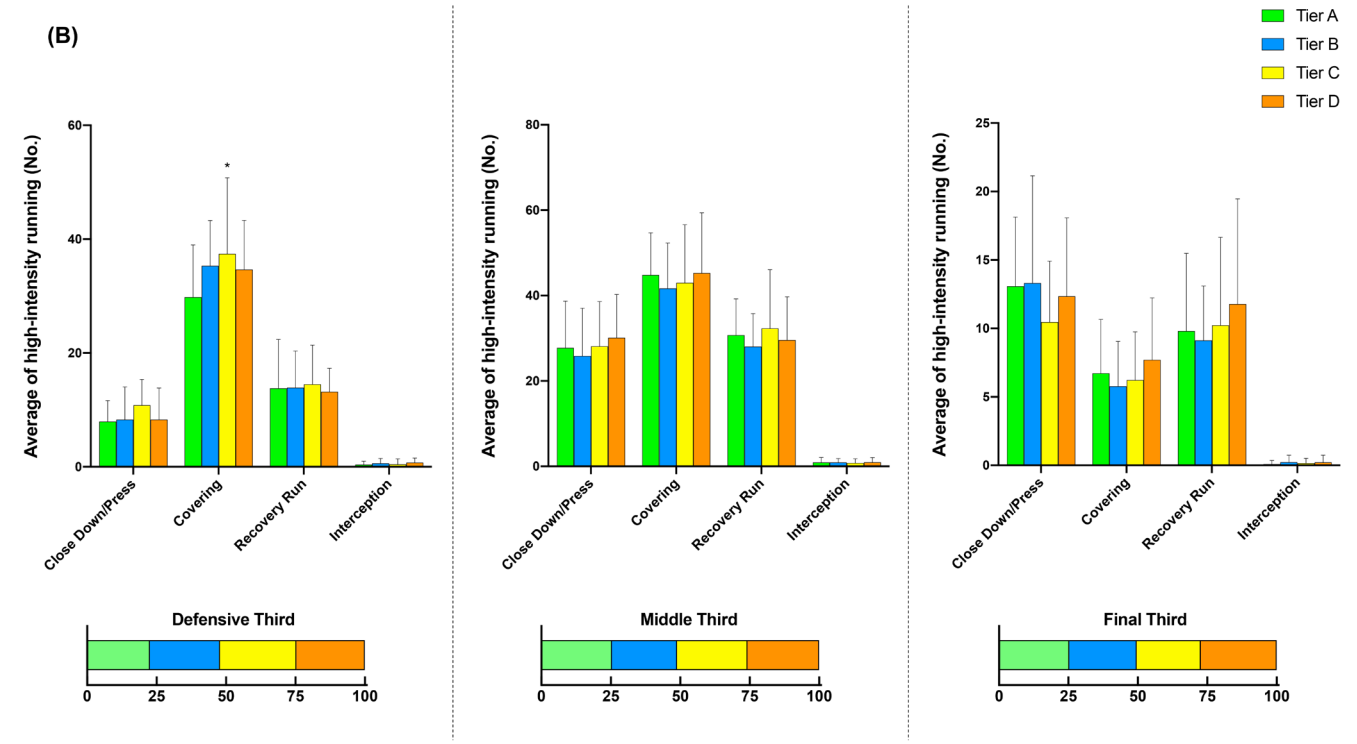


FIG. 3b. Frequency of high-intensity running in relation to (A) in-possession and (B) out-of-possession categories with special reference to different zones (defensive, middle, and final third). Symbols denote differences ($P < 0.05$). ΔMore actions performed than Tiers. #More actions performed than Tier D. *More actions performed than Tier A. ●More actions performed than Tier C and D. ◆More actions performed than Tier C. ■More actions performed than Tier B and C.

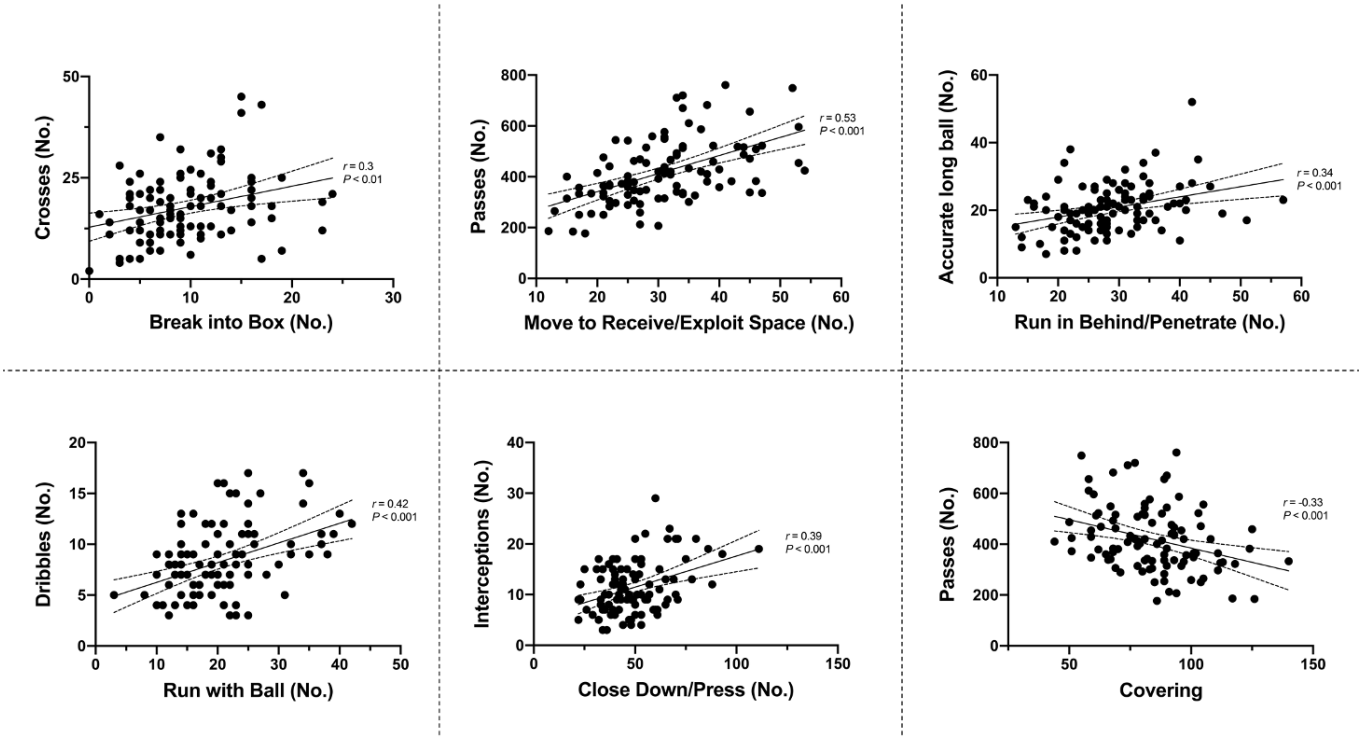


FIG. 4. Correlation between physical-tactical (x axis) and technical (y axis) variables. Dotted lines indicate 95% confidence intervals.

Match-to-match variabilities of team performance

The mean percentage of CVs in high-intensity distances produced by teams was 13 ± 4%. Regardless of physical-tactical variables, the mean percentage of CVs for the contextualised actions was 48 ± 31%.

DISCUSSION

The present study is the first to evaluate the physical-tactical trends of elite football teams and players according to their final league ranking. Tier A teams performed more contextualised actions (e.g., 'Move to Receive/Exploit Space', 'Run with Ball', etc.) as well as better technical skills (e.g., greater number of shots on target, passes, etc.) compared to those in lower Tiers. Regarding positional trends, CDP and WDP in Tier A ran ~65–550% more high-intensity 'Move to Receive/Exploit Space' distance than other Tiers. Moreover, the additional options within the physical-tactical actions and zonal differences exhibited more meaningful insights. These data trends aid our understanding of patterns of play according to final league ranking and the discriminatory factors between Tiers.

Data demonstrates that the total high-intensity distances covered by teams in various Tiers were comparable to others (~7100–7800 m vs 7500 m) [28], exhibiting no differences between Tiers. This contrasts previous studies where lower-ranked teams covered greater total distance in high-intensity running compared to higher-ranked teams [8, 9]. This disparity could be due to the different methodological approach applied in the present study (i.e., team performance rather than individual players). Despite this, high-intensity distance covered in possession revealed meaningful differences, which is supported by previous findings [8–10]. Tier A teams covered ~35% more high-intensity distance when they were in possession compared to those in Tier C and D with only ~5% difference for the distance covered when out of possession. Thus, high-intensity distance covered in possession seems to be an important differentiator between team standards in competitions such as the EPL.

Limited evidence exists in the scientific literature to understand 'WHY' and 'HOW' high-ranked teams cover greater high-intensity distance when in possession. Current findings indicate that although none of the out-of-possession physical-tactical actions displayed any differences between Tiers, meaningful differences were observed regarding in-possession physical-tactical movements. For instance, Teams in Tier A performed ~20–95% more high-intensity distance performing 'Move to Receive/Exploit Space', 'Run with Ball', 'Over/Underlap', 'Run in Behind/Penetrate', and 'Break into Box' activities compared to lower Tier teams. This clearly explains 'WHY' more high-intensity distance is covered by top-ranked teams when in possession than their lower-ranked counterparts. Such contextualised actions

could be the actions that higher-standard teams perform more frequently whilst keeping the ball to exploit space whereby producing a viable attacking threat and ultimately scoring a goal [13, 29]. Therefore, these contextualised actions could be key in discriminating between team standards. An important caveat is that this data is limited to the EPL. Therefore, verification of such trends across different competitive standards or other elite football leagues is necessary as different playing styles are expressed in each competition [6, 30].

Literature reports position-specific characteristics with attackers covering ~70–90% more distance at high-intensity in possession compared to out of possession whilst defenders performed ~60–160% greater distance out of possession compared to in possession [8, 30]. However, this provides only rudimentary insights, which may explain why such data are hardly used within the applied setting [19]. In contrast, the present study provides important insights into individual physical-tactical characteristics across Tiers. For instance, whilst in possession CDP and WDP in Tier A covered ~65–550% more high-intensity distances for 'Move to Receive/Exploit Space' than those in other Tiers whilst WDP in Tier A ran ~70–80% more distances for 'Over/Underlap' and 'Run in Behind/Penetrate' than those in Tier C. This agrees with previous findings where CDP and WDP from higher-ranked teams produced more attacking- and passing-related events than their counterparts from lower-ranked teams [31, 32]. This type of data provides clear insights into 'WHY' players within high-ranked teams cover more distance at high-intensity when in possession. However, when accounting for relative distance (m/min) covered for each tactical activity as a team using effective playing time (i.e., time of ball in play) which can be affected by team playing style as well as contextual factors [33], no differences were observed between Tiers. This indicates that such trend appears to be simply due to the team having a higher percentage of ball possession during matches. Hence, it would be more beneficial if investigating how effective the physical-tactical actions are during matchplay (e.g., did the action create or nullify a chance/threat?). Additionally, it would be of interest to examine how team's physical-tactical performances change pertaining to match status and/or opponent standards since they impact match performance [2, 21].

Data analysed from the additional options within the physical-tactical actions demonstrates that in possession Tier A teams noticeably dominated the central area, producing more high-intensity efforts for 'Support Play', 'Move to Receive/Exploit Space', 'Run with Ball', and 'Run in Behind/Penetrate' than other Tiers. Interestingly, Tier A clubs also performed more 'Move to Receive/Exploit Space' actions while moving backwards compared to other Tiers. For instance, forwards could move back towards their own goal to receive the ball (known as 'Coming Short') or defenders could move back and wide to receive the ball when the ball is played to the goalkeeper during build-up play (known as 'Splitting'). This seems to be due to high-ranked teams more likely adapting a build-up playing style while having a high percentage of ball possession [10, 11, 32]. The analysis of technical data from this study also confirms this notion in which Tier A clubs completed ~25–55% more ball touches and passes than other Tiers, which agrees with previous observations [10, 31]. Although some studies indicate that the EPL teams tend to utilise a counter attack strategy with fast and direct attacks to transition [34, 35], present data demonstrate that EPL teams in the top Tier are more likely to apply a more intricate build-up and possession-based style of play. Nevertheless, as the playing style of teams in top-class teams also differs [36], individual team analysis is warranted to more precisely determine how each team physically and tactically plays during matches. Additionally, as this integrated approach can reveal teams' playing styles, performance analysts within the team could be benefited from using this approach, especially for opponent analyses, which takes a huge part of the match analysis in football [37].

Distinct differences in physical-tactical actions performed in different zones of the pitch by the diffferent Tiers were apparent. In possession, Tier A teams produced ~30–130% more high-intensity 'Move to Receive/Exploit Space' actions from the defensive and middle third compared to lower Tier counterparts. Although previous reports noted that top-ranked teams dominated transition phases [38], they failed to determine what types of tactical actions are critical during this phase of play. Since top-ranked clubs tend to achieve more width and length whilst increasing the offensive play-space than lower-ranked counterparts after regaining the ball [28, 39], this seems to be 'Move to Receive/Exploit Space' actions that high-ranked teams perform more often during the defence-to-attack transition phase (e.g., from defensive and middle third) compared to lower-ranked teams. Furthermore, Tier A teams completed ~90–130% more high-intensity 'Over/Underlap' actions from the middle and final third than lower Tier teams whilst also performing ~45–60% more actions for 'Break into Box' and 'Run in Behind/Penetrate' in the final third. This clearly shows 'HOW' teams in the top Tier dominated opposition in the middle and final third of the pitch. However, since the present study did not include the phases of play, future research should condense such physical-tactical actions into phases of play to provide extra granularity to match analysis [40].

Out of possession, lower-ranked teams such as those in Tier C demonstrated ~25% more high-intensity activities for 'Covering' from the defensive third than higher-ranked teams such as those in Tier A. This action is essential for the team's defensive organisation whilst being goal side of the ball [18, 41]. Therefore, it seems that low-ranked teams tend to focus on the team's defensive stability in the defensive third while being goal side, rather than pressing higher up the pitch, which may explain why teams with a defensive formation (e.g., 4-5-1 formations) cover greater distance when out of possession [5]. In contrast, although there were no statistical differences in the frequency of 'Closing Down/Press' actions performed by each Tier in the final third, high-ranked teams executed ~20% more of these actions than low-ranked counterparts (13 vs 11). This could indicate that higher-ranked teams are more likely to try to regain the ball higher up the pitch and to counter press if they lose it. Since regaining ball possession in the opposition's half is important for

a team's success [42], this physical-tactical action seems very promising to evaluate team performance. However, contextual factors such as match status and match location could alter team playing style during match-play [16].

This is the very first time that the relationships of 'within' (teammates performing together) and 'between' (Team A vs Team B) dualities have been quantified; thus, this provides novel insights into the interactional aspects of physical-tactical components. Producing high-intensity actions for 'Run in Behind/Penetrate' was moderately related to teammates performing 'Support Play' with the opposition executing 'Recovery Run', 'Covering', and 'Close Down/Press'. Additionally, large to very large correlations were found between one team producing 'Support Play' and the other team performing 'Recovery Run' actions. This could be because when a fast transition occurs, for example, the ball is rapidly moved forward, teammates perform 'Support Play' to become involved in the transition or attacking phase with the opponent performing 'Recovery Run' actions [13]. Thus, it could be reasonably concluded that one team's collective behaviour influences the opposition team's performance and their own team's tactical behaviour. Nevertheless, further insight may be gained if investigating the individual antagonistic correlations between selected players (e.g., the actions performed by forwards vs those performed by centre backs of the opposition team). Therefore, future research should examine this aspect.

Tier A clubs produced better technical performance such as greater number of shots on target and passes as well as a higher pass accuracy than other Tiers, which agrees with previous findings [9, 14, 15]. This is possibly due to high-standard teams demonstrating higher levels of technical performance whilst also performing greater number of technical events compared to lower-standard teams [9, 10]. Additionally, the present study found that some technical metrics (i.e., OPTA Sports data) were moderately associated with some physical-tactical actions. High-intensity 'Break into Box' and 'Run in Behind/Penetrate' actions were moderately associated with the number of technical skills such as crosses and accurate long passes, respectively. It may be due to players producing a high-intensity effort trying to enter the opposition box typically expecting a cross from a wide player or to run in behind/penetrate whilst an accurate long ball is being delivered from a deeper player [41]. Moreover, the number of interception events (i.e., technical data) was moderately linked to high-intensity 'Close Down/Press' actions. Explanation may reside with the view point that aggressive pressing (e.g., closing down at high-intensity) is able to force the opposition to make mistakes such as inaccurate passes [43]. Collectively, the physical-tactical data appears to be associated with technical metrics available to professional football clubs; thus, this may be more practical for coaches as the context adds a narrative to the data trends. Practitioners are also moving towards an enhanced ability to quantify the impact of the physical work executed by the team on technical and tactical outcomes. Hence, this type of analysis is key to help drive forward physical requirement of the elite player. However, the complex nature of football where numerous contextual factors impact performance during match-play [16], results in high levels of data variability of team performances (e.g., high-intensity distance and contextualised actions: ~13% and ~48%, respectively), thus practitioners should consider these variabilities when making decisions on the practical application of the data.

Limitations

Firstly, although the present study has integrated physical and tactical performances, this did not integrate 'technical' metrics but rather aggregated within the result. As physical, tactical, and technical parameters are fused to influence match performance, future research should amalgamate all these aspects to provide a comprehensive understanding of the true football match performance. Also, another limitation would be a lack of contextual variables included in the study. Therefore, the physical-tactical profiles with special reference to the standard of opposition or match status may be of interest since they have an influence on match performance [2, 21].

CONCLUSIONS

The contextualised data can help improve the understanding of team playing style and could be used to better discriminate between team standards together with technical metrics. Additionally, players' physical-tactical actions have an influence on not only their teammates but also opposition's activities during match-play. However, it should be acknowledged that the match-to-match variabilities in high-intensity distance and contextualised actions are high.

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Conflict of interest declaration

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Mechanisms of ACL injuries in men's football: A systematic video analysis over six seasons in the Qatari professional league

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ABSTRACT: To assess the mechanisms of ACL injury in male professional football players in Qatar across multiple seasons using systematic video analysis. 15 ACL injuries occurred in competition among the professional football teams that participated in an injury Surveillance Programme during 6 seasons (2013/2014 to 2018/2019). High-definition broadcast videos of these injuries were analyzed (49 views; 34 slow motion) by five analysts who independently described the injury mechanisms (situation, behavior, biomechanical characteristics) using validated observational tools. A knee valgus mechanism was observed in two-thirds of the cases (1 with direct contact to the knee, 3 with indirect contact (other body parts) and 6 with no contact). No visible valgus was reported in 2 of the direct knee contact injuries, while 3 cases of non-contact and indirect contact injuries were unclear. We observed 4 main categories of injury situation among those (n = 12) classified as non-contact/indirect contact (multiple combinations were possible): pressing (n = 6), tackling or being tackled (n = 4), blocking (n = 3) and screening (n = 2). Direct contact injuries (n = 3) were suffered by 2 players during tackling and 1 whilst being tackled. Contact injuries represented only 20% of ACL injuries occurring during competition in Qatari professional soccer players. Independent of the playing situation, knee valgus was frequently observed (10/15 cases). Pressing was the most common situation (6/15 cases) leading to injury. Landing after heading was not reported in any of these ACL injuries.

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INTRODUCTION

Anterior cruciate ligament (ACL) injury for a professional football (soccer) player causes a significant burden [1–3]. On average, each professional football team will experience one ACL tear approximately every two seasons [2, 4]. A 15-year prospective study showed that 3 years after return to play following an ACL tear, only 2 out of 3 players still play at the highest level [5]. Furthermore, there is evidence to indicate that players with history of ACL injury are at a higher risk of sustaining secondary knee injuries [6, 7], early-onset knee osteoarthritis [8] and/or a shorter career [9, 10]. Effective ACL injury prevention programmes exist, but the incidence of injury remains high [5, 11, 12].

Understanding the mechanisms of these injuries could help clinicians refine measures aimed at preventing ACL injuries with long-term health, performance, and financial benefits [13–15]. Systematic video analyses are an important tool [16] which have been employed in several team sports over the past two decades, including handball, basketball and rugby [14, 17–22]. Two early studies analyzed ACL injuries including cases from football, but also from other sports [23, 24]. More recently, four studies have brought more insight into the football-specific mechanisms, although with some limitations related to study design, as low study power, selection bias, insufficient analytical methods including visual inspection of the videos [25–28]. Also, ACL injury incidence can vary according to the geographical region, and the time of year as climatic conditions vary [2, 29, 30]. No systematic video analyses have been performed in the Middle East where the climatic conditions are different (typically hotter and drier) compared to previous research. Fitness levels, training loads and championship intensity may vary as well.

The objective of this study was therefore to describe the mechanisms of ACL injury in professional Qatari football through systematic video analysis, over a 6-year period, based on published, systematic protocols [26], in an attempt to assess whether they reflect those observed in Europe.

MATERIALS AND METHODS

Injury inclusion and video recording

This study was conducted in accordance with previous research in European football players [26]. We identified cases based on the

prospective Aspetar Injury & Illness Surveillance Programme [2, 31, 32] from the 2013/2014 through the 2018/2019 seasons. We extracted data on all complete ACL injuries occurring during official first team matches only. The clubs involved belonged to the first or second division of the football leagues competitions in Qatar and included 14, 16, 10, 15, 17 and 17 teams during the respective seasons. Data for the Aspetar Injury and Illness Surveillance Programme are recorded by medical staff assigned to each football club by Aspetar's National Sports Medicine Programme [2, 31]. We identified 15 complete ACL tears; the clinical diagnosis was confirmed radiologically using MRI in all cases and high-definition (match) broadcast videos were available for all of them (49 views, 34 slow motion sequences). The number of camera views ranged from 1 to 6.

Video processing

We used video-editing software (Adobe Premiere Pro, version 14.1.0, Build 116, Adobe Inc, San Jose, California, USA) to extract the relevant injury sequences from the entire match video into MP4 format. We created one single video for each injury, including a few seconds before and after the injury to assess the environmental and match conditions, injury situations and biomechanical variables. Each sequence included the video of the injury (normal speed) and all available replays with slow-motion (50% speed) from different camera angles (one single replay for 4 injuries, two for 4, three for 5, six for one). One additional injury was filmed with a wide shot with no replay, so we created a zoomed sequence with slow-motion (50% speed) using the same video editing software. Visualization of the videos was performed using QuickTime Player (version 7.7.4, Apple, Cupertino, California, USA) allowing easy frame-by-frame navigation. The different camera views were mounted successively through the single video sequence of each injury. The analysts would then choose the camera view(s) that allowed them to perform the best analysis.

Video analysis

The video analyses were independently performed by five independent reviewers (two sport physicians, one orthopedic surgeon, one clinical research scientist and one physiotherapist) experienced in football, ACL injury, and biomechanics. The methodology used was based on previous systematic video analysis protocols [26]. We modified certain criteria, dividing the section "player action with the ball" and "duel type" into two additional options according to ball possession (Table 1). For each injury, the analysts determined which frame represented the initial contact (IC) of the foot of the injured leg with the ground. They then ticked check boxes related to categorical variables on injury information and circumstances, weather, pitch conditions, and biomechanical characteristics. The flexion angle of the hip, knee, and ankle was assessed at IC, IC+40 ms (one frame later) and IC+80 ms (two frames). We used the same definitions provided by a previous study on epidemiology of ACL injuries [2] to classify injuries as direct, indirect, or non-contact. The player's speed was estimated as zero, low, high, or unsure according to the movement direction (horizontal, vertical). The analysts also assessed whether there was: hip abduction greater than 20°, knee valgus collapse, and/or an ankle eversion. Finally, two consensus in-person meetings were organized to review the five analysts' forms for each injury. The videos were reviewed till agreement on all variables (except joint angles) was reached. A 3rd in-person meeting was held by two analysts and one non-analyst co-author to check data completeness and accuracy.

Statistical analysis

The data were analyzed using Microsoft Excel (version 16.0, Microsoft Office 365 ProPlus, Redmond, Washington, USA) and IBM SPSS statistics version 21.0 (SPSS Inc, Chicago, IL).

Descriptive analysis was performed for all categorical variables. The joint flexion angles were assessed for inter-rater reliability. To calculate the variability across all cases, we measured the intraclass correlation coefficient (ICC) estimates and their 95% confidence intervals for each variable/joint based on a mean-rating ($k = 5$), absolute-agreement, 2-way mixed-effects model. The ICC was of 0.715^c for the knee joint, 0.531^c for the hip joint and 0.651^c for the ankle joint at IC. We calculated for the 5 analysts' measures of these joint angles: the mean, standard deviation, and standard error, along with the 95% confidence interval of the mean. The measurement correlation between analysts was poor, as the IC frame chosen by each analyst differed. Therefore, it was agreed to calculate the mean value of the 5 video frame numbers at IC selected by the 5 analysts (excluding the outliers). These frame images (as many frames as available video views for each injury) were shared again with the 5 analysts who reanalyzed them to recalculate the IC angles on the same images, which was intended to improve the measurement correlation between analysts. The joint flexion angles for IC were reported as the mean of individual estimates along with the standard error for the main injury situations (Table 2). Joint angle measurement at IC+40 ms, IC+80 ms and IF were not recalculated and then excluded from the study.

The injury situation categories were not assessed for the one injury filmed with a wide shot. Joint angles were also not measured in another injury, as the player was masked by an opponent and a teammate in the three analyzed views.

Ethical considerations

Injuries were recorded through the Aspetar Injury Surveillance Programme. Their use was approved by the Anti-Doping Laboratory Qatar Ethics Institutional review board (IRB E2017000252). No personal information regarding the participants was disclosed or used. The high-definition broadcast videos were obtained from Qatari television.

TABLE 1. Categorical variables to describe the ACL injury circumstances and biomechanics.

Variable	Categories
Weather condition	Sunny, rainy, snowy, unsure
Pitch condition	Dry, wet, wet & muddy, unsure
Football-specific variables	
Playing situation preceding injury	Offensive, defensive, set play, other, unsure
Field location at injury	Defensive third, midfield zone 1, midfield zone 2, offensive third, unsure
Player action preceding injury (if no ball possession)	Heading, receiving, screening, turning, passing, shooting, blocking, clearing, other, unsure
Duel type (if no ball possession)	Heading, tackling other player, tackled by other player, collision (unintentional), blocking, screening, running, other, unsure, no duel
Player action preceding injury (if ball possession)	Being tackled, dribbling, heading, receiving, screening/shielding, turning, passing, shooting, blocking, clearing, other, unsure
If kicking	Kicking with right or left leg
Duel type (if ball possession)	Heading, tackling other player, collision (unintentional), blocking, screening/pressing, running, other, unsure, no duel
Player contact preceding injury	Yes, no, unsure
If contact, what type	Direct contact (to injured knee or injured leg), indirect contact (to uninjured leg, trunk, head/arm), other, unsure
Player contact at injury	Yes, no, unsure
If contact, what type	Direct contact (to injured knee or injured leg), indirect contact (to uninjured leg, trunk, head/arm), other, unsure
In balance at IC	Yes, no, unsure
If out of balance, what direction	Forward, backward, sideways
Biomechanical variables	
Player movement at IC	Forward, backward, sideways, other
Cutting angle at IC	Intended change of direction 0–30°, intended change of direction 30–90°, intended stopping or change of direction > 90°, unsure
Loading on one vs. two legs during the contact phase	One leg, two legs with equal load, two legs with main load on injured leg, two legs with main load on uninjured leg, unsure
Horizontal speed at IC	High, low, zero, unsure
Vertical speed at IC	High, low, zero, unsure
Trunk rotation	Toward injured leg, toward uninjured leg, neutral, unsure
Foot rotation at IC	Internal 0–45°, internal > 45°, external, neutral, unsure
Foot strike at IC	Heel, toe, flat, unsure
Knee flexion angle	
IC	Flexion/extension (+/-) straight knee = 0
IC + 40 ms	Flexion/extension (+/-) straight knee = 0
IC + 80 ms	Flexion/extension (+/-) straight knee = 0
IF	Flexion/extension (+/-) straight knee = 0
Hip flexion angle	
IC	Flexion/extension (+/-) straight hip = 0
IC + 40 ms	Flexion/extension (+/-) straight hip = 0
IC + 80 ms	Flexion/extension (+/-) straight hip = 0
IF	Flexion/extension (+/-) straight hip = 0
Ankle flexion angle	
IC	Plantar flexion/dorsal extension (+/-)
IC + 40 ms	Plantar flexion/dorsal extension (+/-)
IC + 80 ms	Plantar flexion/dorsal extension (+/-)
IF	Plantar flexion/dorsal extension (+/-)
Knee valgus collapse	Yes, no, unsure
Large hip abduction (> 20)	Yes, no, unsure
Ankle eversion	Yes, no, unsure
Any additional comments on the injury mechanisms in your own words	

TABLE 2. Knee, hip, and ankle joint angles.

	Knee flexion (°)		Hip flexion (°)		Ankle flexion (°)		Injury situation
Case #	**Mean flexion**	**SE**	**Mean flexion**	**SE**	**Mean flexion**	**SE**	
1	58	9	48	6	3	5	Tackling other player
2	14	2	35	7	6	10	Tackled by other player Screening
3	14	4	41	6	6	6	Pressing
4	25	3	34	4	26	5	Blocking
5	29	5	36	4	16	6	Pressing Tackling other player Blocking
6	22	7	30	6	16	6	Pressing Running
7	21	2	25	3	5	2	Dribbling Running
8	26	2	40	4	3	3	Tackling other player
9	17	6	34	5	11	2	Pressing
10	26	9	16	1	9	3	Tackled by other player Screening
11	18	3	15	5	5	5	Not scored
12	18	3	36	5	10	8	Pressing Blocking
13	62	7	62	9	12	6	Pressing
14	17	10	39	5	7	7	Pressing Tackled by other player Blocking Collision
15	-	-	-	-	-	-	Tackling other player

Note: SE: Standard error. For injury 15, joint angles were not measured as the player was hidden by an opponent and a teammate in the analyzed frames.

RESULTS

Of the 15 injuries, 9 were to the right and 6 to the left knee; 13 occurred in the regular league and 2 in the Qatar Cups. The weather at the time of injury was usually sunny (except one case where the weather was unsure) and the pitch was always dry. Eight, four, and three injuries were classified as non-contact, indirect contact, and direct contact injuries, respectively. Eleven injuries occurred on defense, three on offensive, and one during a breakdown attack. In 12 of the 15 cases, the injured player was not in possession of the ball. The maximum loading at the time of injury was either solely on the injured leg (10/15) or on both legs (5/15) but with main loading on the injured leg.

Injury situations

A knee valgus mechanism was observed in 10 cases (1 with direct contact to the knee, 3 with contact to other body parts and 6 with no body contact). No valgus was observed in 2 cases (both direct knee contact), while 3 were unclear. In all but two cases, the knee was slightly flexed (13 cases, 14° to 29°) at the time of injury (table 2). Of the 12 non-contact/indirect contact situations, we observed four main categories of injury situations (note: multiple combinations were possible): pressing (n = 6), tackling, or being tackled by another player (n = 4), blocking or stopping the ball from reaching another player (n = 3) and screening or protecting the ball with own body (n = 2). In one case, the player was injured while running and dribbling without interaction with any opponent. He did a cutting manoeuvre (30 to 90°) with the foot planted firmly on the ground involving rotational stress on the weight-bearing knee. In the 3 direct contact injuries, the player was tackling in 2 cases and being tackled in the other. No landing after heading situation was reported for any of the injuries.

Injury situation for indirect and non-contact injuries (n = 12)

Of the 8 non-contact and 4 indirect contact injuries, there was one video with no contact, in which it was impossible to assess the situational pattern of the injury (one video incidence with no replay and no lateral view). Players were mainly running forward (11/12) and not jumping (10/12).

Pressing (n = 6)

The injured players were most frequently in a defending situation, pressing another player, while not in possession of the ball (figure 1). Players were running forward, more often at a high speed (n = 4, low speed n = 2), with a variable cutting angle and torso rotation. They all displayed knee valgus. Both indirect contact cases were to the trunk/arm. Half of the players were off-balance sideways. The maximum loading during injury was on one leg in half the cases, with the other half on 2 legs but mainly loading the injured leg. There was a large hip abduction (> 20°) in half of the cases, with a moderate hip flexion (30 to 62°). The knee was slightly flexed (14 to 29°), except for one case. Ankle eversion was observed in only 2 cases. Foot external rotation was noted in 4 cases out of 6. The foot strike was mainly on the heel (n = 5).

Tackling or being tackled (n = 4)

The second more frequent injury situation was tackling from the lateral side (two cases in defensive situation) or being tackled (in a breakdown in an offensive situation), from behind in one case and laterally in the other (figure 2). Players were running forward with a variable cutting angle, in balance (except one case) and not jumping. The hip abduction was variable, while hip flexion was slight (16 to 36°). Knee flexion was slight (14 to 29°). The foot strike was variable but most frequently in external rotation (n = 3) and with no ankle eversion.

Blocking (n = 3) and screening (n = 2)

Blocking and screening were two other injury situations (Figure 3 and 4). The indirect contact was mainly to the trunk/arm in players moving forward (4/5). There was no clear trend for speed, cutting angle or losing balance. The torso rotation was neutral when screening and towards uninjured (n = 2) or injured leg (n = 1) when blocking. The hip abduction was variable and the hip flexion about 34 to 36° (except one case). The knee was slightly flexed (14 to 29°). The foot position was always in external rotation with a foot strike either on the heel or the toe.

Injury situation for direct contact injuries (n = 3)

This direct contact to the injured knee involved players running either forward (n = 2) or a combination of backwards and sideways (n = 1), with low speed to defend against an opponent with the ball. There was no clear trend for the cutting angle or torso rotation. The 3 collisions involved tackling but included different situations (figure

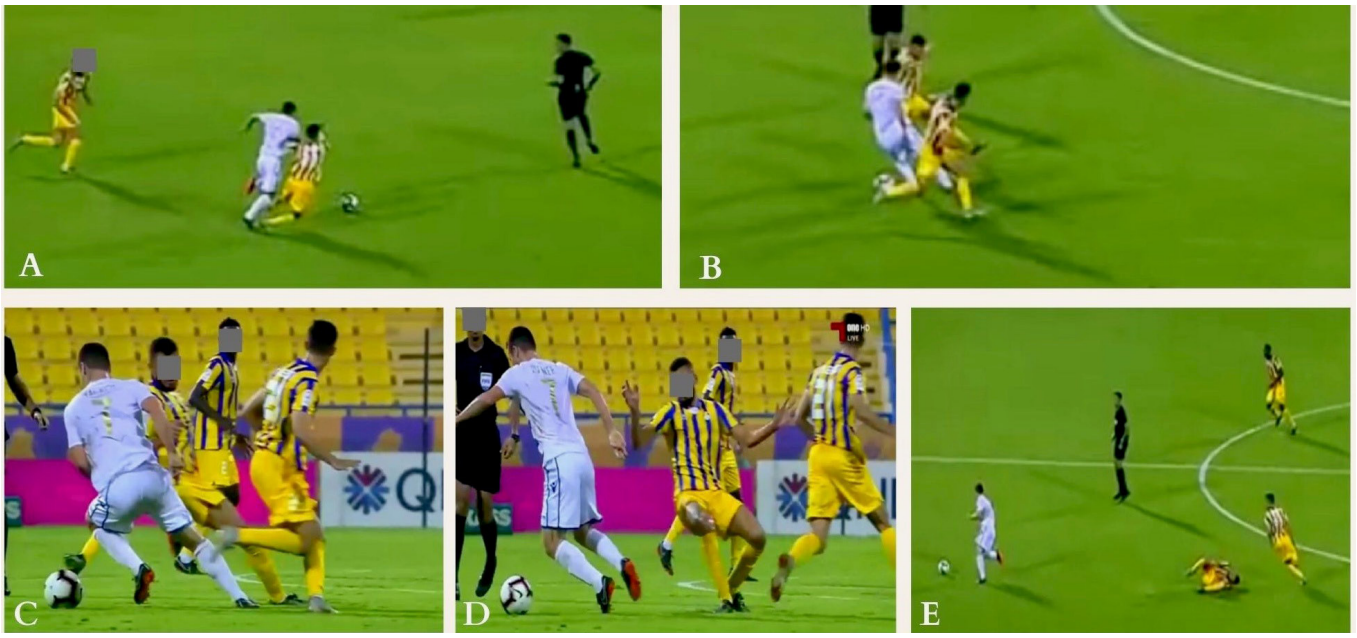


FIG. 1. Indirect contact injury mechanism (Pressing) to the right knee: The injured player (in yellow) was running at high-speed trying to join a teammate in pressing an opponent (frame A). When he joined him, the opponent dribbled both by doing a sudden change of direction of 180° (frame B). The injured player tried to shoot the ball but missed it (frame C). He quickly stopped and changed his main loading from left to right leg while distracted by the ball causing a knee valgus and rotational motion (frame D). Then the player lost balance and fell down (frame E).



FIG. 2. Indirect contact injury mechanism (tackled by other player) to the right knee: the injured player (in orange), gained possession of the ball from an opponent (frame A). The second player immediately tackled him and stepped on his foot (frame B). The injured player continued running forward with his right foot blocked behind on the ground (Frame C). He lost balance and fell (frame D).



FIG. 3. Indirect contact injury mechanism (blocking) to the right knee: The injured player (in red) was running at high-speed trying to stop the ball from being passed to another player (frame A). Then he kicked the ball while his right foot was planted on the ground with a large hip abduction (frame B) causing a knee valgus and rotational motion (frame C). Then the player lost balance and fell down (frame D).



FIG. 4. Indirect contact injury mechanism (Screening) to the right knee: The injured player (in grey), in offensive situation, was running forward at high speed, with ball towards the goalkeeper, alongside the defender (frame A). He was screening/shielding to protect the ball while running. During arm/trunk contact (frame B and C), when loading on his right foot (frame C), the injured player had a right knee valgus stress with compression mechanism causing the injury that resulted in his fall on the pitch and immediate call for medical help (frame D).

5 and 6): 1. knee to knee contact involving anterolateral impact to the knee and leading to a knee compression mechanism in flexed position (58°); 2. body to knee contact with loss of balance, involving a postero-lateral impact to the knee and causing a knee valgus and an upper leg anterior translation; 3. foot to knee contact involving anterior impact and leading to knee hyper-extension. In the 3 cases, there was mainly a large hip abduction (2/3) with a flexed hip (39 to 48°). Foot rotation, foot strike and ankle eversion varied.

DISCUSSION

This study described the ACL injury mechanism in professional Qatari football players over a 6-year period through systematic video analysis. A knee valgus mechanism was observed in two-thirds of the cases. Indirect and non-contact mechanisms were responsible for 12 out of 15 ACL injuries in which the 4 main injury situations were (with multiple combinations): (1) pressing, (2) tackling or being tackled, (3) blocking and/or (4) screening. All 15 injuries occurred in dry conditions, in accordance with previous research, suggesting that warm and dry conditions increase shoe-surface traction and thus are associated with higher incidences of non-contact ACL injuries compared to wet (soft) surfaces [29, 33, 34].

Injury circumstances

In accordance with our findings, previous studies concluded that a non-contact mechanism is more frequent for ACL injuries in football [26, 35, 36]. Conversely, a recent study on professional Italian football players found a higher proportion of contact injuries (56%) [28]. The discrepancy across studies can be explained by a different definition of contact, whether directly to the knee or with other body parts (e.g. pushing an opponent or holding him by the shirt, defined as indirect in our study) [16], as well as different approaches from the collection of videos to sample analyses. Direct contact injuries, 20% in our study, were less frequently reported in the most recent papers [26, 28].



FIG. 5. Direct contact injury mechanism (tackling other player) to the left knee: The injured player (in green), in defensive situation, making short forward and backward steps waiting for the striker to come in front of him (Frame A). Then the injured player stretched his left leg (in a weightbearing position) to tackle the opponent. Both players' knees got in contact (frame B), causing a left knee compression mechanism in flexed position to the injured player. Following this contact, the injured knee went in extension (frame 3), the opponent fell down, the referee whistled a foul and the injured player continued to play (frame 4).



FIG. 6. injury situations in direct contact injuries. Injured knee in frame A (Left knee, green Jersey player), frame B (Right knee, blue and black jersey player) and frame C (Right knee, green jersey player).

Playing situations associated with ACL injury

In our study, 80% of ACL injuries occurred while defending; recent research reported more than two-thirds happening in this phase of play [25, 26, 28]. We observed four main injury situations, of which pressing was the most frequent (40%), consistent with the findings of others [26, 28]. The second mechanism was tackling or being tackled. Two new injury situations (blocking and screening) were observed. A one-legged jump landing has been reported as a common mechanism [26, 28], but was absent in our study. Contrary to a previous research on direct contact injuries [26], where all 3 tackling cases were tackled players with contact to the injured knee and suffering a valgus collapse, we observed a direct contact dynamic valgus in only one case out of three, in a tackling situation by the injured player. This could potentially be attributed to playing style variations [37] or anthropometric differences [28]. In our study, half of the indirect and non-contact injuries occurred in players losing balance, often while trying to shoot or stop the ball while being distracted by the ball or the opponent. Such situations are common with other sports like rugby [21] and American football [19] and should be practiced in controlled environment to prevent ACL tears. This can include perturbation, dual task or partial visual occlusion to increase the perceptual cognitive demands of the task. Furthermore, footwork and running technique training (neuromuscular and postural control) are key recommended elements in the prevention of this injury [38, 39], as well as addressing safe pressing and tackling technique.

Lower limb biomechanics

Faulty mechanics during hazardous sporting movements, due to poor neuromuscular control, have been reported to cause a knee valgus stress and increased load on the ACL, increasing ACL injury risk [38, 40, 41]. These mechanics can result from lateral movement of the trunk, altered load distribution between limbs, and/or lack of movement control [38].

Altered motion in the frontal plane have been reported in literature [42]. In our study, the torso rotation showed no clear trend. Hip abduction (> 20°) was observed in 8 cases out of 15 (in addition to 2 unsure) while hip flexion varied. Similar to knee valgus-type loading, hip abduction motion from IC to the suspected moment of the ACL rupture has also been frequently reported [20, 26, 43, 44], with a planted laterally oriented foot [43, 45]. In our study, the foot was externally rotated in 60% of cases and ankle eversion occurred in only one case out of 3.

All indirect contact and 75% of non-contact injuries happened with the knee close to full extension at IC (< 29°). All, except 3 unsure cases, suffered a dynamic knee valgus stress identified by visual inspection. This is consistent with existing literature in football and other sports [14, 15, 26, 28, 46]. Previous research did not reach consensus whether knee abduction moments and greater angles are associated with greater risk of ACL injuries [47–50]. Moreover, vertical ground-reaction compression force increases during ground contact when the knee is less flexed and the trunk is in a more erect position. This has been shown to lead to an anterior tibial drawer and internal rotation, causing increased loads on the ACL [51]. In other studies, using the model-based image matching technique to assess knee joint motion, from IC to IC+40 ms, a 20° to 25° increase in mean knee joint flexion angle has been observed [20, 26, 28], reflecting sudden compressive forces at the knee joint. This finding was not assessed in our study as we considered only measurements at IC.

The above-described faulty mechanics are modifiable through inclusion of plyometrics, neuromuscular and strength training. A dynamic assessment could potentially recognize the alterations in the trunk and lower kinetic chain to address [38, 40]. Compliance of the football players is essential in these preventive programmes, as well as coach education to overcome obstacles (implementation in warm up) [52].

Methodological considerations

Our study's main strength is that it involves a homogeneous sample from our prospective injury and illness surveillance programme collected by club medical staff working for the same institution and following the same data collection protocol, aligned with the recent IOC consensus recommendations [53]. The diagnoses were also verified as ACL rupture was always confirmed on MRI and all cases went to surgery. All match injuries recorded during the observation period were captured on video, with high-definition quality in all cases but one. Furthermore, we followed the same approach and methodology as in previous research [14, 15, 26, 54]. The sample size, with fewer cases (15 injuries from official matches) than other studies, reflects the outcome from six consecutive seasons in a single country with a relatively limited number of teams and official matches when compared to European football leagues. Although unlikely to dramatically change the pattern from that observed, collecting a larger sample with data from several championships in the Middle East would provide a more granular picture. Thus, our data should be interpreted with some caution, but at least reflect the main mechanisms of ACL injuries in Qatar.

Furthermore, only official match injuries were reported, and these comprised a minority of the total injuries incurred in the league during this period (15 out of 51; training and friendly game injuries could not be included since no video footage was available). Future research should consider methods to describe training injuries, as well, since their mechanisms may differ from match injuries. Should this be the case, there will be important prevention implications as training circumstances are probably more amenable to change than matches. Additionally, these data only apply to adult males, so extrapolation to adolescents and females should be done with caution, if at all. Still, a recent study on female professional football players found similar injury situations and mechanisms as in males [55].

The number of camera views ranged from 1 to 6. In previous studies, the various camera views were manually synchronized based on

different criteria and presented side by side on a single screen [26]. This could result in some misinterpretation. Thus, we implemented the different camera views successively through a single video sequence for each injury. The analysts would then choose the camera view(s) that allowed them to best perform the analysis. Only one injury included a single camera view. Frontal and/or sagittal views were not always available. One video, filmed only with a wide shot, was appraised for all variables but injury situation categories and a second video was not assessed for joint angles as the player at IC was hidden between a teammate and an opponent.

Moreover, we used 5 analysts with expertise in sport medicine coming from different backgrounds. We believe that this insured a better outcome of the organized consensus meetings.

Joint angles were estimated by visual inspection and could not been validated. Previous research has outlined the limitations of visual inspection compared to a three-dimensional motion analysis system [56], leading us to not include data for the joint angle estimates at IC +40 ms, IC +80 ms and IF. Joint flexion angles for IC were reported as the mean of individual estimates along with the standard error for the main injury situations. Consequently, the dynamic progression in time of joint angles and body motion between IC, IC+40 ms and IF was not estimated, limiting the findings to a static description at ground contact. Furthermore, using the images (as many as many camera views) interchangeably for each injury could cause a parallax error.

CONCLUSIONS

This study provides insights about the injury mechanisms in Qatar, a country in the middle East, which is characterized by hot and dry conditions. A common feature of most injuries was that the knee was in valgus and close to full extension. Direct contact injuries were less frequent (20%) and caused by the injured player tackling or being tackled. The indirect or non-contact injuries were related to 4 main injury situations (with multiple combinations): (1) pressing, (2) tackling or being tackled, (3) blocking and/or (4) screening. In contrast to previous research, one-legged jump landing was not observed. Preventive measures should consider the findings of our study.

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Conflict of interest declaration

The authors declare having NO conflict of interest.

Contributors

RNR, KC and RB contributed to the ideation of the study. All authors contributed to the study design and data recoding preparation. RoB, FC, PR, RNR and RW did the video analysis. RNR, MT, KC, and RoB were responsible for the data collection and data analysis. RNR and KC interpreted the data and wrote the first draft of the paper. All authors contributed to the final paper. RNR and KC are responsible for the overall content as guarantors.

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Is there any relationship between match running, technical-tactical performance, and team success in professional soccer? A longitudinal study in the first and second divisions of LaLiga

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ABSTRACT: The aim of this study was to analyze the association between teams' success at the end of the season and match running, and technical-tactical performance in two professional soccer leagues. Match running, and technical-tactical performance data were collected during two consecutive seasons. A Factor Analysis was conducted to reduce the number of performance variables into a fewer number of factors. The scree plot with parallel analysis revealed that five factors should be retained. Then, a multiple linear regression analysis was performed to explain which variables and factors were more associated with teams' success at the end of the season. The main findings of this study were that factor 3, which was correlated with goals scored, possessions ending with a goal, shots on target, goals from set plays, goals from a direct free kick, offsides, and goals conceded, was the most important contributor to teams' success ($\beta = 0.66$). In addition, this study observed a significant interaction ($p = 0.001$) between the second division of LaLiga and factor 2, which correlated with total distance (TD), sprinting distance (SPD), and sprinting actions (SPA) when opponent team owns the ball, tackles, shots inside the box, and fouls received. This implies that factor 2 had a different effect on the total points at the end of the season depending on the league. However, factor 2 had no effect on the first division. In conclusion, technical-tactical performance variables were usually more closely linked to the team's success in both leagues than match running performance data. Regarding the technical-tactical performance, teams may focus on drills that promote goal situations, shooting accuracy, the total of shots performed in match play, and set pieces. However, defensive skills need to be reinforced considering the importance of goals conceded for team success in both divisions. When it comes to the match running performance, teams are encouraged to focus on offensive actions, in which they possess and run with the ball (especially at high speed) and defensive actions in which the players perform continuous and high-intensity physical efforts to prevent the opponents from scoring, avoid counterattacks, stay compact, and defend the area and goal.

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INTRODUCTION

In recent years, technological advances in the sports industry have led to the rapid development of electronic performance and tracking systems (EPTS) such as global positioning systems, local positioning systems, and optical tracking systems [1]. These EPTS have allowed sports scientists and coaching and medical departments to better understand players' performance [1, 2]. Most professional soccer teams currently use EPTS on a daily basis, with several leagues already investing in EPTS to be used on match day for both performance and media purposes. Examples of these multi-camera tracking systems are non-invasive EPTS that collect technical-tactical activity and match running performance [3]. Consequently, practitioners have access to vast amounts of data, which may serve to accurately analyze individual and team performance and the performance of the opposing team.

However, in soccer, team success is a complex construct in which different variables such as shooting accuracy, defensive actions, or running performance may play a significant role in professional soccer matches [4–7]. For instance, a recent study in a German professional soccer league concluded that variables related to shooting accuracy, such as shots on target or goal efficiency, were significantly

correlated with team success at the end of the season [8, 9]. In addition, an investigation of a Chinese professional league found that variables related to ball possession and duels were also linked to team success [10].

Furthermore, match running performance may significantly contribute to team success [5–7, 10]. For instance, previous studies found that high-ranked teams covered shorter distances without ball possession than lower-ranked teams [7, 10]. Also, it was observed that distance covered with ball possession (especially running at high speed) had a positive and significant association with the total number of points obtained at the end of the season [6, 7]. Along these lines, a recent study in LaLiga concluded that the main changes in both the first and second Spanish divisions were the increase in distance covered and the total of efforts performed at high intensity [11].

However, research on the relationship between team success and match running and technical-tactical performance in professional soccer is scarce. From a practical perspective, it is necessary to analyze which performance indicators should be taken into account, not only for team success but also for training purposes and talent identification. Therefore, the aim of this study is to analyze the association between teams' success at the end of the season and variables related to match technical-tactical and running performance in two professional soccer leagues.

MATERIALS AND METHODS

Study design

This study followed a longitudinal design. Match running, and technical-tactical performance data were collected by electronic performance and tracking systems during two consecutive seasons (2017/2018 and 2018/2019) in two professional soccer leagues. In addition, the total number of points obtained at the end of each season by each team were registered to analyze its relationship with match running and technical-tactical data.

Sample

Data were collected from professional soccer teams competing in the first and second division Spanish Professional Soccer Leagues known as LaLiga. The first division is comprised of 20 teams, while the second division is composed of 22 teams. During the season, each first division team played 38 matches (home matches = 19; away matches = 19), while in the second division, each team played 42 matches (home matches = 21; away matches = 21). This resulted in a total of 3368 match observations (1520 match observations for the first division and 1848 match observations for the second division). However, as LaLiga expelled one of the second division teams during the 2018/2019 season, their data were not included in the analysis.

Variables

Regarding match technical-tactical performance, the following variables were collected for each team: goals scored, goals conceded, ball possession (%), tackles, duels, aerial duels, recoveries, attempted crosses, successful crosses, fouls made, fouls received, yellow cards, second yellow cards, red cards, offsides, attempted passes, successful passes, passes ending in own team's half, passes ending in opponent team's half, passes made in the final third, possession width, possession length, possessions ending in attacking third, possessions involving 0–2 passes, possessions involving 3–5 passes, possessions involving 6–8 passes, possessions involving more than 9 passes, possessions starting in attacking third, possessions starting in the middle third, possessions ending with a shot, possessions ending with a goal, chances created from a set play, corners, goals from corners, goals from a direct free kick, goals from a set play, shots on target, shots off target, and shots inside the box. Regarding the match running performance, the following variables were included: total distance (TD) covered (m) when the opponent team possessed the ball (m), TD covered when the own team possessed the ball (m), sprinting distance (SPD, above 21 km/h) when opponent team possessed the ball (m), SPD covered when own team possessed the ball (m), total of sprinting actions (SPA, above 21 km/h) when opponent team possessed the ball, and the total of SPA when own team possessed the ball. Furthermore, each team's total number of points obtained at the end of each season was registered as a representative variable of team success.

Instruments

Electronic performance and tracking systems were used to collect performance variables. Specifically, the computerized multi-camera tracking system TRACAB (ChyronHego, New York, USA) collected positioning and motion data while events were recorded by OPTA (Opta Sports, London, UK). The validity and reliability of these systems have been assessed in previous studies [12–14]. Subsequently, reports that took into account all thevariables were generated using Mediacoach software.

Statistical analysis

First, a descriptive analysis of the match running and technical-tactical performance in both leagues was performed. Then, an Exploratory Factor Analysis was conducted to reduce the dimension of the performance variables. The appropriateness of factor analysis was determined through Kaiser Meyer Olkin measure of sampling adequacy (KMO = 0.7) and Bartlett's test of sphericity ($X^2 = 5308.34$; df = 496; $p < 0.001$). The number of factors was determined using a Scree plot with Parallel Analysis (Figure 1), which revealed that five factors should be retained (i.e., the "elbow" of the curve). The Exploratory Factor Analysis was computed through a maximum likelihood method and the interpretation of the factors was based on orthogonal rotation with the varimax method, since it is the most appropriate when the independence of the factors is assumed [15, 16].

Finally, a multiple linear regression analysis was performed to study the association between teams' success and match performance. Homoscedasticity and linearity assumptions of the linear

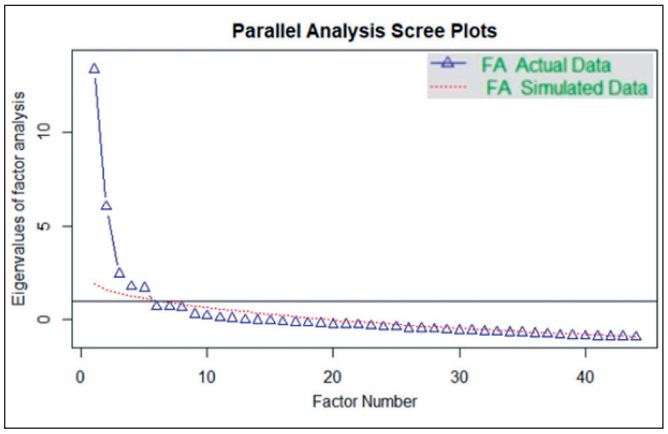


FIG. 1. Scree plot with parallel analysis indicating that five factors should be retained in the factor analysis (FA).

regression models, as well as the normality, no multicollinearity and no autocorrelation of the residuals were checked. The total of points obtained at the end of the season was set as the dependent variable while the leagues (i.e., first or second division), the score values of retained factors, and the variables, which were not well represented by the factors (i.e., low correlations with retained factors), were set as independent variables. In addition, the interactions between these independent variables and the leagues were included in the model to analyze the effect that the league had on the total of points (i.e., to analyze if the effect of any independent variable on the total of points was different depending on the league). Coefficient of determination (R^2) was used as predictive success criteria for the regression model. All statistical analyses were carried out using R Version 3.6.1 (The R Foundation for Statistical Computing, Vienna, Austria) and the R Studio interface Version 1.1.463 (RS Team—RStudio, Inc., Boston, Massachusetts, United States). Statistical significance was set at $p < 0.05$.

RESULTS

Table 1 shows descriptive statistics of match running and technical-tactical performance in the first and second divisions of LaLiga. An Exploratory Factor Analysis was conducted to reduce the dimension of the match technical-tactical and running performance variables and a five-factor model (F1, F2, F3, F4, and F5), which explained 61% of the common variance, was obtained. Factors loadings were estimated, and Table 2 shows the greatest correlations between the performance variables and corresponding factors. Aerial duels, possession width, second yellow cards, and red cards had low correlations with the factors. Consequently, these variables were not well represented by none of the retained factors.

Specifically, Table 3 shows the multiple linear regression assessing the association between team success and match performance in the first and second divisions of LaLiga. The F-test was significant ($F = 9.21$; df = 19 and 63; $p < 0.001$) and the adjusted model explained 73.5% ($R^2 = 0.735$) of the variance of team's success at the end of the season.

F3 (goals scored: 0.83; possessions ending with a goal: 0.83; shots on target: 0.61; goals from set play: 0.53; goals from direct free kick: 0.39; offsides: 0.37; goals conceded: -0.35) was statistically significant ($p < 0.001$) and had a positive effect ($B = 9.365$) on the total of points obtained at the end of the season. This implies that the teams' success was associated with increases in the value of F3 (i.e., increasing goals scored, possessions ending with a goal, shots on target, goals from set play, goals from direct free-kick and offsides whereas the value of goals conceded decreases). Furthermore, according to the Beta weights, which compared the relative importance of each independent variable or factor in standardized terms, showed that F3 had the highest impact on the teams' success ($\beta = 0.66$).

In addition, the interaction between the second division and F2 (SPA when opponent team owns the ball: 0.88; SPD when opponent team owns the ball: 0.85; TD when opponent team owns the ball: 0.63; tackles: -0.51; fouls received: -0.40; shots inside the box: 0.39) was statistically significant ($p = 0.001$) and had a positive effect ($B = 5.473$) on the total of points at the end of the season. This implies that F2 had a different effect on the total points at the end of the season depending on the league (i.e., first or second division). Specifically, the teams' success was associated with increases in the value of F2 in the second division (i.e., increasing TD, SPD, and SPA when opponent team owns the ball and shots inside the box whereas tackles and fouls received decrease) whereas this factor had no effect on team success in the first division.

DISCUSSION

The aim of this study was to analyze the association between teams' success (based on the total of points obtained at the end of the season) and match performance in two professional soccer leagues. The main findings of this study were that F3, which correlated with goals scored, possessions ending with a goal, shots on target, goals from a set play, goals from a direct free kick, goals conceded, and offsides, was the most important contributor to teams' success in both divisions. In addition, this study observed a significant interaction between the second division of LaLiga and F2, which correlated with TD, SPD, and SPA when opponent team owns the ball, tackles, shots inside the box, and fouls received. However, F2 had no significant effect on team success in the first division

One of the main findings, consistent with previous research [7, 10, 17], was that technical-tactical performance variables were usually more closely related to the team's success than match running performance. The results show that not only goals scored determine team success but also how much teams generate close to the opponent's goal (e.g., shots on target or set pieces) and the goals conceded. These may be expected results considering the nature of soccer and previous investigations, which suggested that

TABLE 1. Match running and technical-tactical performance in the first and second division of LaLiga

	First Division			Second Division		
Variables	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**
Goals scored	1.32 ± 0.43	0.63	2.61	1.14 ± 0.22	0.69	1.64
Goals conceded	1.32 ± 0.32	0.58	2.00	1.13 ± 0.27	0.68	1.93
Ball possession (%)	50.00 ± 6.32	40.10	64.40	50.01 ± 3.35	41.73	54.85
Tackles	42.14 ± 2.76	36.51	46.80	44.52 ± 2.40	38.92	49.48
Duels	50.00 ± 2.21	44.66	54.09	50.01 ± 1.35	47.42	52.94
Aerial duels	50.00 ± 3.20	41.33	55.77	50.05 ± 2.38	45.30	56.00
Recoveries	53.49 ± 2.55	47.47	60.18	52.26 ± 2.60	46.63	59.83
Attempted crosses	18.12 ± 3.74	10.37	27.82	18.69 ± 2.52	13.21	23.86
Successful crosses	4.22 ± 1.06	2.21	7.00	4.13 ± 0.69	2.60	5.88
Fouls made	13.71 ± 1.75	10.08	17.71	15.20 ± 1.30	12.45	17.22
Fouls received	13.71 ± 1.32	11.26	18.26	15.17 ± 1.02	13.48	17.59
Yellow cards	2.50 ± 0.40	1.61	3.42	2.60 ± 0.37	1.86	3.37
Second yellow cards	0.06 ± 0.04	0.00	0.13	0.08 ± 0.04	0.00	0.17
Red cards	0.04 ± 0.02	0.00	0.08	0.04 ± 0.03	0.00	0.12
Offsides	2.40 ± 0.47	1.53	3.61	2.34 ± 0.41	1.26	3.10
Attempted passes	433.35 ± 88.54	295.47	666.00	392.34 ± 42.52	279.76	478.24
Successful passes	344.43 ± 94.45	188.13	587.89	295.85 ± 46.28	173.67	395.05
Passes ending in own team's half	190.93 ± 47.97	93.39	274.29	174.61 ± 32.52	83.74	249.66
Passes ending in opponent team's half	242.42 ± 48.85	185.89	391.71	217.72 ± 16.95	194.54	262.02
Passes made in the final third	54.80 ± 6.70	44.37	76.58	55.42 ± 4.35	47.22	66.74
Possession length	23.34 ± 1.96	20.32	29.29	22.78 ± 1.00	20.98	25.00
Possession width	33.99 ± 0.73	32.25	35.53	34.04 ± 0.83	32.46	36.22
Possessions ending in attacking third	37.78 ± 3.72	32.66	47.26	37.80 ± 2.66	31.10	43.33
Possessions (0–2 passes)	42.50 ± 8.37	25.29	60.37	48.06 ± 5.73	38.51	64.90
Possessions (3–5 passes)	26.32 ± 2.65	20.47	31.08	28.15 ± 2.00	23.55	32.31
Possessions (6–8 passes)	12.60 ± 1.38	9.84	15.84	12.51 ± 1.27	8.86	15.10
Possessions (> 9 passes)	16.07 ± 5.94	5.58	30.87	13.09 ± 3.15	4.38	19.93
Possessions starting in attacking third	6.75 ± 1.15	5.26	11.32	6.55 ± 0.99	4.17	8.79
Possessions starting in middle third	37.42 ± 3.92	32.34	50.92	40.05 ± 3.49	32.05	47.44
Possessions ending with a shot	10.62 ± 1.47	8.74	16.18	10.20 ± 1.03	8.48	12.76
Possessions ending with a goal	1.28 ± 0.42	0.61	2.53	1.10 ± 0.22	0.64	1.60
Chances created from set play	1.98 ± 0.41	1.21	2.95	1.97 ± 0.29	1.29	2.54
Corners	4.85 ± 0.84	3.58	7.34	4.91 ± 0.54	3.81	6.17
Goals from corners	0.15 ± 0.08	0.03	0.42	0.14 ± 0.06	0.00	0.26
Goals from direct free kick	0.04 ± 0.04	0.00	0.16	0.04 ± 0.03	0.00	0.12
Goals from set play	0.27 ± 0.11	0.05	0.55	0.28 ± 0.09	0.10	0.48
Shots on target	4.24 ± 0.99	3.00	7.45	3.91 ± 0.49	3.05	4.95
Shots off target	5.09 ± 0.72	4.03	7.16	4.97 ± 0.52	4.07	6.02
Shots inside the box (%)	61.76 ± 4.31	51.81	72.93	57.91 ± 3.81	50.69	67.60
TD when opponent team owns the ball (m)	41372.72 ± 3518.80	34104.61	48213.08	38955.44 ± 1867.74	35740.56	42844.33
TD when own team owns the ball (m)	37933.37 ± 4374.40	29748.76	46029.67	36014.98 ± 2978.50	27116.51	42222.32
SPD when opponent team owns the ball (m)	3149.84 ± 295.57	2446.73	3786.68	2906.38 ± 199.08	2526.55	3347.27
SPD when own team owns the ball (m)	2652.42 ± 287.90	2203.62	3424.89	2493.61 ± 257.00	1774.76	2997.83
SPA when opponent team owns the ball	165.92 ± 15.46	136.65	199.81	151.56 ± 9.97	130.40	177.12
SPA when own team owns the ball	123.62 ± 13.98	96.73	157.95	113.84 ± 11.18	81.93	136.60

Note: SD = standard deviation; Min: minimum; Max: maximum; TD: total distance; SPD: sprinting distance; SPA: sprinting actions

TABLE 2. Factor loadings of the match technical-tactical and running performance using a maximum likelihood method and Varimax rotation

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Possessions (> 9 passes)	0.98				
Successful passes	0.97				
TD when own team owns the ball (m)	0.94				
Possessions (0–2 passes)	-0.93				
Passes ending in own team's half	0.91				
Ball possession (%)	0.86				
Passes ending in opponent team's half	0.81				
Possessions (3–5 passes)	-0.78				
Fouls made	-0.73				
SPA when own team owns the ball	0.71				
Possessions (6–8 passes)	0.61				
Possessions ending with a shot	0.59				
Possession length	0.58				
Duels	0.58				
SPD when own team owns the ball (m)	0.50				
Yellow cards	-0.48				
SPA when opponent team owns the ball		0.88			
SPD when opponent team owns the ball (m)		0.85			
TD when opponent team owns the ball (m)		0.63			
Tackles		-0.51			
Fouls received		-0.40			
Shots inside the box (%)		0.39			
Possession width		-0.12			
Goals scored			0.83		
Possessions ending with a goal			0.83		
Shots on target			0.61		
Goals from set play			0.53		
Goals from direct free kick			0.39		
Offsides			0.37		
Goals conceded			-0.35		
Possessions starting in middle third				0.82	
Passes made in the final third				0.79	
Possessions starting in attacking third				0.73	
Recoveries				0.62	
Possessions ending in attacking third				0.61	
Second yellow cards				-0.27	
Aerial duels				0.23	
Attempted crosses					0.85
Successful crosses					0.84
Shots off target					0.71
Chances created from set play					0.60
Corners					0.59
Goals from corners					0.49
Red cards					0.12
% of variance	**26**	**7**	**9**	**9**	**10**

TABLE 3. Multiple linear regression analysis assessing the association between team success and match performance in the first and second division of LaLiga

		B	*p*
Intercept		50.221	0.000
Second division	0.418	12.108	0.001
Aerial duels	0.113	0.591	0.313
Second yellow cards	-0.059	-20.479	0.610
Red cards	0.010	4.899	0.942
Possession width	-0.032	-0.603	0.783
F1	0.220	3.186	0.068
F2	-0.102	-1.436	0.248
F3	0.656	9.365	0.000
F4	0.136	1.938	0.166
F5	0.004	0.0627	0.976
Second division * Aerial duels	0.146	1.248	0.175
Second division * Second yellow cards	-0.048	-24.998	0.653
Second division * Red cards	0.026	16.525	0.838
Second division * Possession width	0.153	3.736	0.193
Second division * F1	0.154	4.187	0.140
Second division * F2	0.228	5.473	0.013
Second division * F3	0.091	2.554	0.301
Second division * F4	-0.091	-2.037	0.345
Second division * F5	0.060	1.641	0.631

β: standardized regression coefficient; B: non-standardized regression coefficient

higher-ranked teams had better technical-tactical performance than lower-ranked teams in both offense- and defense-related variables [7, 8, 18–20]. For example, a recent study in the German Bundesliga [7] showed significant correlations between the total of points obtained at the end of the season and both offense-related (e.g., goals scored: r = 0.90; assists: r = 0.88; successful passes from open play: r = 0.78; or ball possession ratio: r = 0.78) and defense-related variables (e.g., allowed shots on goal: r = -0.87; goals conceded: r = -0.81; or saved shots on goal by the goalkeeper: r = 0.70). Moreover, a systematic review investigating how to be successful in soccer concluded that the most influential technical-tactical variables were goals per shot, shots on goal, possession, and successful passes [21]. However, team success is also dependent on contextual variables such as quality of opponent and match location, which may play an important role as well [21].

Another novel finding of this study was that a significant interaction between the second division of LaLiga and F2 was observed. This factor, which correlated with match running performance variables (i.e., TD, SPD, and SPA when the opponent team owns the ball) and technical-tactical variables (i.e., fouls received, tackles, and shots inside the box) was a significant contributor to team success in the second division of LaLiga. This may be due to the effect of situational variables such as scoreline. For example, winner teams may spend more time preventing the opponents from scoring, which may imply greater physical efforts to avoid counterattacks, stay compact, and defend the area and goal. However, previous studies observed significant negative associations between team success and distance covered without ball possession in professional soccer leagues [5, 6]. In addition, our results showed that TD, SPD, and SPA with ball possession had a positive correlation with F1, which was significantly correlated with team success at the 0.1 level (p = 0.07). Specifically, F1 was mainly associated with variables related to ball possession, which suggests that higher-ranked teams have greater tactical awareness or technical ability to possess and run with the ball [22]. The above notwithstanding, match running performance seems to play an essential role in team success, especially in current soccer matches, demanding greater distance covered a and total number of actions performed at high intensity [11, 23].

This study presents some limitations which need to be acknowledged. For instance, no internal load variables (e.g., mean heart rate) were collected. Also, additional external load variables (e.g., a total of accelerations or decelerations) could be included in future studies.

Also, the influence of different contextual variables (e.g., length of the microcycle, match location, or scoreline) on match performance were not considered [24–26]. In addition, only two seasons were analyzed. Consequently, it may be of interest for future studies to consider these limitations to further analyze match running and technical-tactical performance in professional soccer.

CONCLUSIONS

Sports science, coaching, and medical staff may take the results from this study into consideration for developing training strategies. Regarding the technical-tactical performance, teams should focus on drills that enhance shooting accuracy and the total of shots performed in match play. However, defensive skills need to be reinforced considering the importance of goals conceded for team success. When it comes to match running performance, teams are encouraged to focus on offensive actions, in which they possess and run with the ball (especially at high speed) and defensive actions in which the players perform continuous and high-intensity physical efforts to prevent the opponents from scoring, avoid counterattacks, stay compact, and defend the area and goal. In this regard, strength and conditioning coaches need to train transitional play since running performance significantly increases during transitions [27]. Sprinting actions with and without ball possession are crucial and should be applied in training, not only by professional soccer players but also by players who aspire to be selected to play professionally. In this regard, medium- and large-sided games can be implemented to ensure high-speed running and sprinting exposure [28]. Moreover, players should be trained to perform at maximum intensity during the most demanding passages of play [29–31] while integrating a contextualized approach [32, 33].

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Conflict of Interest Disclosure

None of the authors have a conflict of interest to declare, and all authors were involved in the study design, data collection and interpretation, and contributed to the writing of the manuscript. This manuscript is original and not previously published, nor is it being considered elsewhere until a decision is made regarding its acceptability by the journal.

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Accuracy of flight time and countermovement-jump height estimated from videos at different frame rates with *MyJump*

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ABSTRACT: Recent improvements in smartphone video technology may provide sufficient accuracy for estimation of jump height via flight time determined from video recordings of vertical-jump tests. The aim of this study is to evaluate the accuracy of jump height estimated from videos at different frame rates. High-definition videos of 10 young adults (6 males, 4 females) performing 5 countermovement jumps were recorded at a frame rate of 1000 Hz and transcoded to frame rates of 120, 240, and 480 Hz. Flight time in the videos was assessed independently by three observers at each of the four frame rates with *MyJump*. Flight time and jump height were analyzed with mixed models for estimation of means and of standard deviations representing technical error of measurement (free of within-subject jump-to-jump variability) at each frame rate. The four frame rates and three observers produced practically identical estimates of mean jump height. The technical errors at 120, 240, 480 and 1000 Hz were respectively 3.4, 1.8, 1.2 and 0.8 ms for flight time, and 1.4%, 0.7%, 0.5% and 0.3% for jump height. Assessed relative to either differences in jump height between elite football players (standard deviation of ~12%) or the smallest expected test-retest variability (typical error of ~3%), the technical error was substantial at 120 Hz but negligible at 240 Hz or higher. In conclusion, use of frame rates above 240 Hz to estimate jump height with *MyJump* will not improve accuracy substantially.

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INTRODUCTION

With the advent of smartphones, digital video cameras with high resolution and high frame rate capabilities have increasingly become available to a consumer level. Consequently, the use of mobile applications for time-based measurements with video analysis for sport sciences has risen. Through video observation, manual digitization is required from the user once the execution has been recorded to localize specific events. Examples of such events are initial and end frames in order to calculate barbell velocity on bench-press exercise [1], different markers that athletes cross while running to measure sprint performance outcomes [2], contact and take-off instants for each foot in treadmill to estimate running mechanics [3] or take-off and landing instants to compute vertical jump height from flight time [4]. All these applications take advantage of the high speed capability of current smartphones and tablets since they are cost effective and easy to use.

For the case of vertical jump height measurement, high-speed video recordings allows the user to manually select the frames closest to both take-off and landing events by visual observation. Then, the app counts the number of video frames between such events and computes flight time using frame rate duration and a basic kinematic equation [5]. One of the most popular smartphone applications, *MyJump*, has been validated with video frame rates of current smartphones, 120 Hz [6] and 240 Hz [4] and also tablets working at 60 Hz [7]. These video frames rates are a fraction of the typical sampling frequencies of 1000 Hz in laboratory-based instruments, such as force plates and jump mats [8]. Just recently, some smartphone models have been launched with very high frame rate video recording capabilities, equalizing the sampling capacity of sport sciences instrumentation. Due to the technological developments, it is expected that consumer end segment smartphone will soon include very high video sampling frame rates, similar to laboratory-based instruments. As of 2022, Sony and Samsung offer image sensors of 1280×720 pixels image resolution at native framerate of 960 Hz.

Authors of the first study with a smartphone capturing at 120 Hz suggested that future technical improvements might result in improved accuracy [6]. However, there are a number of drawbacks in working with ultra-high speed video frame rates. From a technical perspective, the demand for electronic devices to record, process and storage high-speed video recordings is huge [9, 10]. Also, since the main source of data is human observation, it is unclear that an increase in video frame rate would result in an effective rise of accuracy in outcomes due to hesitation in selecting the right key frame, providing the time difference between frames is low enough to look alike. In a review of the use of *MyJump*, smartphones operating at

240 Hz did not appear to offer substantial improvements in observation accuracy in jump performance [11]. The aim of this study was therefore to determine if ultra-high video speed would enhance observation accuracy. Our approach was to partition and estimate the contributions of technical error and biological variability to error of measurement in jump height at various frame rates from 120 Hz to 1000 Hz. We also used this approach to analyse and review the accuracy of *MyJump* in previous studies.

MATERIALS AND METHODS

Subjects

Ten healthy sport sciences students (four females, six males) volunteered to participate in the present study (age 23.1 ± 2.5 y; height 172.0 ± 8.0 cm; Body mass 68.3 ± 11.3 kg). Subjects were a sample of recreational active students with a broad range of abilities and training. None of them showed any lower-limb injury nor they were medicated. Subjects were instructed not to drink alcohol or caffeinated beverages for 24 h before testing. All jumps were performed by each subject at the same time of the day to eliminate effects of circadian rhythm. This study was approved by the Human Research Ethics Committee of the University of Alicante (IRB No. UA-2019-02-25). Each participant signed a written informed consent before participation.

Instrumentation

The study was conducted in a sports biomechanics laboratory. A commercial high speed camera Sony DSC-RX100 IV (Sony Co., Ltd., Tokyo, Japan) was used to record both feet in frontal plane at approximately 1.5 m in order to observe take-off and landing instants, following the guidelines of *MyJump* [6]. The camera was placed on a tripod at a height of 30 cm for all recordings and the focal distance was set to adjust an optimal view of the participant's feet. All trials were captured in high definition (1920 × 1080 pixels, progressive video) and maximum frame rate (1000 Hz), with a shutter speed of 1/32000 s. To compensate the loss of light entering the sensor when working at such high shutter speeds, two Dexel LFS-4/55 lights (Dexel, S.R.L., Buenos Aires, Argentina) where set symmetrically around the subject in the frontal plane.

As shown in Figure 1, video recordings at 1000 Hz were transcoded to generate versions of the same footage at 120, 240 and 480 Hz by means of frame decimation with the ffmpeg command line tool (www.ffmpeg.org). Then, for all observers, videos were analyzed with *MyJump* 2 (v.6.1.5) on the same MacBook Air laptop (Apple Inc., California, USA) with 13.3" screen and 1440 × 900 pixels resolution.

Procedures

This was an observational study consisting of repeated measurements on participants during a single testing session. After a standardized warm-up period of 5 min on a cycle ergometer set up at 80 W power load [12], the subjects performed several familiarization jumps followed by five repetitions of countermovement jumps (CMJ) with a rest period of 1 min between jumps. Subjects flexed knees to an angle of 90 degrees, which was controlled by real-time video analysis in the sagittal plane through digitizing software, and jumped to maximum effort in a continuous movement with hands on hips. If subjects failed to follow the above guidelines, they were instructed to repeat any jump performed incorrectly.

Once all executions were recorded and processed to obtain the four frame rate videos, jump height was assessed by three independent observers with past experience of *MyJump*. Before assessment, observers performed a training phase to agree on criteria when selecting video key frames: the first frame displaying both feet off the ground as take-off instant and at least one foot touching the ground as landing instant [13]. The difference between these time events is flight time. Jump height can easily be computed following the equation described in the literature [5], $h = t^2g/8$, where h is jump height (m), t is flight time (s) and g is the gravity acceleration (9.81 m/s^2). This equation is used natively in *MyJump* to display jump height on screen [6]. In all cases, observers visualized video recordings independently to each other to avoid cross influences. The videos were not analyzed with any consistent ordering of the frame rates or participants.

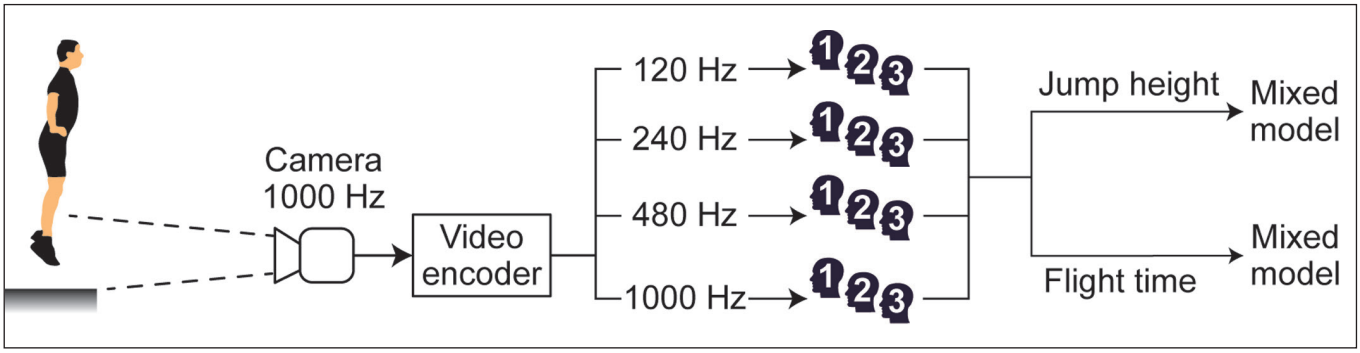


FIG. 1. Graphical representation of the procedure. Countermovement jumps were video recorded at 1000 Hz, resampled to 120, 240, and 480 Hz, coded by three observers, and analyzed for technical errors in flight time and jump height with mixed models.

Statistical Analyses

Jump height and flight time were analyzed separately with mixed linear models, realized with Proc Mixed in the Statistical Analysis System (version 9.4, SAS Institute, Cary NC, USA). The measurements for the four frame rates by the three observers were effectively simultaneous, allowing measurement error for each jump to be partitioned into subject variability and technical error. The fixed effects were trial (five levels), observer (three levels), frame rate (four levels), and the interaction of trial and frame rate (to estimate the means for each jump and the mean paired differences between frame rates and between observers). The random effects, estimated as variances and expressed as SDs, were the identity of the participant (to estimate true mean differences between subjects), the interaction of trial with identity of the participant (to estimate the variability arising from the participant for each jump), and a different residual random error for each of the four frame rates (to estimate the technical error arising from each frame rate for each jump). Jump height was log-transformed for the analysis, and effects and errors were back-transformed to percent units. Flight time was expressed in milliseconds and was analyzed without transformation.

Previous studies of the accuracy of jump height with *MyJump* did not use mixed modeling to extract components of variance, but comparisons of jump height measured with flight time via *MyJump* and either a contact platform or a force plate should yield an estimate of the technical error with *MyJump*, on the basis of the reasonable assumption that the technical error with a contact platform or a force plate is negligible in comparison with that of *MyJump*. For comparison with our estimates of technical error, we derived the technical error from published studies by three methods: the SD of the difference scores (sometimes estimated from the limits of agreement in a Bland-Altman plot) [4, 6, 14–16]; the standard error of the estimate, derived by combining the between-subject SD with a Pearson correlation [4, 6, 14, 15] or an intraclass correlation [16] between the flight times; and the standard error of measurement, derived by combining the between-subject SD with an intraclass correlation coefficient (ICC) for two raters evaluating the same videos [15] or for one rater re-evaluating the same videos [4]. The correlations were often shown as 0.99, which results in considerable uncertainty in the estimate of the technical error, depending on whether the actual value was 0.985, 0.994, or even 0.999 truncated to 0.99, so we used estimates derived from such correlations only as a check on those derived from the difference scores.

Magnitudes of differences between means and of the technical errors were evaluated using standardization, by dividing the difference and errors by an appropriate between-subject SD. Sampling uncertainty in effects and SD is shown as 90% compatibility limits (90%CL), derived by assuming a normal sampling distribution (*t* for effects, *z* for random-effect SDs squared, and chi-squared for residual variances; 90%CL shown in ± form for SD and ×/÷ form for residuals are approximate). Decisions about magnitudes accounting for the uncertainty were based on one-sided interval hypothesis tests, where an hypothesis of a given magnitude (substantial, non-substantial) was rejected if the 90% compatibility interval fell outside that magnitude [17]. The *p* value for a test was the area of the sampling distribution of the effect (*t* for means, *z* for variances) falling in the hypothesized magnitude, with the distribution centred on the observed effect. Hypotheses of inferiority (substantial negative) and superiority (substantial positive) were rejected if their respective *p* values (p_- and p_+) were < 0.05; rejection of both hypotheses represents a decisively trivial effect in equivalence testing. Hypotheses of non-inferiority (non-substantial-negative) or non-superiority (non-substantial-positive) were rejected if their respective p values ($p_{N-} = 1 - p_-$, $p_{N+} = 1 - p_+$) were < 0.05, representing decisively substantial effects in minimum-effects testing. The area of the sampling distribution falling in substantial or trivial magnitudes was also interpreted as the posterior probability of a substantial true magnitude of the effect in a reference-Bayesian analysis with a minimally informative prior [18] using the following scale: > 0.25, possibly; > 0.75, likely; > 0.95, very likely; > 0.995, most likely [18]. Probabilities were not interpreted for unclear effects: those with inadequate precision at the 90% level, defined by failure to reject both substantial hypotheses ($p_- > 0.05$ and $p_+ > 0.05$).

The between-subject SD chosen for standardizing was not that of the subjects in our study, since they do not represent a sample of a population of competitive athletes. Instead, we obtained SD from recent studies on CMJ height of elite male [19–22] and female [23–26] football players. The SD were expressed as coefficients of variation (CV), converted to factors, log-transformed, averaged (via equally weighted variances) and back-transformed.

The technical error in jump height at a given frame rate was also evaluated for magnitude by consideration of how it adds to the biological variability in jump height to give the typical error of measurement. Again, in respect of biological variability, the subjects in the present study are not representative of the kind of competitive athletes who are routinely monitored for jump height. The subjects in one study were competitive athletes [14], and this study also provided the typical error. The typical errors of jump height of athletes in an earlier review [11] were also considered.

RESULTS

The between-athlete SD in studies of elite football players were 14% and 10% for females and males, and the mean was 12%. Magnitude thresholds for small and moderate mean effects, given by 0.2 and 0.6 times the mean CV (via logs), were 2.3% and 7.1% respectively. The thresholds for standard deviations were half those for means [27], 1.2% and 3.5%.

Jump height across all trials, observers and frame rates was 31.7 ± 5.6 cm (mean ± SD). Differences between mean jump heights were most likely trivial for every pairwise comparison of frame rate, the biggest difference being 0.1% (90%CL ± 0.1%; rejection of both substantial hypotheses, $p < 0.005$). The three pairwise differences between means for observers at each frame rate were also most

TABLE 1. Technical error arising from the four video frame rates.

Frame rate (Hz)	Technical error			
	(ms)	(%)	90%CL	Magnitudea
120	3.4	1.4	×/÷1.14	small*
240	1.8	0.7	×/÷1.11	trivial^{00}
480	1.2	0.5	×/÷1.11	trivial^{00}
1000	0.8	0.3	×/÷1.10	trivial^{00}

90%CL, factor 90% confidence limits. [a]Magnitude of the observed error in relation to threshold for small of 1.2% for jump height (0.1 of the SD of elite footballers). Reference-Bayesian likelihoods of true substantial magnitude: *very likely (rejection of the non-superiority hypothesis ($p = 0.02$). Reference-Bayesian likelihoods of true trivial magnitude: ^{00}most likely (rejection of superiority and inferiority hypotheses ($p < 0.005$).

likely trivial (rejection of both substantial hypotheses, $p < 0.005$), the biggest differences for frame rates of 120, 240, 480 and 1000 Hz being respectively 1.7% (± 0.5%), 1.4% (± 0.2%), 1.1% (± 0.2%), and 0.8% (± 0.1%). Differences between means for trials were also all trivial, but all were unclear (rejection of no substantial hypotheses, $p > 0.05$), the biggest difference being 2.1% (± 4.6%), for the last minus the first trial.

The random effects in the mixed model provided estimates for pure differences in jump height between subjects of 19% (90%CL ± 10%) and pure within-subject variability between jumps of 6.4% (± 1.3%). These SD relate to the ability and reproducibility of jump performance of the subjects, but they are not relevant to the evaluation of the technical error at each frame rate provided by the residuals.

TABLE 2. Estimates of technical error in various units by comparison of flight time measured with *MyJump* and a jump mat or a force plate, or with repeated use of *MyJump* on the same jumps. Estimates were obtained via difference scores and via correlations. Studies are sorted in approximate order of increasing technical error. Frame rate was 120 Hz in [6] and 240 Hz in all other studies. All subjects performed countermovement jumps; subjects in two studies [4, 14] also performed drop jumps. The uncertainty in factor 90% compatibility limits (90%CL) applies to both measures and all units of technical error.

Study	Subjects	Jumps	Data	Mean ± SD (cm)	TE via difference scores				*r* or ICC	TE via *r* or ICC		
					(cm)	(%)	(ms)	90%CL		(cm)	(%)	(ms)
Carlos-Vivas et al., 2018 [16]	29 M & 11 F	5	FP	28.7 ± 7.2	0.3	0.9	2.1	×/÷1.10	1.00[a]	-	-	-
Balsalobre-Fernández et al., 2015 [6]	20 M	5	Day 1, JM	35.2 ± 5.4	0.5	1.4	3.8	×/÷1.14	0.995	0.5	1.5	4.1
Gallardo-Fuentes et al., 2016 [14]	14 M athletes	5	Day 1, JM	40.0 ± 6.9	0.6	1.5	4.3	×/÷1.18	0.99	1.0	2.4	6.9
			Day 2, JM	39.2 ± 6.7	0.7	1.8	5.0	×/÷1.18	0.99	1.0	2.4	6.8
	14 M athletes (drop jump)	5	Day 1, JM	33.2 ± 5.4	0.8	2.4	6.3	×/÷1.18	0.99	0.8	2.3	6.0
			Day 2, JM	33.5 ± 6.2	0.7	2.1	5.5	×/÷1.18	0.99	0.9	2.6	6.8
Stanton et al., 2017 [4]	19 F & 10 M (drop jump)	2	Day 1, FP	19.4 ± 8.4	0.6	3.3	6.5	×/÷1.25	0.999	0.6	3.3	6.5
			Day 1 & 8[b]	19.2 ± 8.4	0.4	2.0	4.0	×/÷1.25	0.99	1.2	6.2	12
Gallardo-Fuentes et al., 2016 [14]	7 F athletes	5	Day 1, JM	28.4 ± 5.7	0.9	3.2	7.6	×/÷1.27	0.98	1.1	4.0	9.6
			Day 2, JM	29.2 ± 5.8	1.4	4.8	12	×/÷1.27	0.97	1.4	4.8	12
	7 F athletes (drop jump)	5	Day 1, JM	27.9 ± 2.9[b]	0.7	2.5	6.0	×/÷1.27	0.98	-	-	-
			Day 2, JM	27.7 ± 4.7	0.7	2.5	6.0	×/÷1.27	0.97	1.1	4.1	9.8
Stanton et al., 2017 [4]	19 F & 10 M	2	Day 1, FP	20.6 ± 8.5	1.5	7.5	15	×/÷1.25	0.998	0.8	4.1	8.4
			Day 1 & 8[c]	20.3 ± 8.4	0.5	2.5	5.1	×/÷1.25	0.99	1.2	5.9	12
Driller et al., 2017 [15]	30 M & 31 F	2	Obs 1 & 2[d]	26.8 ± 7.5	-	-	-	×/÷1.16	0.97	1.3	4.9	11

SD, standard deviation; TE, technical error; 90%CL, factor 90% compatibility limits; r, Pearson correlation coefficient; ICC, intraclass correlation coefficient; M, Male; F, Female; FP, Force plate; JM, Jump mat; Obs, observer. [a]Value provided by authors does not permit estimation of TE. [b]SD is too low, presumably a typographical error; TE via r therefore not estimated. [c]Jumps re-analyzed by same observer one week later. [d]Jumps analyzed by two observers; data not provided for difference scores.

Plots of residuals vs predicteds from the mixed models for jump height and flight time showed no evidence of non-uniformity. The mixed model did not permit separate estimation of technical error for each observer, but the SD of residuals for each observer showed differences from each other that would be expected, given their sampling uncertainty, hence estimation of a single SD for technical error for the three observers was justified. Technical errors from the analysis of flight time and jump height at the four frame rates are shown in Table 1. Uncertainties in these errors evaluated relative to magnitude thresholds provided by the between-subject SD for elite football players showed that the error was small at 120 Hz and negligible at higher frame rates.

Table 2 summarizes data from published studies of technical error in jump height measured with *MyJump* derived from difference scores and correlation coefficients. Technical error in the only study conducted with a frame rate of 120 Hz [6] was ~4 ms (~1.5%). Frame rate in all the other studies was 240 Hz; the lowest error was 2.1 ms (0.9%), while the other errors ranged from 4.1 to 15 ms (1.5 to 7.5%). The errors were generally larger when estimated via correlation coefficients than via difference scores.

DISCUSSION

The aim of this study was to evaluate errors in jump height estimated from videos at different frame rates with *MyJump*. Assessed against smallest important differences in jump height defined by standardization with elite footballers, differences in the mean jump height between video frame rates were trivial, indicating no systematic error in using any of the video frame rates. There were also trivial differences in mean height between the three observers for all the frame rates. The technical error was trivial at frame rates above 120 Hz.

A smallest important difference of 2.3% in jump height was calculated from published studies of elite male and female football players performing CMJ tests with a mean between-subject standard deviation of 12%. Although the SD for the differences between subjects in our study was higher (19%), the selection of the smallest important for elite football players is appropriate, since the aim was to test the ability of the instrument to monitor changes in jump performance for such athletes.

Although ours is the first study to estimate technical error in jump height from videos with a range of frame rates, we can compare our findings with those from studies using only one frame rate. In the only previous study that was performed with a frame rate of 120 Hz [6], the estimates of technical error in time or percent units were similar to ours (~4 ms, ~1.5%). Frame rate in the other studies [4, 14–16] was 240 Hz, but the errors were similar to ours in only one study [16] (~2 ms, ~1%) and were otherwise at least 50% and mostly several times larger. The largest error (15 ms, 7.5%) in the study of Stanton et al. [4] seems unrealistic and may have been due to a typographical or computational error. The tendency for higher values via correlation coefficients probably reflects authors providing insufficient decimal places for correlations of ~0.99 and/or truncating the correlations (e.g., reporting 0.997 as 0.99). The uncertainty in the estimates of technical error expressed as factor 90% compatibility limits ranges from $\times/\div 1.10$ to $\times/\div 1.27$, which is insufficient for sampling variation to explain the wide range in technical error between studies. The only plausible explanation for the wide range is that detection of the frames representing take-off and landing is problematic on some smartphones or in some settings, depending on the disposition of the phone, the subject, and lighting [9].

Assessed relative to thresholds for errors derived from the between-subject SD for elite football players, the technical error of jump height using *MyJump* with a frame rate of 240 Hz is substantial in most settings. However, the technical error can also be assessed by consideration of the extent to which it contributes to the test-retest typical error. The lowest typical errors in the *MyJump* studies were 3.1% via flight time with a force platform, 3.3% via flight time with *MyJump*, and 3.6% via take-off velocity with a force platform, for 29 male and 11 female recreationally active students [16]. *MyJump* provided similar values of 3.4% and 3.6% for two different raters of 20 active men [6]. Larger values of 3.9% and 4.5% were obtained for 14 male and seven female athletes respectively with *MyJump*, and 3.9% and 6.3% respectively via flight time with a contact platform [14]; this study also produced estimates for 1-week test-retest errors of 4.6% and 7.5% for males and females with *MyJump*, and 4.6% and 7.8% with the contact platform. Values for the typical error of measurement of various jumps with various times between jumps ranged from ~3.5% to ~5.0% in an early review [11]. We conclude that the smallest error of measurement likely to be encountered when testing athletes is ~3.0%. The technical error of 1.4% we and one other group [6] observed with a frame rate of 120 Hz would increase this typical error to $\sqrt{(3.0^2 + 1.4^2)} = 3.3\%$. While this increase may seem negligible, it would represent the need to increase sample size or number of repeated measurements by a factor of $(3.3/3.0)^2 = 1.21$ or 21% to get the same precision of the estimate of a mean change score. We therefore recommend use of 240 Hz, since the technical error of 0.7% will add to a typical error of 3.0% to give a negligible increase to 3.1%.

Our study has shown that, under presumably near-optimal conditions of video assessment, the contribution of technical error arising from the frame rate itself at 240 Hz and higher frame rates is negligible. The larger technical errors observed in some settings would therefore not be reduced by increasing the frame rate. Instead, researchers or practitioners should increase the number of repeated jumps that each athlete performs on each testing occasion, then average the values, with the aim of reducing the error below the smallest important derived from the between-athlete SD. For example, with an SD of 12% for elite football players, the smallest important error is 1.2% (0.1xSD). If the typical error between repeated jumps when testing these athletes with *MyJump* (or indeed with any other device) is 4.0%, then the number of jumps n needed to give an error less than 1.2% is given by $4.0/\sqrt{n} < 1.2$, i.e., $n > 11$. It is

important to understand that increasing the number of jumps in a given testing session will not reduce any increase in test-retest error arising from real changes in individuals *between* sessions days or weeks apart, but it will improve the precision of the estimates of such changes in each individual.

The main limitation of this study is the use of only three observers. Although there were trivial differences in mean height between the three observers for all the frame rates, a study with a larger number of observers using *MyJump* is needed to determine whether a substantial proportion of observers have systematic bias. The sample size of 10 participants was not in itself a limitation, because the large number of jumps performed and analyzed resulted in useful conclusions about the technical error at each frame rate. However, it is possible that differences in jumping styles between participants could result in perceptible differences in deciding which frames show the beginning and end of contact with the floor. Further study of technical error with athletes, rather than sport science students, would resolve this issue.

CONCLUSIONS

Coaches and trainers can use a video frame rate of 240 Hz with *MyJump* to monitor athletes' countermovement jump height. The use of high speed video recordings above 240 Hz for manual digitizing is unnecessary, because the technical error due purely to frame rate is negligible in comparison with the day-to-day biological variability in jump height and technical errors of up to 5% arising from *MyJump*. The contributions of technical error and biological variability to error of measurement of jump height can be reduced by averaging performance of multiple jumps.

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Conflict of interests

The authors have no conflicts of interest to declare.

Author contribution

Research concept and study design (B. Pueo, W.G. Hopkins, J.M. Jimenez-Olmedo), literature review (B. Pueo, A. Penichet-Tomas, J.M. Jimenez-Olmedo), data collection (B. Pueo, J.M. Jimenez--Olmedo), data analysis and interpretation (B. Pueo, W.G. Hopkins), statistical analyses (B. Pueo, W.G. Hopkins), writing of the manuscript (B. Pueo, W.G. Hopkins, A. Penichet-Tomas, J.M. Jimenez-Olmedo), or reviewing/editing a draft of the manuscript (B. Pueo, W.G.Hopkins, A. Penichet-Tomas, J.M. Jimenez-Olmedo). All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

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Optimal velocity loss threshold for inducing post activation potentiation in track and field athletes

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ABSTRACT: The aim of this study was to determine the optimal velocity loss (VL) threshold that maximises the post activation potentiation (PAP) stimulus for achieving larger and more consistent performance gains in track and field athletes. Twenty-two athletes from athletics participated in four back squat PAP tests with four different VL threshold (5%, 10%, 15% and 20% VL) at an intensity of 85%1RM. Countermovement jump (CMJ) height, power, and momentum were assessed before, and 10 s, 4, 8, 12, 16 minutes after the PAP condition. Repetitions of the squat in all the PAP conditions were also recorded. Only the 5% VL condition produced significant improvements in height (ES = 0.73, P = 0.038), peak power output (ES = 0.73, P = 0.038) and momentum (ES = 0.72, P = 0.041) of CMJ, and these changes appeared 8 minutes after the condition. The total number of repetitions during the 5% VL condition was significantly lower than that observed in the 15% (P = 0.003) and 20% VL (P < 0.001) trials. The results from this study indicate that 5%VL during the 2 sets preconditioning squat at 85%1RM was optimal for eliciting PAP in a CMJ exercise, and resulted in significant increases at the 8-min recovery period. The same squat condition also had the least number of repetitions. However, considering the efficiency in practice, athletes can also choose the rest time of 4-min, which can also achieve similar results.

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Jump height
Peak power output
Momentum
Squat

INTRODUCTION

Post-activation potentiation (PAP) is a physiological phenomenon characterized by the acute increase of muscle force, speed or explosive force after maximal or near maximal intensity resistance exercise [1]. PAP has attracted wide attention as a training and research phenomenon. Previous studies have shown the acute and chronic effects of PAP either in the form of a warm-up [2–4] or contrast training [5–7]. The effects of PAP depend on the mutual relationship between the enhancement and fatigue induced by a pre-loading stimulus [8]. Evidence indicates that only when the enhancement is greater than the fatigue, will PAP be induced, and transiently improve subsequent performance [8].

Traditionally, percentage of maximum repetition (%1RM) and fixed repetitions [9] have been applied to prescribe the load used in any given training program. However, these methods may have some inherent drawbacks owing to individual variability of fatigue at any given number of repetitions or fixed intensity [10]. Moreover, the maximum strength of the individual will fluctuate from day to day, due to the influence of nutrition, exercise and circadian rhythm [11]. As such, the use of %1RM may attenuate any possible enhancements in performance due to a mismatch between the target intensity and the actual intensity needed by the individual at any given time [12]. Consequently, the individual effects of PAP via these traditional methods may lead to a lack of enhancement or excessive fatigue.

Recently, there has been increasing evidence showing that velocity-based training (VBT) is effective in controlling fatigue levels and accurately estimating resistance load in real time [12, 13]. Weakley et al. [14] found that under the same load, with increasing levels of velocity loss (VL), the concentration of RPE and blood lactate at the end of strength training gradually increased, while vertical jump height gradually decreased. Thus, it could be argued that VL is just as an effective method when prescribing training programs, with the intention of avoiding excessive fatigue and achieving the same level of acute stimulation [13], compared with the aforementioned traditional methods. We speculate that different VL thresholds with the same intensity will produce different training effects, with 20–40% VL more conducive to muscle hypertrophy, and < 20%VL more conducive to the development of strength [15–17]. However, with a distinct lack of evidence in this specific area, it remains unclear whether the use of VBT is a viable method for inducing a PAP stimulus in athlete populations.

The traditional PAP condition measures the load by the percentage of maximum repetition (%1RM) and a fixed number of repetitions. This ignores the individual variability of fatigue, which can subsequently impact whether PAP occurs. Therefore, the present study aimed to compare four different VL (5%, 10%, 15% and 20%) conditions to determine the optimal VL threshold which could produce the best PAP response. Given that 5% VL is likely to generate less fatigue than 10–20% VL [14, 18], our hypothesis was that the 5% VL would be the optimal VL threshold in comparison with the other conditions. Our results would help practitioners better prescribe training programs using VBT methods, with the intention of providing an acute PAP response.

MATERIALS AND METHODS

Experimental Approach to the Problem

This study adopted a repeated measures randomized cross-over design to evaluate the PAP effects of squatting on CMJ performance, while using four different VL thresholds (5%, 10%, 15% and 20%). All subjects initially participated in a 1RM back squat test and four PAP squat tests with a minimum of 48-h apart, but at the same time of the day. Each PAP test corresponded to one of the four VL thresholds. CMJ performance was assessed prior to and post each PAP condition.

Subjects

Twenty-two male athletes from athletics (high jump, long jump, three step jump, discus, hammer, 110-meter hurdles, 400-meter hurdles, 100-meter race, 200-meter race, 400-meter race) (Table 1) volunteered to participate in this study in their respective off-season, with written informed consent provided by all. All subjects were clear of cardiovascular or respiratory disease, and free from injury at the time of testing. All subjects were experienced in squat exercises (5.8 ± 2.6 years). Any strenuous activities such as resistance or plyometric training were refrained for at least 48-hours before each testing session. The study was approved by the local ethics committee.

TABLE 1. Physical characteristics of subjects at baseline (n = 22)

Variables	Mean ± SD
Age (years)	21.1 ± 2.0
Height (cm)	180.3 ± 6.1
Body mass (kg)	75.1 ± 9.9
Resistance training experience (years)	5.8 ± 2.6
1RM (kg)	144.3 ± 22.9
1RM/ body mass	1.9 ± 0.2
Body fat percentage (%)	13.8 ± 4.3

RM = repetition maximum

Procedures

1RM squat test

On the first visit, the subjects had their body mass, height and body fat percentage measured, and performed the 1RM free-weight barbell back squat test. After a standardized warm-up (a five-minute run, dynamic stretching for lower extremities, two 20-meter sprints and three CMJs) the subjects started the test with 40 kg. The test weight was progressively increased with an increment of 20 kg until that the attained mean velocity (MV) was lower than 0.5 m/s. Back squat took the standard technique as described in the NSCA textbook [19], whereby subjects held the barbell in a closed pronated grip, with the barbell positioned on the upper trapezius muscle. Initial posture encouraged participants to position their feet approximately shoulder width apart, with slight external rotation of the feet. Participants were instructed to descend to a depth where the upper thighs were parallel to the ground and then extend the hips, knees and ankles to the initial posture as quickly as possible. Thereafter, the weight was increased with smaller increments (i.e. 5 to 1 kg) individually for each subject, so that 1RM could be determined with precision. The weight that each subject could squat only once with standard technique was considered to be their 1 RM. Trained spotters were present on both sides of the barbell during the squat to ensure safety. Three, two, and one attempts were executed at light (i.e. MV > 0.7 m/s), medium (0.7 m/s ≤ MV ≤ 0.5 m/s), and heavy (MV < 0.5 m/s) loads, respectively. Rest periods were 4-minutes for the light and medium loads, and 6-minutes for the heavy load.

PAP test

The following four visits were for the four PAP conditions which were conducted in a counterbalanced randomized order (Figure 1). During each visit, subjects started with a standardized warm-up, which was the same as the 1RM test. After 5-minutes of rest, subjects performed three CMJs and chose the best as the baseline level. Afterwards, the subjects rested for 3-minutes before performing two sets of squats at 85%1RM [20] with 1-minute rest [21, 22] in between as the PAP condition. In the PAP condition, a 5-cm wide line was marked parallel to the barbell bar and set at 30-cm behind the barbell lever. Subjects were required to place their toes on the line, with their foot as wide as the shoulder (or wider), with toes slightly faced outward. One elastic band with 1-m length was set directly 50–70 cm distance away from the mark line. The height of the band was equal to the squatting depth with thigh parallel to the ground. A GymAware Powertool tachometer (Kinetic Performance, Canberra, Australia) was placed on the floor at right side of the squatting rack with the cable aligned perpendicular to the ground to monitor the velocity of each repetition in real-time. All subjects were verbally encouraged to perform the concentric phase of the lift as ballistically as possible, with real-time auditory feedback of the mean velocity for each repetition.

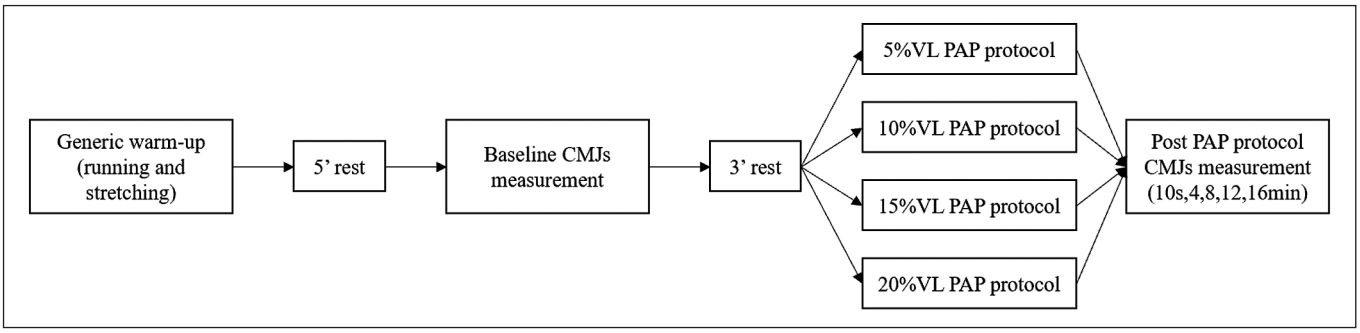


FIG. 1. Schematic representation of PAP test PAP, post activation potentiation; CMJ, counter movement jump.

The VL thresholds were calculated according to the following formula: [stop velocity = initial speed × (1-VL)] [10]. Sets were terminated when the repetition velocity was recorded below the target velocity of each specific zone. The PAP condition design is based on the finding that multiple sets and the high-intensity (≥ 85%1RM) will get better effect of PAP [20], and on the basis of past research to determine between set rest periods of 1-minute [6, 32]. After the two sets of squats, subjects conducted CMJ testing at 10-s, 4, 8, 12, and 16-minutes of the recovery period.

CMJ test

Each assessment of CMJ included 3 trials with 10 s rest between each trial. During each trial, the subjects were in an upright initial position with their hands on hips and their feet approximately shoulder width apart. After hearing the instruction to "jump", athletes performed a countermovement to a self-selected depth (to avoid alterations in jump strategy), before performing an explosive vertical jump. During the flight phase, subjects were required to keep their legs straight and hands on hips throughout [16]. The best of the three trials was chosen for subsequent analysis. Performance variables assessed during the CMJs included jump height, peak power output (PPO) and jump momentum (calculated by multiplying take-off velocity by body mass) [23] using a jump mat (Smartjump, Fusion Sport, Australia). Verbal encouragement was given throughout all CMJs assessments. Room temperature was maintained between 20 and 24°C.

Statistical Analyses

Data were expressed as the mean ± SD. Jump heights, PPOs and momentum in CMJs were then analyzed using a 4 × 6 (VL × assessment time) factorial analysis of variance (ANOVA) with repeated measures. The alpha level was set at $p < 0.05$, and the Huynh-Feldt adjustment was used where required based on a test of sphericity. One-way ANOVA was used to analyze the repetitions of PAP condition. If the homogeneity of variance was satisfied, Tukey test was used for pairwise comparison. Games-Howell test was used to compare the results. Paired samples t-test and Cohen' d effect size were also used to detect the standardized mean differences of jump height, PPO, momentum between the baseline and other time points and the total number of CMJ repetitions between different VL sets. The criteria to interpret the strength of the effect size was as follow: trivial (< 0.2), small (0.2~0.6), moderate (0.6~1.2), large (> 1.2) [24].

RESULTS

Jump Height, Peak Power Output and Jump Momentum

A significant time effect of jump height [$F_{(7.854,164.930)} = 2.303$, $P = 0.024$], PPO [$F_{(7.997,167.946)} = 2.415$, $P = 0.017$] and jump momentum [$F_{(1.868,39.224)} = 11.024$, $P < 0.001$] were found between pretest and posttest in all four PAP conditions (i.e. 4 VL) (Table 2). Post hoc analyses found that at the 10-s of recovery, compared with the baseline, the jump height, PPO and momentum did not change significantly in the 5% VL condition ($P > 0.05$), but decreased significantly in the 10% VL ($P < 0.001$), 15% VL ($P < 0.001$) and 20% VL ($P < 0.001$) condition. At the 8-minute time point, only 5% VL had significant increases compared with baseline data for jump height (ES = 0.73, $P = 0.038$), PPO (ES = 0.73, $P = 0.038$) and momentum (ES = 0.72, $P = 0.041$), while 10% VL ($P > 0.05$), 15% VL ($P > 0.05$) and 20% VL ($P > 0.05$) had no significant changes. There was no significant difference between the jump height, PPO and jump momentum of each VL and the baseline at the 4, 12 and 16-minutes of the recovery ($P > 0.05$) (Table 3).

Number of squat repetitions

The number of squat repetitions in the 2 sets of squats to the 5% VL was significantly less than those to 15% VL ($P = 0.003$), and 20% VL ($P < 0.001$), and 20% VL was significantly more than 10% VL ($P < 0.001$) and 15% VL ($P = 0.002$) (Table 4).

In set 1, squats to the 5% VL were significantly less than those to 20%VL ($P < 0.001$), and 20% VL were significantly more than 10%VL ($P < 0.001$), 15%VL ($P = 0.002$). In set 2, squats to the 5% VL were significantly less than those to 15% VL ($P = 0.040$) and those to 20% VL ($P < 0.001$), and 20% VL were significantly more than 10% VL ($P = 0.023$).

TABLE 2. Jump height, PPO and momentum of CMJ during PAP condition of different VL (n = 22).

CMJ performance variables	VL (%)	Assessment time point					
		Baseline	10 s	4 min	8 min	12 min	16 min
Height (cm)	5	53.43 ± 6.52	51.89 ± 5.95	55.03 ± 7.40	54.88 ± 7.12*	53.98 ± 7.45	53.79 ± 7.09
	10	54.57 ± 6.44	51.13 ± 5.51*	55.12 ± 6.74	55.11 ± 6.65	54.66 ± 6.22	54.08 ± 6.96
	15	54.49 ± 5.66	50.92 ± 6.00*	55.75 ± 6.70	55.49 ± 6.81	54.59 ± 6.93	53.81 ± 6.41
	20	54.43 ± 6.78	50.26 ± 6.12*	55.77 ± 6.45	55.32 ± 6.52	54.74 ± 7.02	54.31 ± 6.25
PPO (W)	5	4589.95 ± 550.54	4496.62 ± 530.30	4686.86 ± 565.86	4677.89 ± 558.92*	4623.34 ± 577.29	4611.69 ± 554.19
	10	4659.42 ± 568.89	4450.48 ± 545.85*	4692.58 ± 569.90	4691.74 ± 547.83	4664.66 ± 540.95	4624.32 ± 582.49
	15	4640.77 ± 479.06	4422.48 ± 495.19*	4713.67 ± 521.57	4714.35 ± 534.90	4658.20 ± 534.63	4604.77 ± 512.70
	20	4650.44 ± 491.68	4397.39 ± 492.40*	4732.04 ± 488.99	4704.58 ± 525.83	4669.83 ± 529.96	4643.29 ± 511.43
Momentum (N·m)	5	242.34 ± 32.30	238.90 ± 31.22	245.71 ± 31.93	245.45 ± 32.29*	243.37 ± 32.49	242.95 ± 31.80
	10	245.08 ± 33.90	237.37 ± 32.88*	246.22 ± 33.60	246.09 ± 32.55	245.20 ± 32.86	243.50 ± 33.83
	15	244.18 ± 29.94	235.81 ± 29.02*	246.79 ± 31.00	246.78 ± 31.56	244.66 ± 31.32	242.74 ± 30.37
	20	244.14 ± 29.09	234.70 ± 28.82*	239.42 ± 45.34	246.44 ± 31.24	245.19 ± 30.73	244.34 ± 30.72

*—significantly different from baseline. PPO, peak power output; PAP, post activation potentiation; CMJ, counter movement jump

TABLE 3. The mean differences between baseline and other time point in Jump height, PPO and momentum

CMJ performance variables	VL (%)	Effect size with 95%CI				
		10 s	4 min	8 min	12 min	16 min
Height (cm)	5	0.56 (0.10, 1.01)	0.69 (0.21, 1.15)	0.73 (0.25, 1.20)	0.23 (-0.20, 0.65)	0.15 (-0.27, 0.57)
	10	1.67 (1.01, 2.32)	0.33 (-0.10, 0.76)	0.26 (-0.17, 0.68)	0.04 (-0.38, 0.46)	0.15 (-0.27, 0.57)
	15	1.29 (0.71, 1.86)	0.59 (0.13, 1.04)	0.41 (-0.03, 0.84)	0.04 (-0.38, 0.46)	0.27 (-0.16, 0.69)
	20	1.53 (0.90, 2.15)	0.69 (0.22, 1.15)	0.42 (-0.03, 0.85)	0.12 (-0.30, 0.54)	0.04 (-0.38, 0.46)
PPO (w)	5	0.56 (0.10, 1.01)	0.69 (0.21, 1.15)	0.73 (0.25, 1.20)	0.23 (-0.20, 0.65)	0.15 (-0.27, 0.57)
	10	1.67 (1.01, 2.32)	0.33 (-0.10, 0.76)	0.26 (-0.17, 0.68)	0.04 (-0.38, 0.46)	0.18 (-0.25, 0.60)
	15	1.29 (0.71, 1.86)	0.58 (0.12, 1.03)	0.41 (-0.03, 0.84)	0.04 (-0.38, 0.46)	0.27 (-0.16, 0.69)
	20	1.53 (0.90, 2.15)	0.69 (0.22, 1.15)	0.42 (-0.03, 0.85)	0.12 (-0.30, 0.54)	0.04 (-0.38, 0.46)
Momentum (N·m)	5	0.53 (0.08, 0.97)	0.64 (0.18, 1.10)	0.72 (0.25, 1.19)	0.19 (-0.23, 0.61)	0.11 (-0.31, 0.53)
	10	1.85 (1.14, 2.53)	0.31 (-0.12, 0.74)	0.22 (-0.21, 0.64)	0.02 (-0.40, 0.44)	0.23 (-0.20, 0.65)
	15	1.31 (0.72, 1.87)	0.59 (0.13, 1.04)	0.48 (0.03, 0.92)	0.08 (-0.34, 0.50)	0.26 (-0.17, 0.68)
	20	1.65 (1.00, 2.29)	0.13 (-0.29, 0.55)	0.45 (0.00, 0.88)	0.18 (-0.24, 0.60)	0.03 (-0.39, 0.45)

PPO, peak power output; PAP, post activation potentiation; CMJ, counter movement jump

TABLE 4. The total number of repetitions in the first and second group of 4 VL conditions

VL(%)	Number of Repetitions		
	Set 1	Set 2	2 sets in total
5	3.2 ± 1.3^{a}	2.3 ± 1.6^{a}	5.6 ± 1.9^{a}
10	4.1 ± 1.3^{a}	3.6 ± 1.5^{a1}	7.6 ± 2.2^{a1}
15	4.7 ± 1.7^{a}	4.2 ± 2.6^{b}	8.9 ± 2.9^{b}
20	6.8 ± 2.8^{b}	5.6 ± 3.0^{b1}	12.4 ± 4.6^{c}

Note: a, b and c are significance symbols, and the values with these symbols are significantly larger or smaller according to the relationship of $a < b < c$, $p < 0.05$. There is no significant difference between a1 and a, b, but it is significantly less than b1.

DISCUSSION

The aim of this study was to determine the optimal VL threshold (i.e. 5%, 10%, 15% or 20% VL) in the back squat at 85%1RM to induce the best PAP effect. The primary findings were that 5% VL threshold resulted in significant increases in CMJ height, PPO and momentum at the 8 min recovery period. The same squat condition also had the least number of repetitions.

This study was among the first to explore the optimal velocity loss threshold for inducing PAP. The findings showed that jump height, momentum and PPO of the subjects increased significantly only after the PAP condition with 5% VL. It is found that muscle contraction produces both enhancement and fatigue, and the PAP effect can be induced only when the enhancement exceeds fatigue [1]. Hamada et al. [25] believed that excessive activation would lead to excessive fatigue effect, and then inhibited the emergence of any PAP effect. Therefore, taking appropriate load to avoid excessive fatigue effect is of great significance to the appearance of PAP effect. Gonzalez-Badillo et al. [10] found that there was a strong correlation($r^2 = 0.83$, SEE = 0.09)between VL and the percentage of repetitions (the number of repetitions completed / the maximum number of repetitions). Weakley et al. [14] found that under the same load, the RPE and concentration of blood lactic acid increased with the increase of VL, while the immediate jump height was the opposite, which indicated that the fatigue effect increases with the increase of VL. In the present study, 10 s after the end of 10%, 15% and 20% VL conditions, the jump height, momentum and PPO of CMJ decreased significantly, the fatigue effect is significant, excessive fatigue finally suppresses the appearance of PAP effect. However, after 10 s of 5% VL condition, the jump height, momentum and PPO were not significantly lower than that of the baseline, and there was no significant fatigue in the subjects, the PAP effect was successfully induced. According to the statistics of the squatting repetitions of the subjects in the experiment, it was found that the difference in load caused by different VL conditions may affect the PAP effect. The total repetitions of the 15% VL and 20% VL conditions were significantly higher than that of the 5% VL condition. Additional load (leading to heightened VL) may contribute to fatiguing effects, which may ultimately suppress the appearance of the PAP effect – something that 5% VL condition did not do. In addition, compared with 10% VL, 15% VL and 20% VL conditions, 5% VL condition resulted in fewer squatting repetitions, so it may also have advantages relating to time-efficiency during training. In summary, it is recommended that practitioners use 5% VL condition to induce the PAP effect. It was found that there were individual differences among the subjects, which was also reflected in the number of squatting repetitions. Furthermore, traditional PAP methods may not be sensitive enough to expose such individual differences. However, using VL as a method to monitor training within sessions is likely to be able to better take into account such individual differences, whilst also achieving the same level of acute stimulation [13]. Meanwhile, it has been proved that the relationship between VL and the percentage of completion repetitions is not affected by exercise level [26] and strength growth [27]. However, these two factors can impact the PAP effect [28]. Therefore, the conclusion of this experiment may be applicable for other athlete populations.

In this study, PAP effect was induced at the 8-minutes of the recovery period after the 5% VL condition, which was similar to that of previous studies [20, 29, 30]. Immediately after PAP condition, the fatigue effect was significantly higher than the enhancement effect, resulting in a decrease in exercise performance, but with the extension of rest time, the muscle enhancement was gradually higher than the fatigue, the PAP effect began to appear and gradually reached the optimal interval time, and muscle contraction marks began to have a positive effect on the subsequent explosive force performance until the PAP effect disappeared [31]. There have been several meta-analyses [20, 29, 30, 32] to explore the optimal interval time of PAP effect. Gouvêa et al. [29] reported that rest intervals of 8 to 12 minutes produced the greatest effect (ES = 0.24). Wilson et al. [30] reported rest intervals of 7 to 10 minutes as the most optimal (ES = 0.70). The results of meta-analysis will be affected by inclusion criteria and the division of intermittent periods, but combined with the results of several meta-analyses, the optimal interval time for PAP seems to be 7–12 minutes. However, PAP effect is a highly personalized phenomenon, the optimal interval time may be influenced by individual factors (e.g. fast muscle fiber ratio, strength level) [28]. Therefore, in practical application, coaches need to conduct further research on individuals if they want to know the optimal interval time for athletes accurately, but considering the convenience and universality of practical use, the best PAP effect can be obtained by combining the 5%VL condition with the interval time of 8 minutes. It is worth noting that under the condition of 5% VL, although the height (55.03 ± 7.40, ES = 0.69), PPO (4686.86 ± 565.86, ES = 0.69) and jump momentum (245.71 ± 31.93, ES = 0.64)

of 4-minutes were not significantly higher than baseline, they were similar to height (54.88 ± 7.12), PPO (4677.89 ± 558.92) and jump momentum (245.45 ± 32.29) recorded at 8-minutes, and still with a moderate improvement. Considering that practitioners may not always have the time to wait 8-minutes to optimize jump performance in practice, the condition of 5% VL at a 4-minute interval may be a viable alternative, with negligible differences in results.

The study also had some limitations which should be noted. First, this study only explored the optimal VL under 85%1RM, but did not carry out with more load intensity. However, 85%1RM is a common intensity used in resistance training [21, 33–35] and helps to distinguish between different VL conditions. Second, this study investigated only male subjects, but previous studies showed that there was no gender difference in PAP effect [36], so the findings of this study are still applicable to females.

CONCLUSIONS

The current findings indicate that if practitioners are using VBT to induce PAP effect, it is advised to use 5% VL, and to leave 8-minutes of recovery between the pre-load stimulus and the explosive activity in order to obtain the optimal benefit. If practitioners do not have the time to wait 8-minutes, they can choose the condition of 5% VL at a 4-minutes interval.

Ethics commite

This study was approved by the Research Ethical Committee of Shanghai University of Sport (approval number: 102772021RT088).

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Conflict of interest declaration

The authors declare no conflict of interest.

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The load-velocity relationship in the jump squat exercise

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ABSTRACT: The purpose of this study was to test the load-velocity relationship in the jump squat (JS) exercise using three different velocity parameters (mean velocity [MV], mean propulsive velocity [MPV], and peak velocity [PV]). Twenty-six male rugby union players (24.3 ± 3.9 years; 1.81 ± 0.09 m; 101.3 ± 15.4 kg) performed a progressive loading test in the JS with loads corresponding to 20, 40, 60, and 80% of the half-squat 1RM (equivalent to 24, 46, 70, and 94% of the estimated JS-1RM). MV, MPV, and PV were continuously recorded during all attempts using a linear velocity transducer. Linear regression models were used to determine the relationships between JS loads and MV, MPV, and PV. Bar-velocity outputs demonstrated high levels of consistency and reliability (coefficient of variation ≤ 5% and intraclass correlation coefficient ≥ 0.90). The predictive power of MV, MPV, and PV were ≥ 91%, for all tested variables ($P < 0.0001$). The equations and bar-velocity values provided in this study can be used by coaches to precisely determine and prescribe JS training loads, from very-light to heavy loading conditions (i.e., ~20–100% JS 1RM).

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INTRODUCTION

Squatting variations are undoubtedly the most frequently used exercises in a wide variety of sport disciplines [1–3]. Whereas "traditional squats" (e.g., front-, half-, or full-squat) are often implemented to develop strength-related qualities (e.g., maximum strength), the ballistic jump squat (JS) is primarily used to increase the ability to apply force at higher velocities (i.e., muscle power) [4–7]. The JS is usually performed with light or moderate loads (i.e., 30–45% of one-repetition maximum [1RM]), prescribed on the basis of the half-squat 1RM (HS-1RM) [4, 8]. Nevertheless, despite their similarities, it is worth noting that HS and JS are different exercises, as the JS can only be executed when a "valid" jump attempt is possible [4, 8].

A recent study sheds light on these mechanical differences, by analyzing the kinematics of the HS exercise during an incremental loading test [8]. In brief, it was observed that at 86% HS-1RM the concentric portion of the lift is entirely propulsive, which means that the athlete does not have to gradually decelerate across the movement in order to stop the barbell [8]. This occurs because the bar-velocity at this load condition is very low (i.e., ≤ 0.4 $m \cdot s^{-1}$), thus preventing the existence of a "braking phase" (i.e., a phase where the force applied by the athlete against the external load is negative) at the end of the lift [8, 9]. From a mechanical perspective, at 86% HS-1RM it is impossible to jump. As a consequence, this relative strength value should be used as a reference for the 1RM in the JS (JS-1RM) [8]. Developing approaches to determine the JS-1RM in a more practical manner (instead of using the time-consuming and demanding HS-1RM measurement) would be relevant for coaches and sport scientists, especially those working in high-performance environments, where time-constraints are a factor.

The load-velocity relationship has been widely used by practitioners to predict loading intensity in several upper- and lower-body exercises [10–14]. A seminal study on the topic stated that "the inextricable relationship that exists between relative load (%1RM) and movement velocity" allows coaches to rapidly determine the 1RM load and the %1RM used with great precision and accuracy [15]. Despite this solid body of evidence, to date, only one study has examined the load-velocity relationship in ballistic versions of the HS. In that study, the authors found strong relationships between %1RM and bar-velocity, for both loaded squat and countermovement jumps (R^2 = 0.88 and 0.96, respectively) [11]. However, the research was conducted with sport science students, with %1RM determined on the basis of the HS-1RM and utilizing only the mean propulsive velocity (MPV) in its predictive models. In this context, it is important to analyze this mechanical relationship in highly-trained subjects, implementing the novel JS-1RM approach in a more comprehensive

manner (i.e., using simultaneously MPV, mean-velocity [MV], and peak-velocity [PV] measures). This is crucial to provide coaches with more precise information regarding the prescription of loaded jumps for elite athletes. Therefore, the purpose of this study was to test the load-velocity relationship in the JS exercise under different percentages of the JS-1RM.

MATERIALS AND METHODS

Participants

Twenty-six male rugby union players from the Brazilian National Team (24.3 ± 3.9 years; 1.81 ± 0.09 m; 101.3 ± 15.4 kg) participated in this study. The study was approved by the local Ethics Committee and all athletes signed an informed consent form prior to participation.

Study Design

This cross-sectional study was designed to test the load-velocity relationship in the JS exercise. Due to the constant training and testing in our facilities, all athletes were well familiarized with testing procedures. The assessments were performed at the end of the preseason period, over two consecutive days. Prior to the testing session, the rugby players performed standardized warm-up protocols including general (i.e., running at moderate pace for 10-min followed by 3-min dynamic stretching and mobility exercises) and submaximal attempts of JS.

Procedures

Maximum dynamic strength in the half-squat and progressive loading test in the jump-squat exercise.

Maximum dynamic strength was assessed in the HS exercise as described previously [16, 17]. Firstly, athletes executed a warm-up set, consisting of 5 repetitions at 50% of the estimated HS-1RM on the Smith-machine device (Hammer-Strength, IL, USA). Subsequently, athletes were allowed up to 5 attempts at approximately 70, 80, 90, and > 95% of the estimated 1RM to obtain the actual HS-1RM value. On the second day, the load-velocity relationship was progressively assessed in the JS exercise, with loads corresponding to 20, 40, 60, and 80% HS-1RM (equivalent to 24, 46, 70, and 94% of the estimated JS-1RM) [8, 16, 17]. For all rugby players, at 80% HS-1RM, the relative contribution of the propulsive phase to the total concentric duration in the HS exercise was ≥ 98% [18]. Athletes were required to perform two repetitions with each relative load and move the barbell as rapidly as possible during the concentric phase of the lift. The measurements were conducted by an experienced researcher who standardized the degree of the knee flexion (i.e., 90° knee angle) through visual inspection [8]. A 3-min rest interval was provided in all trials [8]. MV (mean velocity from the start of the concentric phase until the barbell reaches the maximum displacement), MPV (mean velocity from the propulsive phase), and PV (maximum instantaneous velocity recorded over the entire concentric phase) [19] were continuously measured and recorded at 1000 Hz, using a valid and reliable linear velocity transducer (T-Force System; Ergotech Consulting S.L., Murcia, Spain) attached to the barbell [20, 21].

Statistical Analyses

Data are presented as mean ± standard deviation. A linear regression was performed to establish the load-velocity relationship in the JS. The standard error of estimate (SEE) and the coefficient of determination (R^2) were calculated. The level of significance was set at $P < 0.05$. Absolute and relative reliability between repetitions within the testing session were assessed for bar-velocities across the relative loading ranges, using the coefficient of variation (CV) and a 2-way random effects model intraclass correlation coefficient (ICC), respectively.

RESULTS

Table 1 shows the absolute and relative reliability of the bar-velocities at the different relative loads tested. Figure 1 depicts the relationship between the different percentages of 1RM (independent variable) and bar-velocities (dependent variables). The R^2 of the distinct load-velocity relationships was 0.92, 0.91, and 0.91 for MV, MPV, and PV, respectively ($P < 0.0001$ for all variables). Table 2 presents the bar-velocities attained at different percentages of 1RM during the JS exercise.

TABLE 1. Absolute and relative reliability of bar-velocities across the range of loads in the jump squat exercise.

Relative load (%1RM)	Velocity parameter	CV	95% CI		ICC	95% CI	
			Lower	Upper		Lower	Upper
24% (*20%)	MV	2.32	1.34	3.31	0.92	0.82	0.97
	MPV	2.41	1.07	3.74	0.91	0.79	0.96
	PV	2.06	1.47	2.66	0.94	0.87	0.97
46% (*40%)	MV	1.78	1.17	2.39	0.95	0.88	0.98
	MPV	2.74	1.87	3.61	0.91	0.80	0.96
	PV	1.23	0.86	1.60	0.98	0.96	0.99
70% (*60%)	MV	4.49	2.87	6.11	0.94	0.85	0.97
	MPV	4.67	2.77	6.58	0.93	0.84	0.97
	PV	1.67	1.12	2.23	0.98	0.95	0.99
94% (*80%)	MV	4.44	2.89	6.00	0.90	0.76	0.96
	MPV	4.94	3.29	6.59	0.90	0.76	0.96
	PV	2.49	1.72	3.26	0.98	0.96	0.99

CV: coefficient of variation; CI: confidence interval: ICC: intraclass correlation coefficient. MV: mean velocity; MPV: mean propulsive velocity; PV: peak velocity; 1RM: one-repetition maximum. *The numbers in brackets indicate the percentages of half-squat 1RM.

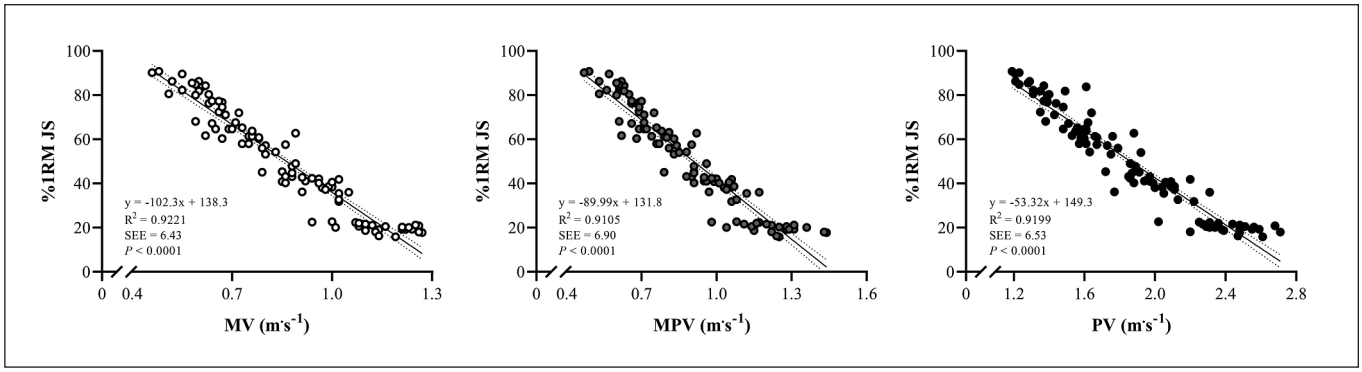


FIG 1. Linear regression models (with 95% confidence limits) representing the relationships between different relative loads (independent variables) and bar-velocity outputs (dependent variables) in the jump squat (JS) exercise. %1RM JS: percentage of one-repetition maximum; MV: mean velocity; MPV: mean propulsive velocity; PV: peak velocity; SEE: standard error of estimate.

TABLE 2. Bar-velocities across the range of loads in the jump squat exercise.

%1RM	**MV** ($m \cdot s^{-1}$)	**MPV** ($m \cdot s^{-1}$)	**PV** ($m \cdot s^{-1}$)
24	1.14 ± 0.09	1.23 ± 0.11	2.41 ± 0.16
46	0.94 ± 0.07	1.00 ± 0.08	2.00 ± 0.14
70	0.76 ± 0.08	0.78 ± 0.09	1.66 ± 0.14
94	0.61 ± 0.08	0.63 ± 0.08	1.38 ± 0.13

Data are expressed as mean ± standard deviation. 1RM: one-repetition maximum; MV: mean velocity; MPV: mean propulsive velocity; PV: peak velocity.

DISCUSSION

We examined the load-velocity relationship in the JS exercise using three bar-velocity outputs (i.e., MV, MPV, and PV) as independent variables. Overall, all these measures exhibited high levels of accuracy and consistency ($R^2 \geq 0.91$, CV ≤ 5%, ICC ≥ 0.90) across the wide range of loads (~20–100% JS-1RM). Therefore, MV, MPV, and PV can be used to predict relative loads in the JS in an interchangeable manner.

For the first time, we adopted the JS-1RM load (i.e., 86% HS-1RM) [8] as the reference for prescribing relative loads in the JS. A previous investigation on the load-velocity relationship in this ballistic exercise also reported a similar shared variance of ~90% between MPV and different percentages of 1RM [11]. Nevertheless, in that study, JS loads were determined based on the traditional HS-1RM approach. In addition, the authors used only the MPV in the linear regressions, thus limiting loading predictions from other bar-velocity outputs. Our results confirm and extend these findings, indicating that either MV, MPV, or PV may be used to determine JS loads with high and similar levels of precision (R^2 = 0.91–0.92). Based on the data provided here, coaches can now prescribe and monitor the JS intensity in a very practical manner, irrespective of their personal preferences (using MV, MPV, or PV) and technical possibilities (i.e., via linear transducers or accelerometers) [22].

Despite the ballistic nature of the JS and the probable influences of distinct mechanical factors on its respective load-velocity relationship (e.g., higher movement velocities, the existence of flight phase, use of mean or peak velocity measures), the predictive power and consistency of the linear equations reported here are similar to those described for other "traditional" (i.e., non-ballistic) exercises ($R^2 \geq 0.90$, CV ≤ 5%, and ICC ≥ 0.90) [11, 18]. Furthermore, the inclusion of very-light relative intensities (i.e., ~20% JS-1RM) in the linear regressions allows coaches to precisely determine and prescribe lighter and faster JS loads, which seem to be essential to improve the athlete's ability to apply force at higher movement velocities [4, 6, 23, 24]. It is worth noting that the mechanical differences between JS and HS decrease progressively with increasing load, which may compromise, or at least reduce, the "potential advantages" (i.e., greater force and power outputs at light-to-moderate loads) of ballistic exercises [6, 8, 23]. In this regard, the use of the appropriate JS-1RM load together with the reference bar-velocity values and equations provided herein (Table 2) is highly recommended, especially in high-performance training settings.

In summary, the load-velocity relationship in the JS is stable and consistent, even when including very-light loads (i.e., ~20% JS-1RM) in the predictive models. Among mean and peak velocity measures, PV appears as the most reliable and sensitive parameter [25]; nonetheless, all bar-velocity outputs have acceptable reliability, as indicated by their low CVs (≤ 5%) and high ICCs (≥ 0.90). Hence, any of these reference values can be accurately used to determine relative loads in the JS exercise. Future studies are required to examine and compare the effects of performing loaded JS under this novel loading strategy (i.e., determining JS loads from the load-velocity relationship based on the JS-1RM).

CONCLUSIONS

We tested and confirmed the stability of the load-velocity relationship in the JS exercise, from very-light loading conditions (i.e., ~20% JS-1RM) up to the JS-1RM (i.e., ~86% HS-1RM) [8]. Coaches and sport scientists can utilize the equations and reference values provided here to precisely prescribe and monitor JS loads during different training phases, bearing in mind that this "novel loading strategy" will preserve the mechanical characteristics of the ballistic JS, thus potentially optimizing neuromuscular training adaptations (i.e., ability to apply force at high velocities) [8].

Conflict of interest declaration.

The authors declared no conflict of interest.

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From human writing to artificial intelligence generated text: examining the prospects and potential threats of ChatGPT in academic writing

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ABSTRACT: Natural language processing (NLP) has been studied in computing for decades. Recent technological advancements have led to the development of sophisticated artificial intelligence (AI) models, such as Chat Generative Pre-trained Transformer (ChatGPT). These models can perform a range of language tasks and generate human-like responses, which offers exciting prospects for academic efficiency. This manuscript aims at (i) exploring the potential benefits and threats of ChatGPT and other NLP technologies in academic writing and research publications; (ii) highlights the ethical considerations involved in using these tools, and (iii) consider the impact they may have on the authenticity and credibility of academic work. This study involved a literature review of relevant scholarly articles published in peer-reviewed journals indexed in Scopus as quartile 1. The search used keywords such as "ChatGPT," "AI-generated text," "academic writing," and "natural language processing." The analysis was carried out using a quasi-qualitative approach, which involved reading and critically evaluating the sources and identifying relevant data to support the research questions. The study found that ChatGPT and other NLP technologies have the potential to enhance academic writing and research efficiency. However, their use also raises concerns about the impact on the authenticity and credibility of academic work. The study highlights the need for comprehensive discussions on the potential use, threats, and limitations of these tools, emphasizing the importance of ethical and academic principles, with human intelligence and critical thinking at the forefront of the research process. This study highlights the need for comprehensive debates and ethical considerations involved in their use. The study also recommends that academics exercise caution when using these tools and ensure transparency in their use, emphasizing the importance of human intelligence and critical thinking in academic work.

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INTRODUCTION

In the last decade or so, the field of artificial intelligence (AI) has seen remarkable advances, and Chat Generative Pre-trained Transformer (ChatGPT – open AIs GPT-3 model) is a striking example of this progress [1]. Academic research has traditionally relied on laborious manual methods to sort and analyse large volumes of text. However, recent advances in natural language processing (NLP) technology have made it possible to automate many of these tasks. ChatGPT is one such technology that has shown promising prospects in academic research. ChatGPT is a large language model (LLM) that has been trained on an extensive corpus of text, enabling it to generate human-like text responses. For a few years now, it has been evident that AI can produce coherent language, and it is becoming increasingly challenging to distinguish AI sentences from those created by humans. In 2022, the journal *Nature* reported that scientists were already using chatbots as research assistants to help them organize their thoughts, receive feedback on their work, write codes, and even summarize research literature [2].

ChatGPT has the ability to create well-written student essays, summarize research papers, answer questions well enough to pass medical exams, and generate helpful computer codes, for instance [2]. It has even created research abstracts that scientists found difficult to distinguish from those written by a human [2]. However, this

technology has also the potential to produce spam, ransomware, and other harmful outputs, which is substantially worrisome for our societies [2]. Given the potential for LLMs, like ChatGPT, to disrupt various fields, there is an urgent need for the research community to engage in a comprehensive debate on the potential uses, threats and limitations of these tools. Therefore, the aims of this correspondence were to *(i)* provide an overview of ChatGPT and other NLP technologies, their emergence, limitations, and related practical implications; and *(ii)* examine the prospects and consequences of using these tools in academic writing

MATERIALS AND METHODS

This manuscript was based on a literature review of relevant scholarly articles, only published in peer-reviewed journals indexed in Scopus as quartile 1. The search was conducted using keywords such as "ChatGPT," "AI-generated text," "academic writing," and "natural language processing". To ensure the reliability and quality of the sources used in this paper, we excluded preprints from our references. Indeed, the lack of pertinence of the latter and the potential bias they may contain, particularly with the recent emergence of National Library of Medicine (NLM) technologies did not ensure that they would provide a trustworthy and unbiased assessment of the state of the field. The analysis was carried out using a quasi-qualitative approach, which involved reading and critically evaluating the sources, and identifying relevant data to support the research questions.

RESULTS AND DISCUSSION

Is NLP technology, including ChatGPT, really a new concept?

NLP has been an area of study since the dawn of computing. The creation of electronic computers in the mid-20th century marked the first attempts to develop computer programs capable of comprehending and generating human language. The roots of products like ChatGPT lie in early AI research from the 1950s and 1960s [3]. Scientists have been aiming at creating computer programs that could understand and respond to natural language in a manner that mimics human communication. This task was challenging due to the complexity, ambiguity, and variability of human language with complex cultural influences that rendered the task even more difficult. The scientific field dedicated to this problem has been called "NLP". In the 1980s and 1990s, NLP gained renewed interest due to technological advances that led to the development of more advanced AI systems [4]. Researchers designed a new generation of statistical AI models capable of learning from vast amounts of text data. These models were a significant improvement from previous rule-based systems and generated responses that sounded more natural [4]. The field of NLP underwent a significant transformation in the 2010s [5, 6]. Indeed, the widespread availability of internet text data and the development of deep learning methods changed the way scientists approached the problem of natural language understanding. Large-scale deep learning models such as recurrent neural networks and transformer models were trained on vast text datasets, enabling them to produce highly realistic human-like responses [6]. These models learned the nuances and structure of language from the input data, making them more effective than previous statistical models [6].

One of the most widely known and commonly used deep learning models is GPT, developed by OpenAI in 2018 [7]. The GPT model was trained on massive amounts of internet text data and was capable of generating responses that closely resembled human writing [7]. It quickly became popular for use in chatbots and other conversational AI applications. OpenAI subsequently developed even more sophisticated models, such as GPT-2 in 2019 and GPT-3 in 2020, which were capable of generating text that was almost indistinguishable from human writing and excelled in various language/style tasks [8]. Despite the effectiveness of ChatGPT and other NLP technologies, they were relatively unknown to the scientific community for a while. However, in November 2022, OpenAI made multiple updates and improvements to ChatGPT, enhancing its ability to handle a wider range of queries and provide more accurate, relevant, and helpful responses to users [2]. The improvements included more training data, improved language understanding, an expanded knowledge base, and higher accuracy and precision [2]. The success of GPT and similar models has led to the development of conversational AI models by other companies and research organizations. For instance, Google's Bidirectional Encoder Representations from Transformers (BERT) and Facebook's RoBERTa models (a reimplementation of BERT with some modifications to the key hyperparameters and minor embedding tweaks) were trained on even larger text datasets and achieved state-of-the-art results in a range of NLP tasks [9, 10].

Is NLP, including ChatGPT, really a source of concern?

There are several concerns about how ChatGPT may impact education, especially in academic writing. While ChatGPT is capable of generating essays on various topics, its scholarly writing still needs improvement, as evidenced by its performance when given an exam and a final project from a science denial class at George Washington University [11]. Nonetheless, the advent of AI in education may encourage instructors to rethink their teaching methodologies by providing assignments that demand critical thinking and problem-solving beyond the actual capabilities of AI that will evolve, probably in an endless race with humans. Another, more significant worry is the possibility of AI-generated content infiltrating scientific papers [2, 11, 12]. In a 2023 study, reviewers identified only 63% of the fake abstracts created by ChatGPT [12]. This raises pertinent issues concerning the authenticity and credibility of research publications, which is backed by an exclusively human based reviewer process as of now. The Science family of journals has always required authors to sign a license certifying that their work is original [11]. Interestingly, to ensure that this standard is met, the license and editorial policies have recently been updated to explicitly prohibit the use of AI-generated text, figures, images, or graphics in research publications. Moreover, AI programs cannot be considered authors of scientific papers. While AI tools can

undoubtedly aid scientific research in many ways, it is crucial to recognize that they should function as a supplementary aid rather than a complete substitute for human creativity and ingenuity. Moreover, there are certain responsibilities that all authors of scientific research papers bear, which cannot be assumed by any computer or program.

How can academic efficiency benefit from NLP, including ChatGPT?

ChatGPT offers numerous advantages that make it a valuable tool for academic research. One of its greatest strengths is its ability to process vast amounts of textual data in a short period, which can save researchers significant time and effort. In fact, ChatGPT and other NLP technologies have the potential to automate many tasks that were previously carried out manually. For instance, ChatGPT can be utilized to analyse academic papers by scanning them and extracting important details such as the author(s), publication date, and significant findings [11, 13]. This feature not only saves time but also enables researchers to avoid the tedious manual searching of papers. Another benefit of using ChatGPT in academic research is in the creation of summaries. Summarizing lengthy academic papers can be a time-consuming process, but ChatGPT can be trained to automatically generate them [12, 14, 15]. This feature guarantees an objective and unbiased summary, generated by a machine instead of a human (drawbacks and caution are discussed below). Furthermore, researchers can also use ChatGPT to generate research questions. By inputting a topic or research area into ChatGPT, researchers can obtain a list of potential research questions [2]. This feature can be particularly useful for new researchers or those seeking inspiration for a research project. However, it is important to use ChatGPT with caution and in conjunction with other research methods [12]. Researchers should carefully consider the scope of their research questions, be aware of the limitations of ChatGPT (see below), take care to attribute sources appropriately, exercise caution with sensitive or controversial topics, and remain informed about new developments in NLP.

Will ChatGPT replace academic researchers?

ChatGPT is a robust LLM with various capabilities, yet it also possesses limitations that make it unsuitable for certain academic research types [2, 12]. The utilization of ChatGPT in research could result in the integration of false or biased information into papers, potentially leading to unintentional plagiarism and/or the misattribution of concepts. Moreover, researchers employing LLMs like ChatGPT run the risk of not adequately citing original sources or authors, leading to inadvertent misattribution of information [2]. Furthermore, the lack of transparency in the training sets and LLMs underlying ChatGPT and other conversational can cause biases and inaccuracies [2]. Importantly, the dearth of transparency and inability to access the internal workings of these models is contradictory to the current trend of transparency and open science. Additionally, concerns persist that conversational AIs can be influenced by the biases of their developers and training data, resulting in inaccuracies and incomplete knowledge. Van Dis et al. [2] demonstrated an instance of ChatGPT's potential inaccuracies in their endeavour to summarize a systematic review on cognitive behavioural therapy for anxiety-related disorders. ChatGPT generated a response containing factual errors and misrepresentations, which could be attributed to the absence of relevant articles in its training set and/or the incapacity to differentiate between credible and less credible sources. To address these concerns, it is vital for researchers to maintain vigilance and integrate expert-driven fact-checking and verification processes into their work. Additionally, high-quality journals may opt to include human verification steps or technologies capable of identifying LLMs' interference. The development and implementation of open-source AI technology present another means of addressing transparency and accuracy concerns [2]. Non-commercial organizations and academic collaborations have already started to create open-source LLMs that can promote innovation and reliability [2, 16]. Tech companies may also benefit from releasing relevant portions of their models and corpora as open source, encouraging greater community involvement and enabling the creation of more accurate and comprehensive results [2]. Similarly to how modern technology has not replaced engineers, computer scientists, or transportation companies, but rather improved their efficiency; academic researchers will not lose their importance with the advent of NLP technology. Instead, they will hopefully continue to grow, improve, and adapt. Hence, we firmly hold the view that NLP cannot substitute academic researchers because it could jeopardize research activities as a whole. ChatGPT has recently brought more light on one of the most pressing challenges faced by academic researchers, namely the threat of 'fake science'. Scientists shall adapt to contemporary changes while continuing to excel as they have always done throughout history.

What should be done in regard to NLP, including ChatGPT? A call for action

Primarily, we recommend that researchers, reviewers, editors, and publishers should try out ChatGPT for themselves. This will allow them to explore the capabilities of such a program and hopefully follow its development, keeping a close eye on any potential pitfalls or issues. Ultimately, we hope that they will act as guardians of honest science. In this regard, educators should discuss the use and ethics of this technology with undergraduate students. In the absence of any external guidelines so far, responsible group leaders and teachers should determine how to use ChatGPT with honesty, integrity, and transparency and establish some basic rules of engagement [12]. All contributors to research should be reminded that they would be held accountable for their work, whether it was generated with the support of ChatGPT/equivalent support, or not. Therefore, every author should take responsibility for thoroughly fact checking their text, results, data, code(s), and references. One additional critical issue to address is the implications for diversity and inequality in the research field. LLMs could be a double-edged sword [12]. Indeed, and

importantly, LLMs could help level-off the playing field by removing language barriers and hopefully enabling more people to write high-quality text. However, it is likely that high-income countries and privileged researchers will quickly find ways to exploit LLMs in ways that accelerate their research and widen inequalities even more. Here, we urge the managers and developers to consider these global/language inequities and integrate in the development of future tools features that will provide equal chances to people independently of their language and access to technologies. Therefore, we propose that the U.S. NLM (https://www.nlm.nih.gov/) should create software similar to a plagiarism checker ("NLP pattern checker" could be suggested as a name) to help editors and publishers detect text generated by LLMs instead of researchers and/or reviewers. We foresee an epic battle between ChatGPT's developers and whoever will be in charge of detecting non-human created text. In that regard, and as of now, ChatGPT's raw output can be detected on careful inspection, particularly when the text contains more than a few paragraphs and the subject relates to scientific work. This is because LLMs produce patterns of words based on statistical associations in their training data and prompts, meaning that their output can appear generic or contain simple errors.

Should ChatGPT be mentioned in the list of authors?

There are growing concerns regarding the ethical use of LLMs such as ChatGPT in academic research. There is a risk that researchers and students may rely too heavily on these models, resulting in unfair and unreliable work and/or even plagiarism [2]. To address these concerns, some scientific publishers, such as Springer *Nature*, have already established guidelines for ethically using LLMs. These guidelines advise against crediting LLMs as authors on research papers since, as mentioned above, AI tools/computers cannot take responsibility for the work. Researchers are also encouraged to document their use of LLMs in the methods or acknowledgements sections of their papers [17]. As an illustration of the latter [18], we asked ChatGPT to generate the abstract of the present manuscript (Box 1). Despite these guidelines, some papers have already credited LLMs as co-authors, such as an editorial in *Nurse Education in Practice* [19]. However, despite the honest behaviour of the authors to credit the help of ChatGPT, the journal's editor-in-chief has further acknowledged this as an oversight from the journal editorial board and has promised to make the necessary corrections [20]. Another paper, published in *Oncoscience*, credited ChatGPT as a co-author of a perspective article [21]. The author of the paper, the chief executive officer of *Insilico Medicine*, strikingly stated that his company has published over 80 papers produced by generative AI tools [21]. While some argue that LLMs can produce higher quality work than earlier generations of AI tools, there are still concerns about their ethical use in research. Publishers such as Springer Nature have established guidelines to promote ethical and transparent use of LLMs while holding researchers accountable for their work [22]. To maintain transparency, it is essential to acknowledge the use of any NLP software, including simpler tools such as Grammarly and ProWritingAid, in the methodology or acknowledgement section of all manuscripts. This recommendation applies not only to ChatGPT and other NLP technologies but should also apply to publishers, editors, and reviewers who should encourage transparency in their own reviews and feedback to authors. Basic fairness would naturally result in acknowledging the contribution of any tool that aided in producing better research outcomes.

Furthermore, we believe that grey literature, including pre-prints, should not be considered as references for the time being. This is because it may contain significant bias due to being totally or partially generated by AI tools. We would like to emphasize that we are not opposed to the use of AI technology in academic writing, but it is important to note that manuscripts that have not undergone a robust peer review process may increase the risk of failing to identify AI-generated/supported articles. This means that academics who serve

BOX 1. Verbatim version of the abstract created by ChatGPT based on the article manuscript final version (Date: March 5, 2023). Readers will identify ChatGPT actual limitations in constructing a well-structured abstract that covers all aspects of the article.

ChatGPT is a powerful tool for academic research with the ability to process vast amounts of textual data and automate tasks that were previously done manually. It can be used to scan academic papers and extract important details, generate objective and unbiased summaries, and create research questions. However, researchers must exercise caution when using ChatGPT as it can also integrate false or biased information into papers, potentially leading to unintentional plagiarism and misattribution of concepts. The lack of transparency in the training sets and underlying models can also cause biases and inaccuracies. To address these concerns, researchers should maintain vigilance, integrate expert-driven fact-checking and verification processes, and encourage the development and implementation of open-source AI technology. Educators should also discuss the use and ethics of this technology with undergraduate students, and all contributors to research should take responsibility for thoroughly fact-checking their work. Additionally, the implications for diversity and inequality in the research field should be considered, and the development of future tools should aim to provide equal chances to people regardless of their language and access to technologies. Finally, the proposal for the creation of a plagiarism checker similar to NLP pattern checker to help detect text generated by LLMs is suggested to help editors and publishers detect potential issues. Overall, ChatGPT has the potential to improve the efficiency of academic research, but researchers must use it responsibly and with caution to avoid any unintended consequences.

Note from the authors: While ChatGPT may prove to be beneficial to researchers; it is still a long way from being able to replace academics.

BOX 2. Verbatim' answer of ChatGPT to the following request: "How can we use ChatGPT in sports?" (Access date, February 28th 2023).

ChatGPT's answer:	
ChatGPT can be used in sports in several ways, such as:	
	ChatGPT can be used to:
1. *Providing real-time updates*	Provide real-time updates on live sports events, such as scores, highlights, and player statistics. This can help fans stay up-to-date on their favourite teams and players.
2. *Answering fan questions*	Answer fan questions about sports, such as rules, regulations, and historical facts. This can help fans better understand the sport and appreciate it more.
3. *Providing personalized training programs*	Provide personalized training programs for athletes based on their individual needs and goals. This can help athletes improve their performance and achieve their full potential.
4. *Conducting market research*	Conduct market research on sports fans, such as their preferences, opinions, and behaviours. This can help sports organizations better understand their audience and tailor their offerings to meet their needs
5. *Providing sports betting tips*	Provide sports betting tips and predictions based on historical data and statistical analysis. This can help bettors make more informed decisions and improve their chances of winning

as reviewers should make the necessary efforts to follow the evolution of LLMs in order to reduce the likelihood that machines will imperceptibly replace humans in research.

Is the use of NLP, including ChatGPT, by academic researchers any different in the sports science field?

We searched MEDLINE on March 4, 2023, using the combination of the following two terms: ChatGPT AND Sport. Only two editorials were found [23, 24]. The use of ChatGPT in academic research, including sports science, has both advantages and disadvantages that are not fundamentally different from other academic fields. One potential limitation is that ChatGPT was trained on a small academic database [25], which may not capture the full breadth and depth of knowledge in sports science. Furthermore, ChatGPT has been trained on a dataset that ends in September 2021 [25], while the academic sports science field is rapidly evolving, with new research emerging at an unprecedented pace. Within a year, evidence can quickly become outdated as new discoveries and advances are made. This emphasizes the importance of keeping up to speed with the latest research and constantly reassessing and updating scientific knowledge in the field, which increases the potential for bias in ChatGPT's responses to sports science questions. Likewise, much of the online sports science information may be biased or based on anecdotal evidence rather than empirical research. This is because much of the content available on the internet is created by non-experts or individuals with a vested interest in promoting specific ideas or products. As a result, the quality and reliability of the available information may limit ChatGPT's responses to sports science questions. Moreover, the popularization of sports science has resulted in an increase in the availability of biased or inaccurate information on the internet [26]. Athletes and fitness enthusiasts frequently share their experiences and advice, which may or may not be supported by empirical research and may be influenced by commercial interests. As a result, ChatGPT should prioritize peer-reviewed academic sources and be sceptical of non-academic sources in order to ensure the accuracy and reliability of its responses. This is especially important in sports science research, where inaccurate or biased data can have serious consequences for athletes' health and performance.

The limitations of ChatGPT, however, are not unique to sports science research. In many fields, the internet is rife with biased or inaccurate information, and researchers must always be cautious when evaluating online sources. Furthermore, overreliance on ChatGPT-generated responses is a risk in any academic field. While ChatGPT can offer useful insights into research questions, it should not be used as the sole source of analysis. In conjunction with other research methods, researchers should always critically evaluate and interpret ChatGPT-generated responses. To illustrate our discussion with a practical example, the integral answer of ChatGPT to the question *"How can we use ChatGPT in sports?"* is reported in Box 2. We deliberately decided to keep Box 2 as is, even though at the time of our manuscript writing-up (February 2023), ChatGPT's database was set up to September 2021 only. Therefore, statements as "*Providing real-time updates*", should obviously considered with caution.

How easy is it to fool reviewers, editors, journals, and publishers with fake papers?

It is worth noting that in 2013, *The Guardian* newspaper/website published an article which detailed a sting operation conducted by the science journalist John Bohannon [27]. Over a period of 10 months, Bohannon submitted a fake scientific paper to 304 open access journals worldwide. The hoax paper had "fatal flaws" and used fabricated content, authors and universities. Surprisingly, and worryingly, the fabricated text was accepted by 157 journals, including those published by industry giants Sage, Elsevier, and Wolters Kluwer. The sting operation raised concerns about the quality control of open access journals and the "gold" open access model. The article suggested that the hoax reflected a weakness in peer review rather than a flaw in the gold open access model. Nowadays, we

BOX 3. Verbatim' answer of ChatGPT to the following request: Please consider coming-up with tools that will protect science and academics from the misuse of large language models (LLMs) (access date, February 20th 2023 – Importantly, this outcome is strictly independent from the content of the present manuscript. The authors would like to emphasize that we asked ChatGPT to answer this question after having completed our paper draft. We were surprised by some text sections that were extremely close to our manuscript, and ensure the readers that we did not take the below responses into account to bring any modification to our article).

ChatGPT's answer:

There are several steps that can be taken to protect science and academics from the potential misuse of LLMs like ChatGPT. Here are a few suggestions:

1. *Educate researchers and academics*: It is crucial to educate researchers and academics about the capabilities and limitations of LLMs, as well as the potential risks associated with their use. This could involve providing training on best practices for using LLMs in research and emphasizing the importance of maintaining academic integrity.
2. *Develop guidelines and standards*: The research community could develop guidelines and standards for using LLMs in academic research. This could include standards for verifying the authenticity of research outputs and guidelines for detecting and addressing potential misuse of LLMs.
3. *Develop tools for detecting AI-generated content*: It is important to develop tools that can detect AI-generated content in scientific publications and research outputs. This could involve developing algorithms that can identify language patterns and other characteristics of AI-generated text.
4. *Promote responsible use*: It is crucial to promote responsible use of LLMs in academic research. This could involve developing ethical guidelines for the use of LLMs in research and encouraging researchers to use LLMs in a way that supports human intelligence and critical thinking, rather than replacing it.
5. *Engage with the broader community:* It is important to engage with the broader community, including policymakers and the public, to raise awareness about the potential risks and benefits of LLMs in academic research. This could involve developing educational materials and hosting public discussions to foster informed and responsible use of LLMs in research.

Overall, protecting science and academics from the potential misuse of LLMs will require a collaborative effort from the research community, policymakers, and the broader public. By working together, we can develop the tools, guidelines, and standards needed to ensure that LLMs are used in a responsible and ethical manner, in support of scientific research and academic excellence.

interpret that journal article differently. Indeed, with the excellent academic skills of NLP technology, less-skilled reviewers are less likely to detect or distinguish fake from true scientific articles. This will inevitably increase the threat of fake science.

It is now clear how easy it is to fool reviewers, editors, journals, and publishers with fake papers. Therefore, the three main messages of our article are as follows:

(i) NLP, including ChatGPT, should no longer be considered a threat to academics, as they have always existed, and their output continues to improve, just like scientific researchers' output will do. Their existence will contribute to the improvement of science, but only if high-quality ethical standards are applied

(ii) We call for highly skilled academics and pioneering leaders in big academic institutions to impose higher standards for academic writing, such as double author identification verification, or criteria for each author to submit in relevant journals. The same goes for peer reviewers; upon reviewers' selection, editors may rely on their H-index or the number of their reviews to increase the standards, double institutional review board verification, and/or banning pre-prints or imposing more criteria for deposition before accepting pre prints (we believe that this is less likely to happen; therefore we call on the research community to avoid relying on pre-print manuscripts to back the research)

(iii) It is essential to include a module for medical students, as well as for master's and PhD students, on NLP technologies, ethics, and the best way to use them.

When asked to "*consider coming up with tools that will protect science and academics from the misuse of LLMs*", the integral answer of ChatGPT is reported in Box 3. The authors call on the readers to judge whether ChatGPT did a satisfactory job for the assignment. Our personal opinion is that the text is really good.

CONCLUSIONS

With the growth of AI technology, science, like many other fields, is not only greatly benefiting, but also currently facing challenges to its core principles, methods, norms and ethics. The priority should be to embrace the opportunities presented by this development and optimally manage any associated risks. It is believed that science can make the most of conversational AI while still maintaining the essential elements that make it such a rewarding and significant pursuit, such as curiosity, creativity, and exploration. Actually, the progress of AI technology may limit and obscure people's/researchers' contributions in the future. Indeed, AI chatbots may be able to generate research questions and hypotheses, develop methodology, create experiments' research protocols, analyse and interpret data, and write manuscripts. Although we are still some way off from this scenario, there is no doubt that conversational AI technology will increasingly impact all stages of the scientific publishing process. Indeed, we believe that research institutions and academics will not be able to exclude the use of this technology. Therefore, this is a call for action for academics to act in the field of academic research. They shall focus on educating research students on the basic

BOX 4. Main messages of this paper.

Message 1. Is NLP technology, including ChatGPT, really a new concept?
The evolution of ChatGPT and similar products is closely linked to the development of AI and NLP. From the early days of rule-based systems to today's cutting-edge deep learning models, the field has made tremendous strides in generating highly realistic human-like text and performing a wide range of language tasks.

Message 2. Is NLP, including ChatGPT, really a source of concern?
While ChatGPT's capabilities offer exciting prospects for education and research, there are potential hazards associated with its usage that deserve full consideration. Maintaining the integrity of scientific research necessitates strict adherence to ethical and academic principles, with human intelligence and critical thinking at the forefront of the research process.

Message 3. How can academic efficiency benefit from NLP, including ChatGPT?
While ChatGPT has several benefits that make it a promising and effective tool for academic research, researchers must exercise caution and use it appropriately in conjunction with other research methods with cautious checks all along the way, to ensure trustful/reliable results.

Message 4. Will ChatGPT replace academic researchers?
While ChatGPT and other LLMs have numerous potential uses in academic research, they are not suitable for all types of research and pose accuracy and transparency threats/risks. Researchers employing these tools must maintain vigilance and integrate expert-driven fact-checking and verification processes into their work. Importantly, if some field of data science could be taken in charge by computers, most of the research experiments need humans to be ran. Thankfully, we do not expect humans to be completely replaced by computers yet.

Message 5. What should be done in regard to NLP, including ChatGPT? A call for action
We propose that the U.S. NLM creates a software similar to a plagiarism checker to help editors and publishers detect text generated by LLMs instead of researchers and/or reviewers.

Message 6. Should ChatGPT be mentioned in the authors' list?
Current guidelines advice against crediting LLMs as authors on research papers since, as mentioned above, AI tools/computers cannot take responsibility for the work. However, if the authors use such tools, it would be fair mentioning it in the acknowledgements' section of the manuscripts.

Message 7. Is the use of NLP, including ChatGPT, by academic researcher any different in the sports science field?
The advantages and disadvantages of using ChatGPT in academic research for sports science are not fundamentally different from the advantages and disadvantages of using ChatGPT in other academic fields. ChatGPT has the potential to shed light on important issues in sports science research, but its limitations must be considered and addressed. In conjunction with other research methods, researchers should prioritize the use of peer-reviewed academic sources and critically evaluate and interpret ChatGPT-generated responses.

Message 8. How easy it is to fool reviewers, editors, journals, and publishers with fake papers?
It is essential to include a module for medical students, as well as for master's and PhD. students, on NLM technologies, ethics, and the best way to use them.

AI: Artificial Intelligence. **LLM**: Large Language Model. **NLM**: National Library of Medicine. **NLP**: Natural Language Processing.

principles and ethical considerations involved in academic research. It is also important to emphasize the transparency of their work by acknowledging the use of any AI/LLMs at any stage of their research. Additionally, researchers should always crosscheck any information provided by these technologies with relevant sources. In doing so, researchers can ensure the ethical and transparent use of these tools in academic research. The race is now ongoing between humans and LLMs to come up with the best ways to limit the threats of such new AI-based tools while optimizing the benefits they will bring to humanity. Box 4 summarises the main messages of this review.

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Conflicts of interest

We, hereby declare that we have no financial or personal relationships that could potentially influence or bias the content of this paper. Specifically, none of the authors holds any financial interests or conflicts of interest associated with the ChatGPT or NLM technologies discussed in this paper. Furthermore, none of the authors has affiliations with any organizations that might have a financial interest in the research or its outcomes. Moreover, we confirm that we have no personal or professional relationships that could potentially affect the research or its findings. None of the authors has collaborated or consulted with any individuals or organizations that have a financial or other interest in the ChatGPT or NLM technologies. Additionally, we have not received any funding or other types of support from any sources that could influence the research or its findings. We affirm that the research presented in this paper is entirely based on our own

analysis and interpretation of the facts/data. We assure that there are no conflicts of interest that could impact the objectivity or integrity of the research. We make this declaration of no conflict of interest to ensure transparency and maintain the credibility of the research manuscript presented.

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