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Physical qualities and body composition predictors of running performance in national level women's official soccer matches

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ABSTRACT: The purpose of the study was to (1) determine match running performance, anthropometry and various physical qualities of national level women soccer players and (2) identify key physical qualities and anthropometric predictors of match running profile during a competitive season. Twenty-five national level Finnish soccer players participated in the study. Players performed countermovement jump, loaded squat jumps, 30-meter sprint, maximum isokinetic knee flexor and extensor contractions, an incremental treadmill test and underwent body composition assessment in the lab. Match running performance was analyzed from 115 match observations during competitive league matches over 11 weeks after the laboratory tests. Pearson's correlation was used to determine bivariate relationships between match running variables and physical qualities and anthropometric variables. Identified significant bivariate relationships were then entered into multiple regression analyses to identify the best predictors of match running performance. Physical qualities and anthropometric variables predicted 65% of very high-intensity (VHIR) (> 19 km/h) and 63% of high-intensity (HIR) (13–19 km/h) running distances covered during matches, but only 22% of low-intensity (LIR) and 43% of total distances. Body fat percentage and high-speed knee flexor concentric strength were the most important predictors to VHIR and HIR while aerobic capacity-related variables were most important predictors to LIR and total distance. Physical qualities and anthropometry can predict a large portion of players' VHIR and HIR performance during matches in women's national level soccer. To increase player's VHIR and HIR distance, coaches could aim to develop players' high-speed (especially knee flexor concentric) strength and optimize player's body composition.

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INTRODUCTION

In the 2019 World Cup, elite (outfield) women soccer players covered an average 9–11 km during the match, in which they averaged 349–591 meters at speeds of 19–23 km/h and 111–255 meters at speeds of > 23 km/h [1]. It is known that match running demands increase in-line with competition level [2, 3]. From match running variables, high-intensity running (HIR) should be emphasized because straight sprinting is the most frequent action in goal situations, at least in men's professional soccer [4]. Even though a player's running performance in soccer is a complex phenomenon, differing depending on multiple factors such as player's position [5], aerobic capacity [6, 7], opposition standard [8], field surface [9], match outcome [9, 10], heat and altitude [10], it is important to be able to recognize which physical qualities and anthropometric variables predict match running performance. The identified qualities could then be improved to allow player development to fulfill match running demands of a higher level.

Elite women soccer players have higher physical qualities compared to lower-level counterparts [11, 12]. Previous studies have shown that, on average, elite women soccer players' maximal oxygen uptake (VO_2max) varies from 50 to 55 ml/kg/min [7, 12, 13, 14], countermovement jump height from 30 to 36 cm [11, 13, 15] and time in a 30-meter sprint test from 4.35 to 4.55 seconds [11, 15]. The relationship between match running performance and physical qualities is extensively documented in elite men and in male youth players, but very few studies have examined women players [16]. Correlation coefficients between total and HIR distances covered during the match and performance in different variations of yoyo--tests have varied considerably in women soccer players (r = 0.12–0.76) [6, 7, 17, 18]. Although previous studies have found strong correlations between VO_2max and HIR (r = 0.76–0.83) [7, 19], there are disparities in coefficients between VO_2max and total distance covered during the match (r = 0.20–0.76 [7, 19]). McCormack et al. [19] examined predictors of HIR capacity in collegiate women players and found that VO_2max, dominant leg vastus lateralis thickness and pennation angle were the strongest predictors of HIR distance.

Associations between match running performance and strength, speed or power qualities in women soccer players are not widely

studied, and findings from these few studies have been partly conflicting [17, 18]. It seems that the number of high-intensity accelerations is the in-match variable that is most related to strength (r = 0.26–0.49), power (r = 0.24–0.76) and speed qualities (r = -0.34 to -0.77) [17, 18]. In terms of high-speed/sprint distances covered during matches, Goncalves et al. [17] found weak-to-strong associations with power (r = 0.11–0.56) and speed qualities (r = -0.11 to -0.70), while Villaseca-Vicuna et al. [18] did not find any significant correlations between high-speed running distance and strength, speed or power qualities. Further, the only association between strength, speed and power qualities and total distance reported in women players is a surprising significant negative correlation (r = -0.40) between back squat 1RM and total distance [18]. This conflicts a finding in elite men players that greater muscle strength helped to maintain running distance throughout the match [20]. Demonstrating the confusion in the literature whether such physical qualities can predict match running performance at present.

Previous studies regarding women soccer players' anthropometry have shown that elite women are ~167–172 cm tall, weigh ~60–64 kg and have a fat percentage of ~20–22% [14, 15, 21], but there are no studies that would have examined associations between women players' anthropometry and match running performance. Some previous studies in elite men have shown sporadic associations between anthropometry and match running performance [22, 23]. However, one recent study found systematic associations between body fat percentage and HIR (r = -0.38) as well as sprint running (r = -0.57) distances in professional men players [24]. Thus, associations between these variables should be tested and confirmed in women soccer players to inform coaching practices.

Even if women's soccer has grown in popularity a lot during recent years [1], there is a lack of knowledge regarding how anthropometry and various physical qualities as well as their inter-relationships, influence match running performance in national level women's soccer. Therefore, coaching practice and targeted player development cannot be optimized. Hence, the purpose of the study is to (1) identify physical qualities, anthropometry and match running profiles of national level women soccer players, and (2) determine which physical and anthropometric qualities predict match running performance during a competitive season.

MATERIALS AND METHODS

Participants

Thirty-six national level [25] women soccer players from a single club in Finland volunteered for the study. Twenty-five players fulfilled the inclusion criteria; 1) outfield playing position, 2) performed fitness tests before the start of the match season, and 3) played at least 75 minutes in two matches during an 11-week period after the tests, and were included in data analyses. Players were from two teams: the 1st team (n = 14, 6 defenders, 5 midfielders and 3 attackers, age 21.7 ± 2.5 years) playing in the highest national league, and the U18-team (n = 11, 4 defenders, 4 midfielders and 3 attackers, age 16.9 ± 0.9 years) playing in the highest U18-national league. All participants provided written informed consent prior to testing, the study was conducted according to the Declaration of Helsinki (2013) and was approved by the ethics committee of the University of Jyväskylä (5U/2019).

Experimental overview

This study was a prospective, observational study performed during the 2020 competitive season. Physical quality and body composition tests were performed 1–2 weeks before the start of the league season and match data was collected during an 11-week period after the tests, when teams played against all other teams in their league once. The 1st team played 9 matches during the data collection period (2 wins, 1 draw and 6 losses) and U18-team played 10 matches (5 wins, 3 draws and 2 losses). Two matches (both wins) from the U18-team were excluded from analyses because of hardware related technical problems. Both teams played in a 4-4-2 formation. Players performed all fitness tests during a single session in the laboratory, which took approximately two hours. The tests began with a standardized warm-up (5-min cycling, 10 reps of squats, lunges and hip thrusts and dynamic mobility exercises for lower limbs) followed by countermovement jump and loaded squat jump tests. Thereafter, players performed a 30-meter sprint test and isokinetic strength tests. The session ended with an incremental running test on a treadmill. Players used running shoes in all laboratory tests. Body composition measurement was performed on a separate morning after a 12 h overnight fast.

Measurements

Match activity data was collected and analysed from competitive league matches using polar team pro player tracking system (Polar Electro Oy, Kempele, Finland) with GPS sampling at 10 Hz. Ten Hz GPS devices have been shown to be valid and reliable across linear and team sport simulated running [26]. Good-to-moderate reliability (< 5% CV) and validity for total distance, linear running and team sport simulation circuit have been shown for the same Polar team pro system used in the present study [27]. The following variables were used to represent match activity: total distance [m] covered during the match, distance covered [m] in speed zones 1–5: zone 1 (< 7 km/h), zone 2 (7–13 km/h), zone 3 (13–19 km/h), zone 4 (19–23 km/h and zone 5 (> 23 km/h), which were similar to thresholds used for the FIFA Women's World Cup 2019 [1]. For correlation and regression analyses, distance covered in zones 1 and 2 were combined into one variable to describe distance covered in low-intensity running (LIR, 0–13 km/h) and zones 4 and 5 were combined into one variable to describe very high-intensity running (VHIR, > 19 km/h). Zone 3 was used to describe high-intensity running (HIR, 13–19 km/h).

Overall, 115 (65 from the 1st team and 50 from U18-team players) individual match activity observations were used in this study

and each player's individual match activity profile was calculated from 4.6 ± 2.3 matches (1st team players 4.6 ± 2.5 and U18-team players 4.6 ± 2.1, range 2–8). Players' match activity data was accepted to the analyses if the player played more than 75 minutes in at least two matches. Match activity data was standardized to 90 min values, when added time after first and second halves were excluded. Most previous studies have included match data only if a player has played full match (90 minutes) [3, 7, 28] but in some studies analyses have even been performed from as little as 15 [29] or 20 [30] minutes of match play. In the present study, 75 minutes was selected as the acceptance threshold, because the introduction of a 5-substitute rule due to COVID-19 led to more frequent substitutions and a lower number of players who played until full-time in the matches. One [19] or two [6, 28] matches per player have been used in previous similar studies to investigate match performance analysis.

In the lab, countermovement jump height was measured using an infrared mat (Spintest, Estonia). Players performed two warm-up trials and four test trials. The highest jump was used in final analysis. Rest intervals between trials were one minute. A loaded squat jump test modified from Samozino et al's [31] method was used to evaluate players' force, velocity and power output in a ballistic movement. In the present study, players performed jumps using four different loads, which varied from 0–55% of body mass and loads were performed in increasing order. Evaluations of force, velocity and power developed by the lower-limb extensor muscles during squat jumps were calculated by the computations provided by Samozino et al. [31]. The same equipment was used as in countermovement jump test.

For the 30-meter sprint test, players started 50 cm behind single beam photocell gates (Newtest Oy, Finland), which were 30 cm from the ground. Players performed two warm-up trials and three test trials, and the best time was used in analyses. Rest intervals between trials were two minutes.

Peak knee extensor and flexor force in both concentric and eccentric muscle actions were measured using two different speeds: 60 and 180 degrees per second. The range of motion of the dynamometer (Custom built in University of Jyväskylä) was 78 degrees (knee angle 90–168 degrees, 180 = fully extended). Players performed four trials in each condition separated by 20-second rest interval between trials [32]. Subjects always performed knee extensor followed by knee flexor trials and a speed of 60 degrees per second followed by 180 degrees per second. The order of muscle action (concentric or eccentric) was randomized. The highest peak torque of each condition adjusted to the subject's body mass was used in final analyses. The test was performed by the right leg only. Based on a meta-analysis between-limbs, muscle strength measured by maximal isokinetic dynamometry demonstrates symmetry across ages, genders, and levels of play in soccer players [33].

Maximal oxygen uptake was measured by an incremental treadmill (Telineyhtymä Oy, Kotka, Finland) test (starting speed 7 km/h, 1 km/h increase every 3rd minute) following methods from Vesterinen et al. [34], except that the highest running speed (sMax) of the test was defined as the highest completed speed level. Oxygen consumption was measured breath-by-breath (OxyconPro, Jaeger, Hochberg, Germany) and heart rate was monitored continuously (Polar V800, Polar, Kempele, Finland). The determination of lactate thresholds was based on the first rise and change in inclination of the blood lactate curve during the test [34].

Body composition was measured following an overnight fast using dual-energy X-ray absorptiometry (DXA) and Encore software (version 9.3, LUNAR Prodigy Advance; GE Medical Systems, Chicago, IL) as described previously [35].

Statistical analyses

Statistical analyses were conducted using SPSS Statistics 24 (IBM, Armonk, NY). Results are reported as means ± standard deviation (SD). Data normality was assessed using the Shapiro-Wilk test and all variables were normally distributed (distance covered in zone 5 after logarithmic transformation). Between-group differences in physical quality, anthropometric and match running variables were analyzed using independent t-test. For pairwise comparisons, effect sizes were calculated by using Hedges' *g*. Effect sizes were classified using the following criteria: 0.2–0.5 small, 0.5–0.8 medium, > 0.8 large. As there were only minor differences between groups in physical qualities, anthropometric and match running variables, groups were combined to form a larger sample to correlation and regression analysis, decreasing the possibility of statistical error through small sample size.

Pearson's product moment correlation was used to assess correlations between match activity variables, physical qualities, and body composition variables. Correlation magnitudes were classified using the following criteria: < 0.3 weak; 0.3–0.7 moderate, > 0.7 strong. To identify the variables most strongly predictive of match running performance, multiple regression analyses were conducted by automatic linear modelling (forward stepwise method). Those parameters significantly related with a selected match running variable in the Pearson's correlations were introduced into the regression models. Significance level was set at $p < 0.05$.

RESULTS

Group differences. Table 1 shows the descriptive characteristics for the 1st team and U18-team players. The only statistically significant difference between the two teams was found in knee extensor peak torque in concentric action with a speed of 180 degrees per second.

Bivariate relationships. Table 2 shows correlation coefficients between match running and physical and anthropometrical variables. Several statistically significant (positive and negative) moderate-to-strong correlations were observed between specific variables.

Match running performance predictors. Table 3 shows linear regression models that predict total distance and distance covered in different speed zones in matches. Regression equations were:

TABLE 1. Descriptive characteristics for the 1st team and U18 team players, and average values (mean + SD).

A	Age (years)	Height (cm)	Body mass (kg)	Body mass index	Fat percentage (%)	Lean mass (kg)	30-m sprint (s)	CMJ (cm)	
Average	19.6 (3.1)	169.1 (4.9)	64.5 (9.4)	22.4 (2.8)	24.3 (5.1)	45.6 (5.5)	4.67 (0.16)	31.2 (3.3)	
First team	21.7 (2.5)	168.0 (5.3)	64.2 (10.2)	22.6 (2.7)	23.3 (5.2)	46.0 (6.4)	4.63 (0.18)	32.3 (3.4)	
U18 team	16.9 (0.9)	170.0 (3.9)	64.8 (8.6)	22.2 (3.1)	25.8 (5.0)	44.8 (6.4)	4.74 (0.12)	30.0 (2.8)	
p-value		0.158	0.882	0.759	0.249	0.570	0.118	0.080	
Hedges' g		-0.566	-0.060	0.132	-0.486	0.215	-0.633	0.714	
B	**VO_2max (ml/kg/min)**	**sMax (km/h)**	**LT2 VO_2 (ml/kg/min)**	**LT2 speed (km/h)**	**LT1 VO_2 (ml/kg/min)**	**LT1 speed (km/h)**	**F0 (N/kg)**	**V0 (m/s)**	**P_{max} (W/kg)**
Average	45.8 (3.3)	14.9 (1.1)	40.6 (3.6)	11.8 (0.9)	33.8 (2.8)	9.4 (0.8)	30.8 (3.5)	2.28 (0.26)	17.5 (1.6)
First team	46.0 (2.4)	15.2 (1.1)	40.5 (2.8)	11.9 (0.8)	33.6 (2.5)	9.5 (0.7)	31.5 (3.3)	2.23 (0.26)	17.7 (1.5)
U18 team	45.6 (4.2)	14.5 (1.1)	40.9 (4.6)	11.8 (1.1)	34.1 (3.4)	9.4 (1.1)	30.0 (3.6)	2.35 (0.24)	17.4 (1.7)
p-value	0.825	0.140	0.767	0.751	0.666	0.875	0.299	0.267	0.707
Hedges' g	0.087	0.596	-0.117	0.125	-0.170	0.062	0.414	-0.443	0.148
C	**Econ60 (Nm/kg)**	**Eecc60 (Nm/kg)**	**Econ180 (Nm/kg)**	**Eecc180 (Nm/kg)**	**Fcon60 (Nm/kg)**	**Fecc60 (Nm/kg)**	**Fcon180 (Nm/kg)**	**Fecc180 (Nm/kg)**	
Average	2.7 (0.5)	4.3 (0.7)	1.9 (0.4)	3.9 (0.8)	1.3 (0.2)	1.8 (0.4)	1.0 (0.2)	1.8 (0.3)	
First team	2.9 (0.3)	4.5 (0.8)	2.1 (0.3) *	4.2 (0.9)	1.2 (0.2)	1.7 (0.3)	1.0 (0.2)	1.7 (0.3)	
U18 team	2.5 (0.6)	4.0 (0.5)	1.5 (0.3) *	3.6 (0.4)	1.4 (0.3)	1.8 (0.4)	1.1 (0.3)	1.9 (0.3)	
p-value	0.067	0.080	< 0.001	0.054	0.257	0.606	0.370	0.277	
Hedges' g	0.868	0.727	1.790	0.772	-0.505	-0.213	-0.399	-0.432	
D	**Total distance (m)**	**Zone 1 distance (m) (0–7 km/h)**	**Zone 2 distance (m) (7–13 km/h)**	**Zone 3 distance (m) (13–19 km/h)**	**Zone 4 distance (m) (19–23 km/h)**	**Zone 5 distance (m) (> 23 km/h)**	**LIR distance (m) (< 13 km/h)**	**HIR distance (m) (13–19 km/h)**	**VHIR distance (m) (> 19 km/h)**
Average	9203 (882)	3468 (291)	3840 (620)	1600 (405)	238 (109)	56 (60)	7308 (485)	1600 (405)	295 (161)
First team	9205 (871)	3457 (298)	3811 (528)	1623 (436)	248 (119)	66 (72)	7268 (489)	1623 (436)	315 (184)
U18 team	9200 (938)	3481 (295)	3878 (746)	1571 (380)	226 (99)	45 (40)	7359 (499)	1571 (380)	271 (131)
p-value	0.989	0.843	0.794	0.758	0.620	0.385	0.754	0.652	0.492
Hedges' g	0.005	-0.078	-0.103	0.122	0.196	0.345	-0.179	0.122	0.262

A = anthropometry, 30-meter sprint speed and countermovement jump height (CMJ), B = Maximal oxygen consumption (VO_2max) and maximal speed during VO_2max test (sMax), speeds at lactate thresholds 1 (LT1 speed) and 2 (LT2 speed). Oxygen consumption at lactate thresholds 1 (LT1 VO_2), 2 (LT2 VO_2) and force (F0), velocity (V0) and power (Pmax) outputs from loaded squat jumps. C = Body mass adjusted peak torques of knee extensors in concentric action with 60 degrees (Econ60) and 180 degrees (Econ180) per second and in eccentric action with 60 degrees (Eecc60) and 180 degrees (Eecc180) per second. Body mass adjusted peak torques of knee flexors in concentric action with 60 degrees (Fcon60) and 180 degrees (Fcon180) per second and in eccentric action with 60 degrees (Fecc60) and 180 degrees (Fecc180) per second. D = Distance covered in different speed zones in matches and combinations of speed zones: low-intensity running (LIR), high-intensity running (HIR) and very-high-intensity running (VHIR) used in later analysis. * = Statistically significant difference between groups, $p < 0.05$.

- Total distance [m] ($F = 9.892$, $p = 0.01$, SEE = 668.138) = 1106.58 + 145.04*VO_2max [ml/kg/min] + 1403.88*Fcon180 [Nm/kg]
- LIR [m] ($F = 7.589$, $p = 0.011$, SEE = 429.890) = 4161.81 + 265.75*LT2 speed [km/h]
- HIR [m] ($F = 11.360$, $p < 0.001$, SEE = 245.274) = -1312.43 + 690.07*Fcon180 [Nm/kg] + 35.59*F0 [N/kg] + 146.06*LT2 speed [km/h] – 5.85*Fat percentage
- VHIR [m] ($F = 16.141$, $p < 0.001$, SEE = 94.898) = 1911.33 – 19.65*Fat percentage + 213.39*Fcon180 [Nm/kg] – 290.51*30-m speed [s]

Adjusted R-squared values were higher for distances of HIR and VHIR than total distance and LIR distance. The analysis shows that the most important predictors of HIR distance is Fcon180 and fat percentage for VHIR distance.

TABLE 2. Correlation coefficients between match running and physical and anthropometrical variables in both groups together.

	Total distance (m)	LIR distance (m) (0–13 km/h)	HIR distance (m) (13–19 km/h)	VHIR distance (m) (> 19 km/h)
Height (cm)	-0.13	-0.04	-0.10	-0.31
Body mass (kg)	**-0.42***	-0.21	**-0.43***	**-0.55***
Body mass index	-0.41	-0.21	**-0.43***	**-0.49***
Fat percentage (%)	**-0.56***	-0.28	**-0.59***	**-0.73***
Lean mass (kg)	-0.18	-0.07	-0.18	-0.30
F0 (N/kg)	**0.47***	0.39	**0.42***	0.36
V0 (m/s)	-0.20	-0.15	-0.20	-0.15
Pmax (W/kg)	0.37	0.25	0.28	**0.55***
30-m sprint speed (s)	-0.23	-0.14	-0.16	**-0.44***
CMJ (cm)	0.16	0.11	0.05	0.39
VO_2max (ml/kg/min)	**0.57***	**0.46***	**0.54***	**0.41***
Max speed (km/h) in VO_2max test	0.21	0.27	0.21	-0.21
LT2 VO_2 (ml/kg/min)	**0.56***	**0.41***	**0.52***	**0.51***
LT2 speed (km/h)	**0.56***	**0.50***	**0.55***	0.19
LT1 VO_2 (ml/kg/min)	0.29	0.13	0.27	**0.48***
LT1 speed (km/h)	**0.53***	**0.45***	**0.52***	0.22
Econ60 (Nm/kg)	0.23	0.22	0.18	0.16
Eecc60 (Nm/kg)	0.07	0.02	0.06	0.24
Econ180 (Nm/kg)	0.35	0.17	0.31	**0.59***
Eecc180 (Nm/kg)	0.10	0.17	-0.01	0.11
Fcon60 (Nm/kg)	0.29	0.22	0.28	0.25
Fecc60 (Nm/kg)	-0.20	-0.23	-0.13	-0.09
Fcon180 (Nm/kg)	**0.45***	0.23	**0.52***	**0.43***
Fecc180 (Nm/kg)	-0.07	-0.01	-0.07	-0.18

Distances covered in low-intensity running (LIR), high-intensity running (HIR) and very-high-intensity running (VHIR). Force (F0), velocity (V0) and power (P_{max}) outputs from loaded squat jumps. Countermovement jump height (CMJ), Maximal oxygen consumption (VO_2max) and maximal speed during VO_2max test (sMax), speeds at lactate thresholds 1 (LT1 speed) and 2 (LT2 speed). Oxygen consumption lactate thresholds 1 (LT1 Vo2) and 2 (LT2 Vo2). Peak torques of knee extensors in concentric action with 60 degrees (Econ60) and 180 degrees (Econ180) per second and in eccentric action with 60 degrees (Eecc60) and 180 degrees (Eecc180) per second. Peak torques of knee flexors in concentric action with 60 degrees (Fcon60) and 180 degrees (Fcon180) per second and in eccentric action with 60 degrees (Fecc60) and 180 degrees (Fecc180) per second. * = Statistically significant correlation between selected anthropometry or physical variable and running distance in selected intensity, $p < 0.05$.

DISCUSSION

Several statistically significant, small to large, correlations were found between match running performance and physical qualities and anthropometry in the present study. Multiple regression analysis revealed that the identified variables could predict 22–65% of match running distances. Predictions were higher for VHIR (65%) and HIR (63%) compared to LIR (22%) and total (43%) distance. The most important quality to predict total distance was VO_2max, while the speed at the second lactate threshold best predicted LIR distance. HIR distance was influenced most by knee flexor peak concentric torque at a speed of 180 degrees per second, while body fat percentage best predicted VHIR distance.

The present study's match running performance was lower than reported in elite players during the 2019 World Cup [1]. Especially distance covered at speeds > 19 km/h were noticeably lower (~40–65% depending on position) compared to elite players [1]. This finding is supported by previous studies, which have shown that match running ability/demands increase with competition level [2], especially in terms of HIR and sprint distance [3]. Thus, it may be surprising that there were no statistically significant differences, and

TABLE 3. Regression models to predict match running variables.

Dependent variable	Adjusted R^2	Predictors	B (95%CI)	Standard error	Importance	Significance
Total Distance (m)	0.426					
		Constant	1106.58 (-2965.03 to 5178.20)	1963.29		0.579
		VO_2max (ml/kg/min)	145.04 (57.80 to 232.27)	42.06	0.664	0.020
		Fcon180 (Nm/kg)	1403.88 (218.02 to 2589.73)	571.81	0.336	0.022
LIR distance (m)	0.215					
		Constant	4161.81 (1792.43 to 6531.19)	1145.37		0.001
		LT2 speed (km/h)	265.75 (66.19 to 465.30)	96.46	1.000	0.011
HIR distance (m)	0.633					
		Constant	-1312.43 (-3458.05 to 833.19)	1028.98		0.217
		Fcon180 (Nm/kg)	690.07 (246.10 to 1134.05)	212.84	0.396	0.040
		F0 (N/kg)	35.59 (5.01 to 66.17)	14.66	0.222	0.025
		LT2 speed (km/h)	146.06 (14.00 to 278.12)	63.31	0.201	0.032
		Fat percentage	-25.85 (-50.47 to -1.24)	11.80	0.181	0.040
VHIR distance (m)	0.654					
		Constant	1911.33 (731.08 to 3091.60)	567.54		0.003
		Fat percentage	-19.65 (-28.21 to -11.09)	4.12	0.649	< 0.001
		Fcon180 (Nm/kg)	213.39 (42.71 to 384.08)	82.08	0.192	0.017
		30-m sprint speed (s)	-290.51 (-546.20 to -34.82)	122.95	0.159	0.028

LIR, HIR and VHIR = low- (< 13 km/h), high- (13–19 km/h) and very high-intensity (> 19 km/h) running distance during the match, Confidence interval (CI), maximal oxygen consumption (VO_2max), speed at lactate threshold 2 (LT2 speed), concentric knee flexor peak torque with a speed of 180 degrees per second (Fcon180) and force output in loaded squat jumps (F0).

mostly trivial effect sizes, in match running performance between 1st team and U18-team players observed in the present study. The only statistical difference between the two teams was peak isokinetic knee extensor torque at 180 degrees per second. As there were no major differences in physical qualities between groups, this could explain why there were no observed differences in match running performance. On the other hand, running performance in a soccer match is affected by several contextual aspects [8, 9, 10] not just competition level [2, 3], physical qualities (VO_2max [7, 19], strength [18, 20] or sprint speed [17, 18, 20]) or body composition [24]. Physical performance is suggested to be greatest in matches against similarly ranked opponents, perhaps due to a greater perceived chance of winning [8]. Based on the teams' league ranking during the 11-week period (1st team bottom three and U18-team mid-table), the U18-team played more matches against similarly ranked opponents, which could have increased match running performance compared to the 1st team, reducing the otherwise expected differences.

This study's national level players' height and body mass were similar than previously reported in elite women players, but body fat percentage was higher compared to elite women players [14, 15, 21]. Multiple regression analyses revealed that physical qualities and anthropometry predicted 65% of VHIR distance covered in the match and body fat percentage was the most important (importance 0.649) predictor in that model. Significant negative correlations between body fat percentage and HIR (r = -0.38) and sprint running (r = -0.57) distances have been reported in professional men players previously [24]. Nevertheless, findings of the present study highlight the role of body composition also in women players. Based on the present predictive modelling, one percentage point decrease in body fat would increase VHIR distance covered in the match by 19.65 meters. Improvement in body composition would also improve body mass adjusted strength and power, consequently having a positive effect to match running performance. Thus, strength training is recommended to national level women soccer players to improve absolute strength and body mass adjusted power qualities, as well as increase lean mass, thus, improving muscle: fat ratio [36].

Other important variables to predict VHIR were Fcon180 (importance 0.192) and 30-meter sprint time (importance 0.159). Associations between VHIR and Fcon180 was expected in the present study since leg muscle thickness and architecture along with VO_2max

were predictors of high intensity running in women collegiate soccer match [19]. Also, moderate-to-strong correlations between 30-meter sprint time and HIR and sprint distances covered in the match have been previously reported [17]. Overall players performance in a 30-meter sprint test [11, 15] and in isokinetic strength tests reported in the present study were weaker than reported with elite players [37]. Thus, there appears to be a need to improve both maximum strength and power/sprint ability in the players of the present study, which should increase players' VHIR and HIR distances in the match, based on findings of present study.

Fcon180 (importance 0.396), F0 (importance 0.222), LT2 speed (importance 0.201) and fat percentage (importance 0.181) predicted 63% of HIR distance. Thus, compared to predictors of VHIR, the role of strength qualities increases and body fat percentage decreases for this variable. Such predictors are similar to those reported by McCormack et al's [19] regression model where VO_2max, vastus lateralis thickness and pennation angle were the strongest predictors of HIR distance covered in women collegiate soccer matches. In the present study, knee flexor strength at relative high contraction speed and estimated body mass adjusted maximum force in ballistic movement (F0) were most important to predict HIR distance. These findings are likely in agreement because pennation angle increases alongside increases in muscle mass [38] and muscle mass is the greatest predictor of strength [39]. The only exception between studies was our model placed more emphasis on LT2 speed instead of VO_2max to predict HIR distance, whereas VO_2max was the only variable to describe aerobic capacity in McCormack et al. [19].

Multiple regression analyses predicted 22% of LIR and 43% of total distance covered in the match. Based on these findings, anthropometry and physical qualities have a greater influence on VHIR and HIR distance than LIR and total distance covered in the match. Mohr et al. [3] found that higher-level players outperform lower-level counterparts in HIR and sprint distance while there was no major difference in total distance covered in the match. Thus, it is possible that total and LIR distance covered in the match are more stable variables, not reliant on specific qualities or trainable characteristics. Of note, absolute VO_2max values were lower than reported in previous studies with elite players, which averaged 50–55 ml/kg/min [7, 12, 13, 14]. Findings of the present study showed that if players' VO_2max would be improved to an elite level (+10 ml/kg/min) total distance covered in the match could theoretically increase by 1450 meters. The association of VO_2max and total distance is logical, although there are varying coefficients reported between total distance and VO_2max [7, 19]. Therefore, improving VO_2max may have a direct impact on total distance covered during the match, but this interpretation should be confirmed in a randomized-controlled trial.

The strengths of the study were high-quality laboratory test methods (incremental treadmill test, isokinetic strength, DXA) used to measure players' physical qualities and anthropometry. Also, the relatively high number of match observations from official league matches providing ecological validity of match demands at the national level. Further, the typically neglected use of multiple regression analysis allowed deeper insights into the relative importance of specific physical qualities and anthropometry to match running performance. This may also explain higher R^2 values in present study compared to previous studies, which have used simple linear regression [17, 18].

The biggest limitation of the study, as in other studies [16], was that players' positions were not taken into consideration in analysis. Previous studies have shown that players' running performance during the match, anthropometry and physical qualities vary between playing positions [5] and compiling all positions together would likely increase the variability in the data. In this study, subjects were national level players, so conclusions cannot be directly generalized to elite-level players in which the variance of physical qualities and anthropometry can be smaller compared to national level players [11, 12].

Practical applications

Coaches should be aware of women players' physical qualities and place particular emphasis on improving e.g. sprint speed, maximum (high-speed) strength, and muscle:fat ratio along with tactical and technical aspects of soccer. To improve HIR and VHIR distance in matches, the results suggest that sprint training as well as resistance and power/plyometric training should be an integral part of women players' periodized training program. While body composition was also a predictor of HIR and VHIR, it should be noted that the body composition of young athletes is influenced by their growth and maturity status, and there is a high inter-individual variation in healthy body composition. Further, given the influence of strength variables on performance, the emphasis should be to increase muscle mass (thus reducing fat %) rather than reduce fat mass *per se*. To improve total and LIR distances, it is recommended to improve aerobic capacity through small-sided games and/or interval training.

CONCLUSIONS

Physical qualities and anthropometry are related to, and can predict 22–65% of, national level women players' running performance during matches. Physical qualities and anthropometry demonstrated greater prediction magnitudes of very high-intensity running (> 19 km/h) (65%) and high-intensity running (13–19 km/h) (63%) than to low-intensity (< 13 km/h) (22%) and total (43%) running distances. To increase total distance covered in the match, the most important quality to improve would be VO_2max. To increase high-intensity and very high-intensity running distances, improvement of high-speed (especially knee flexor) maximum force production, body composition, and sprint speed are identified as the most important in the present study.

Conflict of interest declaration

The authors declare no conflict of interest.

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Position specific physical demands in different phases of competitive matches in national level women's football

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ABSTRACT: The purpose of the present study was twofold: to investigate position-specific physical match demands of national level women's football; and to examine if demands change during a match (comparison between first and second half and in 15-minute intervals). Seven teams from the Finnish National League participated in the study. Eighty-five players met the inclusion criteria, and a total of 340 individual match observations from 68 individual matches were included for analysis. The Polar Team Pro -player tracking system (with 10 Hz GPS units, including 200 Hz tri-axial accelerometer, gyroscope, magnetometer and HR monitor) was used to assess positional data and HR response of the players. This study demonstrated that women's national level football matches place a range of physical demands on players, which in general were highest for wide midfielders, and lowest for central defenders. Wide midfielders and forwards performed significantly more 'very high-speed' running, sprinting, accelerations, and decelerations than other outfield positions ($p < 0.05$). HRmean varied from 84–87% of HRmax and was significantly lower for central defenders than central midfielders ($p < 0.001$). External load variables varied during a match and generally decreased especially after 60 minutes of play compared to first 15-min period of the match. Present study showed that national level women football players' positional differences in match demands are similar to those reported with elite players in previous studies. On national level, players' physical performance tended to decrease towards the end of the match, especially in terms of total distance (~10%), high-speed running (~20%), and decelerations (~20%).

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INTRODUCTION

A comprehensive understanding of position and match-specific physical demands is vital to apply a systematic approach to training that reflects the physical load players will face during games [1, 2]. Studies have shown that physical demands are highest in the beginning of the match and decrease towards the end of the match [3–6]. To date there are only a limited number of studies that have investigated position-specific physical demands during different phases of a match. Furthermore, scientific literature has focused primarily on physical demands of elite players, leaving a gap in the literature that is essential for understanding and enhancing player development [2].

Previous studies have shown that elite female players cover a total distance (TD) of 9–11 kilometres [1, 4, 7–11]. The highest TD recorded has been observed in central midfielders (CM) and the lowest in central defenders (CD) [1, 11, 12]. Dividing a match into 15-minute periods allows for the identification of changes in movement patterns and helps to understand the impact of fatigue on performance [13]. In a sample of elite level outfield players, a significant decrease in TD has been observed at 60–75 minutes and 75–90 minutes compared to 0–15 minutes [4]. Position-specific analyses have shown that TD decreases from the first to last 15 minutes by 5–13% in all outfield positions except forwards (FW) [14].

Instead of TD, volume of high-intensity running appears to better reflect the requirements of the game [7, 15–17] as elite athletes tend to cover larger distances at high intensities than domestic athletes [2]. Regrettably, there is inconsistency in women's football research concerning speed zones and their definitions [1]. High-speed running (16–20 km/h) and sprinting (> 20 km/h) zones have been used in the previous literature [8, 12, 18–20]. Recent studies [10, 11] however, have used thresholds including 12.5 km/h for high-speed running (HSR), 19.0 km/h for very high-speed running (VHSR), and 22.5 km/h for sprinting (SPR) as suggested by Park et al. [21]. A match analysis of the FIFA Women's World Cup 2019 used almost identical thresholds for the highest three zones: 13 km/h (Zone 3), 19 km/h (Zone 4), and 23 km/h (Zone 5) [1]. Elite level female players have been shown to complete from 1676–2749 m of HSR, 349–666 m of VHSR and 82–255 m of SPR depending on the playing position [1, 11].

The volume of high-intensity running has been shown to vary considerably between different positions [1, 8, 9, 12, 22]. CD cover the lowest distances in high-intensity zones [1, 11, 12, 22] whereas

CM run substantially more HSR than other players [1, 11, 12], and wide midfielders (WM) perform the highest volume of VHSR and SPR. Full backs (FB) and FW also cover a higher volume of VHSR and SPR than CD and CM [1, 11, 12].

A decrease of up to a range of 25–35% in HSR has been observed between the first and last 15 minutes of the match in a sample of all positions [3, 4, 6, 9]. Panduro et al. [14] showed that HSR and VHSR of all outfield positions decreased significantly in the last 15-minute period of a match compared to the first 15-minute period. Similar results were found with SPR in all positions except FW [14]. Evidence from other studies, however, has shown that SPR distance does not change significantly between the 15-min periods, unlike between the first and second halves [4, 5].

Acceleration and deceleration parameters in women's football have received only limited attention, despite metabolic consumption being higher compared to steady running [23, 24]. Indeed, a number of accelerations and decelerations vary considerably between studies [7, 8, 25, 26] and a common definition for acceleration and deceleration thresholds does not exist. Recent studies in men have used thresholds of > 2 m/s^2 and < -2 m/s^2 with a range of 76–94 accelerations and 54–99 decelerations per match [23, 27]. In women's international level matches, ~160 accelerations (> 2.26 m/s^2) have been reported [8, 25]. International level players tend to perform more accelerations and decelerations during match [7] than national level players [28] and no major position-specific differences have been observed [7, 26]. A recent study [14] reported a higher number of moderate accelerations (1.50–2.99 m/s^2) and decelerations (-1.50 – -2.99 m/s^2) for CM and WM than CD. They also reported that the total number of accelerations and decelerations was significantly lower during the match's last 15-minutes period compared to the first 15-min in all outfield positions [14], but their comparison was limited only to the first and the last 15-min periods of a match.

Heart rate (HR) measurement is often used as an indirect measure of intensity during training or matches and is used to observe the internal load of players [29]. As a result of short and intense efforts, the average HR of women footballers during matches has been reported to be 84–89% and the HR peak 98–100% [3, 30, 31]. A HR of about 85% of maximum HR corresponds to about 75% of maximal oxygen uptake [15, 17, 27, 32]. This indicates that players experience a high aerobic load throughout the match [33]. Average HR were reported significantly higher in the second half in all outfield positions except FW, however there were no differences in average HR between first and last 15 minutes period in the match in any position [14].

Scientific literature is still lacking research of women's national level position-specific match demands. Therefore, purpose of the study is to (1) identify positional differences in match demands of national level female football players and to (2) investigate if positional match demands change during a match (between 1st and 2nd halves or between 15-minute periods).

MATERIALS AND METHODS

During the 2020 season, 10 teams from the highest Finnish women's football league were recruited and 7 teams participated to in this observational study. A minimum of four and maximum of nine matches for each team were included for analysis with an average of 7.6 ± 1.7 matches per team. Only data from players completing full matches (90 min) were included. Of the eligible 125 players in the league who provided consent for participation, a total of 85 players (age: 23.7 ± 4.1 years, height: 168.0 ± 6.2 cm, weight: 64.3 ± 8.1 kg) were accepted in the analysis. On average 4.0 ± 2.6 matches per player were analysed (range 1–9 matches). In total, 340 match observations were completed from 68 matches. All participants provided written informed consent prior to participating the study. The study was conducted according to the declaration of Helsinki and was approved by the ethics committee of the University of Jyväskylä (1064/13.00.04.00/2020).

Positional data and HR response were collected using Polar Team Pro units (Polar Electro Oy, Kempele, Finland) with GPS (Global Positioning System) sampling at a 10 Hz frequency, 200 Hz tri-axial accelerometer, gyroscope, magnetometer and HR monitor, and analysed using proprietary software. According to Scott et al. [34], all GPS devices can determine distances accurately during team sport simulations (trainings and matches) and can therefore reasonably be used in team sports. Good to moderate reliability (< 5% CV) and validity for total distance, linear running and team sport simulation circuit have been shown for the Polar Team Pro system [35].

Players were divided into five distinct outfield playing positions for analysis: central defender (CD, number of observations 86), fullback (FB, 40), central midfielder (CM, 98), wide midfielder (WM, 31) and forward (FW, 48). Full-game data is presented to describe the complete match demands of the game for each position. Moreover, to examine possible changes in demands during matches, data from first to second half and between 15-minute periods were compared and analyzed [5, 7]. In addition, full-game values and values for each half are presented for goalkeepers.

Prior to starting analysis, player data were excluded in cases where it was missing fully or partly from the match, i.e., in situations where the player tracking system did not record data for the whole match (n = 8). During data review, error peaks were removed from peak heart rates (e.g., player heart rate peak well above 100% of HRmax) and peak speeds (e.g., all speed peaks above 35 km/h).

Mean and peak HR were analysed based on a continuous measurement throughout the match, excluding the half-time break. HRmax was defined as each individual player's maximum HR collected during the measurement period. Mean and peak HRs are presented as a percentage relative to maximum heart rate (% HRmax). Time spent in different HR zones (as a percentage of total playing time) was classified as follows: HRZ1 (50–59% of maximum heart rate), HRZ2 (60–69%), HRZ3 (70–79%), HRZ4 (80 –89%), HRZ5 (90–100%). Time spent in HRZ1 and HRZ2 was limited and thus is not presented in the results.

Positional analysis of distances covered in different speed zones, peak speed, and total distances were extracted using proprietary software. The movement velocity of the players was divided into five speed zones: speed zone 1 (< 7 km/h), speed zone 2 (7–13 km/h), speed zone 3 (HSR, 13–19 km/h), speed zone 4 (VHSR, 19–23 km/h), and speed zone 5 (SPR, > 23 km/h) [1]. The distances covered in HSR, VHSR and SPR are presented. Accelerations and decelerations were summarized when the acceleration or deceleration speed exceeded the threshold of ± 2.00 m/s^2 as defined in previous research [5, 24].

Data analyses were performed using SPSS software (version 26, IBM SPSS Statistics, Chicago, IL, USA). The threshold for statistical significance was set at $p < 0.05$. Data are presented as mean ± standard deviation unless otherwise stated. The Shapiro-Wilk test was used to test for normal distribution. If the requirement for a normal distribution was not met, variables were removed from analysis (e.g., 15 min period HRZ1 & HRZ2) or the variables were combined (e.g., in 15-minute periods the VHSR and SPR were combined) to meet the assumption of a normal distribution.

For each full match, position-specific differences were assessed using one-way ANOVA. Goalkeepers were excluded from the statistical analysis. To determine whether there was a position-specific significant interaction between first and second half, as well as between 15-minute periods, a two-way ANOVA (position*time) was used with repeated measures. If a significant interaction was observed, a one-way ANOVA was used between the first and second half or 15-minute period values. Effects were further analysed by performing Bonferroni corrected pairwise comparisons.

RESULTS

Table 1 shows positional differences in full match demands. WM and CM had highest TD covered, while CD covered the significantly

TABLE 1. Positional differences in match demands.

	GK	CB	FB	CM	WM	FW
TD [m]	4788 ± 389	9275 ± 566 ^{b,c,d,e}	10063 ± 762 ^{a,c,d}	10634 ± 707 ^{a,b}	10797 ± 681 ^{a,b,e}	10295 ± 731 ^{a,d}
HSR [m] (13–19 km/h)	148 ± 84	1515 ± 289 ^{b,c,d,e}	1785 ± 336 ^{a,c,d,e}	2251 ± 470 ^{a,b,e}	2233 ± 449 ^{a,b}	2027 ± 365 ^{a,b,c}
VHSR [m] (19–23 km/h)	10 ± 15	215 ± 71 ^{b,c,d,e}	317 ± 100 ^{a,d,e}	326 ± 156 ^{a,d,e}	445 ± 113 ^{a,b,c}	405 ± 126 ^{a,b,c}
SPR [m] (≥ 23 km/h)	2 ± 8	45 ± 31 ^{b,d,e}	82 ± 52 ^{a,d,e}	61 ± 62 ^{d,e}	136 ± 76 ^{a,b,c}	115 ± 70 ^{a,b,c}
Peak speed [km/h]	20.1 ± 2.7	26.3 ± 1.7 ^{b,d,e}	27.4 ± 1.9 ^{a,c}	25.8 ± 2.0 ^{b,d,e}	27.7 ± 1.8 ^{a,c}	27.5 ± 1.9 ^{a,c}
Accelerations [n] (> 2.00 m/s^2)	25.8 ± 9.2	67.5 ± 16.3 ^{c,d,e}	74.3 ± 16.8 ^{d,e}	82.5 ± 20.9 ^{a,d,e}	98.3 ± 19.1 ^{a,b,c}	92.9 ± 21.6 ^{a,b,c}
Decelerations [n] (< -2.00 m/s^2)	24.9 ± 11.2	79.0 ± 16.5 ^{c,d,e}	90.3 ± 20.6 ^{c,d,e}	105.1 ± 23.4 ^{a,b,d,e}	121.5 ± 18.3 ^{a,b,c}	118.4 ± 26.3 ^{a,b,c}
HR mean (%/ HR_{max})	75.2 ± 5.2	84.2 ± 5.3 ^{c}	86.0 ± 3.9	86.9 ± 3.5 ^{a}	85.2 ± 4.4	85.8 ± 3.3
HR peak (%/ HR_{max})	90.6 ± 4.6	96.2 ± 2.6	97.5 ± 2.8	97.1 ± 2.3	97.5 ± 2.4	97.3 ± 2.8
HRZ3 (70–80%/ HR_{max})%/ total time	41.4 ± 13.5	17.0 ± 11.6 ^{c}	13.4 ± 9.2	10.9 ± 8.3 ^{a}	14.1 ± 8.8	12.8 ± 8.1
HRZ4 (80–90%/ HR_{max})%/ total time	26.4 ± 16.8	48.0 ± 13.3	49.3 ± 14.7	43.2 ± 14.2 ^{e}	48.3 ± 15.1	54.7 ± 15.6 ^{c}
HRZ5 (90–100%/ HR_{max})%/ total time	3.7 ± 22.5	27.9 ± 20.9 ^{c}	33.5 ± 20.3	42.1 ± 21.5 ^{a,e}	31.7 ± 21.8	28.6 ± 21.3 ^{c}

TD = total distance covered during match, HSR = High-speed running distance covered during match, VHSR = very high-speed running distance covered during match, SPR = sprint distance covered during match, HR = heart rate, HRZ3–5 = heart rate zones 3–5. GK = goalkeepers, CD = central defenders, FB = full backs, CM = central midfielders, WM = wide midfielders, FW = forwards. Statistically significant difference ($p < 0.05$) compared to a = central defenders, b = full backs, c = central midfielders, d = wide midfielders, e = forwards.

lower TD compared to other outfield positions. WM and FW players had significantly more VHSR, SPR, number of accelerations and decelerations than other outfield positions, while CD results in same parameters were significantly lower than other positions.

Mean HR was 85.7% of HRmax. The only statistically significant difference observed was a higher average HR in CM compared to CD. Players spent about 50% of the match time on HRZ4. CM spent significantly more time in HRZ5 compared to CD and FW. Only 3–6% of total match time was spent in HRZ1 and HRZ2.

Table 2 shows match demands during the first and second halves. Statistically significant decrement in external load was observed only in TD and HSR of CM, while VHSR distance of CD increased significantly from first to second half. In terms of internal load, time spent in HRZ5 decreased significantly in FB and CM. Time spent in HRZ3 increased significantly in FB, CM and WM.

Table 3 shows match demands in 15-minute periods. In TD each position decrement from 0–15 minutes to 60–75 minutes and to 75–90 minutes periods was statistically significant. In HSR, the decrement towards the end of the match was highest and statistically significant compared to the 0–15 minutes in center positions (CD, CM and FW, $p < 0.05$). In combined VHSR & SPR distance only WM had statistically significant differences between 15-min periods. The number of decelerations decreased significantly towards the end of the match in all positions, but the number of accelerations only decreased significantly in only CM.

There were some statistically significant differences between 15-min periods in HRmean with FB, CM, and FW, and in HRpeak with CD, CM, and WM. Time spent in HRZ3 was higher during the last three 15-minute periods compared to first three periods in all positions, but statistically significant differences were observed only with FB and

TABLE 2. Positional match demands during first and second half

	Half	GK	CD	FB	CM	WM	FW
TD [m]	1st	2416 ± 200	4642 ± 390	5075 ± 385	5373 ± 390*	5396 ± 307	5205 ± 371
	2nd	2372 ± 250	4632 ± 380	4988 ± 449	5261 ± 363	5401 ± 417	5090 ± 401
HSR [m] (13–19 km/h)	1st	65 ± 37	759 ± 160	901 ± 168	1169 ± 264*	1122 ± 246	1042 ± 179
	2nd	83 ± 56	756 ± 158	885 ± 195	1083 ± 235	1111 ± 240	985 ± 200
VHSR [m] (19–23 km/h)	1st	2 ± 4	100 ± 38*	165 ± 59	165 ± 80	218 ± 69	203 ± 78
	2nd	8 ± 13	115 ± 49	153 ± 63	162 ± 87	226 ± 72	202 ± 72
SPR [m] (≥ 23 km/h)	1st	0 ± 1	23 ± 20	41 ± 29	30 ± 35	65 ± 41	57 ± 45
	2nd	2 ± 7	22 ± 19	41 ± 27	31 ± 34	71 ± 44	58 ± 40
Peak speed [km/h]	1st	18.1 ± 2.1	25.3 ± 1.9	26.4 ± 2.0	25.1 ± 2.2	26.9 ± 1.8	26.4 ± 2.1
	2nd	19.8 ± 3.0	25.3 ± 1.9	26.5 ± 2.3	25.0 ± 2.0	26.8 ± 2.0	26.7 ± 2.0
Accelerations [n] (> 2.00 m/s^2)	1st	12.5 ± 4.8	33.4 ± 11.4	37.7 ± 8.7	41.7 ± 11.4	49.1 ± 11.9	47.4 ± 11.8
	2nd	13.3 ± 6.2	34.0 ± 11.6	36.6 ± 11.2	40.9 ± 11.6	49.2 ± 10.4	45.5 ± 12.8
Decelerations [n] (< -2.00 m/s^2)	1st	12.5 ± 4.8	39.5 ± 9.0	46.2 ± 10.8	53.8 ± 12.5	62.8 ± 11.0	60.9 ± 13.3
	2nd	13.3 ± 6.2	39.5 ± 10.0	44.1 ± 11.4	51.3 ± 12.9	58.8 ± 10.2	57.5 ± 15.1
HR mean [%HR_{max}]	1st	75.4 ± 5.4	84.4 ± 5.6	86.9 ± 3.9	87.9 ± 3.3*	86.1 ± 4.5	86.2 ± 3.8
	2nd	75.1 ± 5.4	83.8 ± 5.8	85.2 ± 4.4	85.9 ± 4.4	84.1 ± 4.6	85.1 ± 3.5
HR peak [%HR_{max}]	1st	89.5 ± 4.6	95.4 ± 2.9	96.6 ± 2.7	96.5 ± 2.3	97.1 ± 2.2	96.2 ± 3.0
	2nd	89.4 ± 5.4	95.2 ± 2.7	96.0 ± 3.2	96.1 ± 2.6	96.5 ± 2.6	96.2 ± 3.5
HRZ3 (70–80%/HR_{max}) %/ total time	1st	41.6 ± 13.8	16.1 ± 12.3	10.0 ± 8.9*	8.4 ± 8.1*	11.0 ± 8.9*	11.2 ± 8.9
	2nd	41.4 ± 15.1	18.0 ± 12.6	16.7 ± 10.7	13.4 ± 10.0	17.6 ± 11.5	14.4 ± 9.3
HRZ4 (80–90%/HR_{max}) %/ total time	1st	28.1 ± 20.8	47.8 ± 15.4	47.1 ± 16.4	41.3 ± 16.7	45.9 ± 18.3	53.7 ± 17.3
	2nd	24.8 ± 19.2	48.3 ± 14.3	51.5 ± 14.9	45.1 ± 14.1	51.2 ± 14.9	56.1 ± 16.7
HRZ5 (90–100%/HR_{max}) %/ total time	1st	3.0 ± 6.1	29.7 ± 23.0	39.3 ± 22.5*	47.7 ± 22.9*	37.5 ± 24.3	31.6 ± 23.7
	2nd	4.2 ± 9.0	26.4 ± 20.5	28.1 ± 21.1	36.8 ± 22.3	26.2 ± 21.0	26.0 ± 20.6

TD = total distance covered during match, HSR = High-speed running distance covered during match, VHSR = very high-speed running distance covered during match, SPR = sprint distance covered during match, HR = heart rate, HRZ3–5 = heart rate zones 3–5. GK = goalkeepers, CD = central defenders, FB = full backs, CM = central midfielders, WM = wide midfielders, FW = forwards. * = Statistically significant difference ($p < 0.05$) compared to second half.

TABLE 3. Positional match demands in 15 minutes intervals

	Period	CD	FB	CM	WM	FW
Total distance [m]	*0–15 min*	1544 ± 118 [2,3,4,5,6]	1654 ± 131 [5,6]	1789 ± 143 [2,3,4,5,6]	1782 ± 140 [5,6]	1730 ± 160 [2,5,6]
	15–30 min	1449 ± 122 [1,6]	1602 ± 134 [5]	1684 ± 142 [1,5,6]	1676 ± 144	1619 ± 129 [1,6]
	30–45 min	1458 ± 138[1,5,6]	1599 ± 159 [5]	1692 ± 150 [1,5,6]	1694 ± 164	1646 ± 142 [5,6]
	45–60 min	1479 ± 129 [1,5,6]	1576 ± 143	1676 ± 133 [1,5,6]	1714 ± 147	1645 ± 130 [5,6]
	60–75 min	1396 ± 129 [1,3,4]	1500 ± 159 [1,2,3]	1596 ± 150 [1,2,3,4]	1654 ± 161 [1]	1543 ± 160 [1,3,4]
	75–90 min	1383 ± 125 [1,2,3,4]	1516 ± 168 [1]	1570 ± 138 [1,2,3,4]	1600 ± 147 [1]	1518 ± 145 [1,2,3,4]
HSR [m] (13–19 km/h)	*0–15 min*	282 ± 71[2,3,4,5,6]	303 ± 61	422 ± 106 [2,3,4,5,6]	400 ± 105 [6]	378 ± 86 [2,3,5,6]
	15–30 min	233 ± 65 [1]	292 ± 76	367 ± 91 [1,5,6]	347 ± 96	315 ± 63 [1]
	30–45 min	224 ± 69 [1]	277 ± 76	346 ± 96 [1]	338 ± 97	314 ± 72 [1]
	45–60 min	248 ± 70 [1]	294 ± 79	363 ± 92 [1,6]	356 ± 89	337 ± 73 [6]
	60–75 min	223 ± 61 [1]	265 ± 72	327 ± 83 [1,2]	335 ± 90	294 ± 81 [1]
	75–90 min	226 ± 58 [1]	258 ± 75	310 ± 84 [1,2,4]	326 ± 91 [1]	284 ± 82 [1,4]
VHSR & SPR [m] (≥ 19 km/h)	*0–15 min*	44 ± 28	69 ± 37	72 ± 43	119 ± 46 [2,3,4]	97 ± 46
	15–30 min	38 ± 26	72 ± 30	62 ± 46	82 ± 38 [1]	74 ± 50
	30–45 min	39 ± 26	61 ± 31	55 ± 45	72 ± 37 [1]	79 ± 41
	45–60 min	44 ± 29	60 ± 32	59 ± 43	88 ± 39 [1]	87 ± 46
	60–75 min	41 ± 25	60 ± 36	60 ± 40	95 ± 34	79 ± 31
	75–90 min	42 ± 28	56 ± 36	59 ± 44	94 ± 42	75 ± 42
Peak speed [km/h]	*0–15 min*	23.5 ± 2.1	24.3 ± 2.6	23.8 ± 2.3	25.7 ± 2.3	25.2 ± 2.1
	15–30 min	23.5 ± 2.6	24.7 ± 2.2	23.5 ± 2.4	25.0 ± 2.3	24.2 ± 2.7
	30–45 min	23.4 ± 2.5	24.6 ± 2.0	23.2 ± 2.4	25.2 ± 2.3	24.7 ± 2.0
	45–60 min	23.1 ± 2.2	23.9 ± 2.1	23.4 ± 2.2	25.1 ± 2.0	25.1 ± 2.5
	60–75 min	23.6 ± 2.2	24.4 ± 2.6	23.4 ± 2.2	25.8 ± 1.9	25.2 ± 2.0
	75–90 min	23.6 ± 2.3	24.4 ± 3.0	23.4 ± 2.4	25.0 ± 2.3	24.7 ± 2.2
Accelerations [n] (> 2.00 m/s²)	*0–15 min*	12.0 ± 3.9 [3]	13.0 ± 4.2	15.1 ± 4.9 [2,3,5,6]	16.7 ± 5.5	16.8 ± 4.7
	15–30 min	10.6 ± 4.1	11.9 ± 3.8	12.7 ± 4.5 [1]	14.8 ± 4.9	14.2 ± 4.9
	30–45 min	9.9 ± 3.2 [1]	11.2 ± 4.0	12.6 ± 4.8 [1]	15.6 ± 5.0	14.9 ± 4.4
	45–60 min	10.6 ± 4.3	11.0 ± 3.9	13.6 ± 4.7	16.0 ± 4.7	14.9 ± 4.7
	60–75 min	10.2 ± 4.1	11.6 ± 4.1	11.8 ± 4.5 [1]	14.4 ± 3.6	13.9 ± 5.1
	75–90 min	10.5 ± 4.6	11.1 ± 4.3	12.2 ± 5.4 [1]	15.0 ± 5.3	13.9 ± 4.5
Decelerations [n] (< -2.00 m/s²)	*0–15 min*	13.6 ± 4.1 [6]	16.2 ± 5.2 [5,6]	18.6 ± 5.4 [5,6]	21.5 ± 5.4 [5,6]	21.2 ± 4.7 [2,5,6]
	15–30 min	12.5 ± 3.8	14.2 ± 4.5	16.8 ± 5.1	18.8 ± 4.5	17.5 ± 4.9 [1]
	30–45 min	12.2 ± 3.8	14.1 ± 4.3	16.6 ± 4.8	20.3 ± 5.8	19.8 ± 4.4 [5]
	45–60 min	13.1 ± 4.4	14.9 ± 4.2	17.6 ± 5.6 [5,6]	18.8 ± 5.6	19.6 ± 4.7 [5]
	60–75 min	12.0 ± 4.0	12.9 ± 4.1 [1]	14.8 ± 4.5 [1,4]	17.5 ± 3.6 [1]	16.3 ± 5.1 [1,3,4]
	75–90 min	11.6 ± 3.7 [1]	13.0 ± 4.3 [1]	15.1 ± 4.9 [1,4]	17.7 ± 4.7 [1]	17.8 ± 4.5 [1]
HR mean [%HR_{max}]	*0–15 min*	84.3 ± 4.9	86.3 ± 3.9	86.9 ± 3.8 [3]	85.8 ± 4.5	85.4 ± 3.8
	15–30 min	84.8 ± 6.0	87.5 ± 4.4 [4]	88.0 ± 3.7 [4,6]	86.3 ± 5.1	86.3 ± 3.7
	30–45 min	85.0 ± 5.8	87.2 ± 4.7	88.7 ± 3.6 [1,4,5,6]	86.3 ± 5.2	87.0 ± 4.4 [4]
	45–60 min	83.0 ± 6.3	84.5 ± 3.5 [2]	85.4 ± 4.4 [2,3]	84.4 ± 4.2	84.4 ± 3.7 [3]
	60–75 min	83.9 ± 6.2	84.8 ± 5.2	86.3 ± 4.2 [3]	84.2 ± 5.0	85.6 ± 3.3
	75–90 min	84.3 ± 6.3	85.9 ± 4.9	86.0 ± 5.0 [2,3]	84.2 ± 5.7	86.0 ± 3.4
HR peak [%HR_{max}]	*0–15 min*	93.7 ± 3.3	95.5 ± 2.7	95.2 ± 2.6	95.3 ± 2.7	94.3 ± 3.2
	15–30 min	94.2 ± 3.3 [4]	95.8 ± 2.9	95.5 ± 2.3	96.2 ± 2.6 [4]	94.6 ± 2.9
	30–45 min	94.0 ± 2.9	95.4 ± 2.9	95.9 ± 2.4 [4]	95.9 ± 2.5 [4]	95.1 ± 3.3
	45–60 min	93.1 ± 3.2 [2]	93.4 ± 2.7	94.5 ± 2.9 [3]	93.4 ± 2.9 [2,3,5]	94.2 ± 3.7
	60–75 min	94.1 ± 3.0	94.8 ± 3.3	95.2 ± 2.5	95.7 ± 3.1 [4]	94.6 ± 3.7
	75–90 min	93.9 ± 3.1	95.1 ± 3.3	94.8 ± 2.8	94.7 ± 3.0	94.9 ± 3.1
HRZ3 (70–80% HR_{max}) % total time	*0–15 min*	16.1 ± 13.4	11.5 ± 10.2	9.4 ± 9.3 [5]	9.8 ± 8.8	12.5 ± 10.8
	15–30 min	16.2 ± 14.1	10.0 ± 10.2 [5]	9.4 ± 10.0 [5]	11.2 ± 10.7	11.1 ± 10.4
	30–45 min	15.3 ± 15.6	8.2 ± 10.0 [4,5]	6.2 ± 8.6 [4,5,6]	11.6 ± 12.2	9.9 ± 10.2
	45–60 min	19.4 ± 14.7	16.8 ± 10.3 [3]	13.5 ± 11.2 [3]	16.1 ± 12.7	17.1 ± 12.7
	60–75 min	17.4 ± 14.1	18.7 ± 13.8 [2,3]	14.2 ± 11.4 [1,2,3]	17.1 ± 10.9	13.8 ± 11.2
	75–90 min	16.9 ± 14.2	14.9 ± 13.8	12.8 ± 10.9 [3]	17.5 ± 14.8	12.3 ± 9.2

TABLE 3. Continue.

	Period	CD	FB	CM	WM	FW
HRZ4 (80–90% HR_{max}) % total time	*0–15 min*	50.9 ± 17.1	48.1 ± 17.1	44.7 ± 19.6	47.6 ± 22.0	55.3 ± 16.9
	15–30 min	45.3 ± 17.5	45.9 ± 20.9	40.2 ± 18.7	46.0 ± 20.4	54.0 ± 19.7
	30–45 min	47.6 ± 19.4	47.8 ± 19.8	39.4 ± 20.1 [4]	44.4 ± 20.1	52.3 ± 23.6
	45–60 min	49.4 ± 17.8	57.0 ± 14.9	47.2 ± 16.2 [3]	55.8 ± 18.9	57.1 ± 19.3
	60–75 min	47.6 ± 16.1	48.3 ± 18.4	42.9 ± 15.6	49.2 ± 17.2	57.2 ± 18.8
	75–90 min	47.9 ± 17.6	49.4 ± 19.4	45.2 ± 16.3	48.9 ± 18.0	54.7 ± 17.3
HRZ5 (90–100% HR_{max}) % total time	*0–15 min*	26.4 ± 21.9	36.1 ± 22.7	41.7 ± 25.7 [3]	35.5 ± 27.0	27.4 ± 22.0
	15–30 min	32.0 ± 25.6	41.5 ± 26.8 [4]	48.7 ± 25.3 [4,6]	37.8 ± 27.1	31.8 ± 24.1
	30–45 min	31.3 ± 27.0	40.4 ± 24.8 [4]	52.7 ± 25.4 [1,4,5,6]	39.3 ± 27.0	35.2 ± 29.0
	45–60 min	22.4 ± 21.7	22.5 ± 17.5 [2,3]	33.8 ± 23.4 [3]	22.9 ± 22.3	20.7 ± 21.5
	60–75 min	27.7 ± 23.1	28.2 ± 24.0	39.4 ± 23.7 [3]	27.4 ± 23.7	26.2 ± 22.6
	75–90 min	28.3 ± 23.3	32.1 ± 26.1	37.2 ± 24.4 [2,3]	27.5 ± 24.4	29.9 ± 23.0

TD = total distance covered during match, HSR = High-speed running distance covered during match, VHSR = very high-speed running distance covered during match, SPR = sprint distance covered during match, HR = heart rate, HRZ3–5 = heart rate zones 3–5, CD = central defenders, FB = full backs, CM = central midfielders, WM = wide midfielders, FW = forwards. Statistically significant difference ($p < 0.05$) compared to 1 = 0–15 min period, 2 = 15–30 min period, 3 = 30–45 min period, 4 = 45–60 min period, 5 = 60–75 min period and 6 = 75–90 min period.

CM. Only statistically significant difference in HRZ4 was found in CM who had higher time during period 45–60 minutes compared to period of 30–45 minutes. In general, time spent in HRZ5 was higher in the first three periods than the last three periods, but statistically significant differences between periods were found only in FB and CM.

DISCUSSION

The aim of the study was to identify positional differences in match demands of national level women's football and to investigate whether positional match demands change during a match. The main finding was that positional differences identified in match demands were similar to those reported in previously in elite players [1, 11, 12]: total distance was highest in CM and WM and lowest in CD. VHSR and SPR distances and number of accelerations and decelerations were highest in WM and FW and lowest in CD. Between the first and second halves of the matches, statistically significant differences were observed only in CM who showed reduction in TD and HSR distance, and in CD who increased VHSR. However, significant decrement in TD and HSR distance and number of decelerations were observed in comparisons of 0–15 min and 75–90 min in all positions. In addition, position-specific differences between 15 min periods in combined VHSR & SPR, number of decelerations and HR related variables were found. Although significant differences were observed only for some positions and variables, the internal load increased towards the end of the halves while the external load decreased towards the end of the match. Apparently, the present study is in line with the previous studies players experience fatigue towards the end of the match [37].

Average TD per position in matches varied from 9275 to 10797 meters (average 10134 m). These TDs are similar than reported in previous studies from national and elite level players [1, 9–11, 14]. Comparing different positions, CM and WM covered the highest TD, CB the lowest, as in previous studies [1, 8, 9, 11]. While there were no major differences in the current sample of national level players' TD compared to values reported with elite level players, the distances covered in VHSR and SPR zones were noticeably lower than reported previously from elite players [1]. This finding is supported by other studies which have shown that TD is more stable between different competition levels, whereas the amount of high-intensity running increases in-line with competition level [2, 3, 32]. One explanation for differences in VHSR and SPR distances between levels can be that physical qualities are related to high-intensity running covered during match [33, 36]. Indeed, typically elite players are shown to perform better in general fitness tests than lower-level counterparts [38, 39].

This study found HSR of FB to be significantly lower than that of both WM and FW. This differs from previous studies that have shown the amount of HSR to be similar between FB, WM and FW players [1, 11, 12]. In men, FB high-intensity running demands are shown to increase the most compared to all other positions [40] and most likely similar increase will happen also with national level female players in the future. Consistent with previous studies distance covered in VHSR and SPR zones was highest for WM and FW and lowest for CB and CM [1, 11, 12]. When comparing match demands between positions we do not know if players who run the most are maybe accustomed to running more, or may be selected based on

their physical characteristics, for example to meet the higher demands of WM position found in present study. A challenge exists in establishing the causal relationship between playing position and running demands. It is possible that players who run the most may be selected to those positions which have a higher running demand as found in this study.

In contrast to previous studies [7, 26], statistically significant differences in number of accelerations and decelerations between positions were found. WM and FW accumulated the highest total amounts and CD the lowest, whereas previously no differences in number of accelerations and decelerations have been observed between positions [5, 7]. Further comparison with other studies is difficult due to differences in research methods, thresholds, and positional categories. For example, in studies by Ramos et al. [7] and Trewin et al. [8] there is no WM positional categorisation.

In line with previous studies, HR of outfield players in matches averaged 86% of HRmax and statistically significant difference was only observed between CM and CD. Mean HR of 86% corresponds with about 75% of maximal oxygen uptake [15, 17, 27], which indicates that aerobic energy system is heavily taxed in national level match play. Players spent most of their time in HRZ4 (49%) and HRZ5 (33%). Time spend in HRZ5 appears to be a very similar to the elite levels (32% vs. 33% respectively) [31]. The time spent in different HR zones differed slightly from the reports by Krustrup et al. [33] and Panduro et al. [14], in which no differences were observed between positions in the time spent in different HRZ. Compared to elite level players, national level players could produce smaller VHSR and SPR outputs with a similar internal response. One logical explanation could be that the national level players have lower-level physical characteristics compared to elite players. Physical tests were not included for the present study and thus the effect of physical characteristics on performance remains speculative.

The decrease in mean HR from the first to the second half was 1–2%, which corroborates previous observations [3, 30, 31], although there were no significant differences between halves in any other position than CM. When internal load, in terms of HR variables, decreased slightly from the first half to the second, it is logical that a similar decrement was also observed in the external load variables. Statistically the only significant decrements from first to second half was found in CM TD and HSR. On average, TD decreased from first to second half about 2%, which is less than previously reported ~5% [4, 5]. VHSR and SPR distances remained unchanged or even increased from first to second half. The number of decelerations decreased an average of 5% from the first to the second half and the number of accelerations decreased an average of 2%. Still there was much variation and the acceleration rates for CD and WM increased in the second half. Previously VHSR, SPR [9, 26], acceleration and deceleration counts have decreased in the second half of games [5].

External load variables varied between 15-min periods. TD was logically highest at the beginning of the match between 0–15 mins as in previous studies [4, 5], likely because match fatigue had not yet accumulated. Furthermore, TD was generally lower in the last two 15-minute periods similarly to Hewitt et al. [4]. As in previous studies, combined VSHR and SPR was relatively evenly spread between the 15-minute periods in all positions [4, 5], except for WM during the first 15-minute. HSR decreased significantly during a match, and all positions had decrement from 0–15 to 75–90-minute periods as reported in other studies [3, 4, 6] regardless of different thresholds used. In the present study, a general decreasing trend in deceleration counts was observed regardless of the position, but acceleration counts did not decrease significantly, except for CM.

The mean HR is generally increased towards the end of the halves. Within the 15–minute periods, time spent in both the first and second halves in HRZ5 increased towards the end of the halves, which may be related to concurrent increase in HR. The time in HRZ4 was evenly distributed during the match. This demonstrates that the internal load increases towards the end of the halves while the external load seems to decrease. As mentioned before, this could be a sign of players fatigue because of the physical load of the game.

The strengths of the study were that data regarding both external and internal match load were collected and analyzed. As analysis was done in 15-minute periods, the present study can offer more detailed information about possible signs of decrements in female players' position-specific match demands. Some limitations were also identified in the study. Playing positions were self-reported and no further confirmation (video analysis) was completed by the authors. The study could not consider factors influencing movements of an individual on the pitch, such as teams' playing style or formations, level of opponent or the score of the match [13]. Furthermore, players motivation, fatigue, recovery time from previous match and conditions (e.g., temperature and weather conditions, surface), effect of away / home game [13, 18] were not controlled. The present study aimed to assess the changes in physical demands during competitive matches and thus, in present study we compared halves and 15-min fixed periods, in line with several previous studies [5, 7]. Demands of fixed periods are not as high as the most demanding passages/ worst case scenarios quantified by using rolling average method [41] and for that reason the findings of present study represent only changes in national level women's match demands and not absolute peak demands. The most demanding passages/ worst case scenarios are extensively documented in men's football [42] and in the future similar analysis should be completed with women.

CONCLUSIONS

In summary, women's national level football matches require a wide variety of physical demands and the differences between positions are aligned with the elite level. In general, match load can be interpreted as high, although the intensity of the national level matches appears to be lower compared to the international level, especially in terms of very high-speed and sprint running distances. Physical

demands in terms of external load appears to decrease during the match, especially after 60 minutes of play, while internal load seems to increase. Findings of present study followed previous studies, which have shown that demands of very high-speed running and sprint running increase in-line with competition level, while total distance remains more consistent.

Practical applications

From a coaching point of view, it would be important to improve players capability of very high-speed running and sprinting, which would prepare national level players to perform at elite level. Furthermore, position-specific match demands need to be taken into account in individualized training prescription. For example, central midfielders total distance covered during the match is usually very high, so the amount of running in training sessions should also be high. Wide midfielders and forwards cover the highest amount of running meters in very high-speed and sprinting intensities so these players should train more high intense actions. Also, it may be worth assigning players with certain physical profiles to specific positions where their physical abilities align with physical demands.

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Conflict of interest declaration

The authors declare no conflict of interest.

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Technical and locomotor demands in elite soccer: manipulating area per player during small-sided games to replicate official match demands

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ABSTRACT: The present study aimed to investigate the area per player (ApP) to replicate the technical and locomotor match demands using small-sided games (SSGs) in male soccer players ($n = 20$) competing in major European and UEFA competitions. The relative number of each individual technical activity per minute (number·min^{-1}; technical demands) was counted and the relative (m·min^{-1}) total (TD), high-speed running (HSRD), very high-speed running (VHSRD), sprint and acceleration+deceleration (Acc+Dec) distances were collected during different SSG formats ($n = 24$; 4 vs 4 to 10 vs 10 with an ApP from 60 to 341 m^2·player^{-1}) and official matches ($n = 28$). Data were collected during two full seasons. A linear mixed model analysis was used to calculate the individual relationship between technical/locomotor demands and the ApP during SSGs; the correlation coefficient was also calculated. With the exception of an inverse *moderate* ($r = -0.457$) correlation for Acc+Dec, each locomotor metric (TD, HSRD, VHSRD and sprint) showed a positive *large* to *very large* ($r = 0.560$ to 0.710) correlation with ApP ($P < 0.001$). The technical demands showed an inverse *moderate* correlation ($r = -0.529$) with ApP. Additionally, inverse *moderate* to *large* correlations ($r = -0.397$ to -0.600; $P < 0.05$) between the technical demands and the locomotor demands (TD, HSR, VHSR and sprint) were found. Lastly, an ApP of ~243 m^2·player was found to replicate the official match technical demand and it was quite similar to the ApP required to replicate HSRD, VHSRD and sprint. These findings may help practitioners to replicate, overload and underload both technical and locomotor demands using a specific ApP during SSGs in elite soccer.

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INTRODUCTION

In modern soccer, the training prescriptions follow a game-based approach in which ball-drill prescriptions are focused on the game as a whole [1]. In this approach, key learning occurs from the game itself and game-related activities [2]. The aim is not only to teach the skills required to play a game, but also to allow one to develop the ability to understand the game's tactics and strategies within a highly specific environment [2]. In this regard, small-sided games (SSGs) should be highlighted due to their ability to integrate physical fitness, technical, tactical and conditional stimuli in contexts similar to a real game [3–5]. Usually, SSGs are utilized as soccer-specific ball-drills [4, 6] for maximizing technical, tactical and physical performance [7, 8]. The manipulation of pitch sizes, number of players, specific rules, etc., may affect technical, tactical and physical demands [3, 4, 6]. Increase in pitch size and reduction of the number of players were shown to increase the total distance and the distance covered at different speeds [9, 10]. Moreover, as the dimensions of the pitch increase in SSGs, the tactical principles such as penetration, defensive balance and defence unity become more frequent [11], and the periods in which teams retain possession of the ball become longer [12]. Conversely, when the pitch size is reduced and the number of players is increased, players perform more technical activities (e.g., stops, passes, shots, intercepts) and the prevalence of the locomotor demands tends to be characterized by accelerations and decelerations [4, 9].

During the training interventions using SSGs, manipulating the area per player (ApP, expressed as m^2 × player) [4, 6, 13] enables practitioners to design the SSGs for different purposes [4, 13]. It was recently shown that ApP during SSGs was *very largely* correlated with the relative (m·min^{-1}) total distance, high-speed running and sprint covered, while no correlation for acceleration/deceleration was found both in adult [4] and youth [5] elite soccer players. This was in line with previous findings suggesting that SSGs in a higher ApP resulted in stronger physical and physiological responses [10]. Additionally, a specific high ApP (i.e. ~300 m^2 × player) was reported to induce internal/external load responses near to the individual maximal physiological capacities [14], to replicate official match metabolic and cardiovascular responses [15], to replicate official match sprint distances [4] and to simulate match tactical behaviours [13].

Moreover, an ApP similar to official match demands has been suggested to replicate the 4-min match-derived maximal intensities in elite soccer players [16]. Therefore, a large specific ApP was suggested to increase locomotor [4, 5], physiological [14] and tactical [3] demands up to the maximal official match demands [16] through a soccer-specific learning environment [5].

Although soccer requires technical, tactical and physical capacities, technical abilities such as stops, passes and shots are some of the main performance factors [17]. During official matches, several technical data (e.g. number of shots, passes, crosses) are usually collected to inform coaches and players about the individual and team technical performance [18]. Similarly, technical metrics have been collected to determine the individual activities with the ball during different formats of SSGs [6, 19, 20]. In this regard, the technical demands increased with small pitch sizes or with a lower number of players [21]. For these reasons, small pitch sizes are usually used to increase the amount of the individual technical activities during a soccer-specific training routine. Indeed, two reviews reported that ApP of ~91 $m^2 \cdot$ player [4] or ~93 $m^2 \cdot$ player [24] during SSGs is suitable for these purposes. However, these may lower the locomotor demands, leading to a possible mismatch between SSGs and match-play requirements, especially in the high-speed to sprint activities [22]. Consequently, the use of small ApP could affect the physiological [14], physical [4, 5] and tactical [13] responses, reducing the training specificity usually advocated as a key factor of SSGs.

An integrated approach considering technical, tactical and physical demands contextualized across the official match performance requirements could be useful to maximize the development of the physical performance using SSGs [4, 5, 9]. Unfortunately, none of the previous studies coupled the technical with the locomotor demands to suggest a specific ApP to replicate both the technical and the locomotor activities typically required during official matches. Therefore, the present study aimed to determine the minimal ApP that could be used to replicate both the official match technical (i.e. the combined number of stops, passes, shots, crosses, tackles, etc. per minute per player) and locomotor demands in elite soccer players.

MATERIALS AND METHODS

Participants

Twenty-five elite soccer players competing in major European and UEFA competitions were included in the present study (age: 26 ± 6 years; body mass: 80 ± 7 kg; body height: 1.85 ± 0.08). As an inclusion criterion, each player should have played a minimum of six official matches for at least 85 minutes. Goalkeepers were excluded from the data collection. The club's medical staff certified the health status of each player. As an exclusion criterion, an injured player was excluded from data collection for at least one month after their return to full training with the team. The procedures were fully explained to the participants and the club staff. The participants gave their written consent. The Ethics Committee of the Università degli Studi di Milano (protocol #102/14) approved the study, which was performed in accordance with the principles of the Declaration of Helsinki (1975) for studies involving human subjects.

Experimental design

The present investigation was carried out during the competition period across two consecutive seasons. To avoid possible variation in training status, only the data collected during the in-season period were collected; to avoid possible individual cardiorespiratory and metabolic variations, the individual fitness status was continuously monitored across the season by a high-qualify technical staff, as previously reported [23]. The magnitude of the individual changes in fitness status (i.e. either a significantly higher or lower fitness level) was calculated on individual bases as previously proposed [23] and used as an exclusion criterion.

The participants undertook their traditional weekly training routine (5 training sessions, 1 match day and 1 day off). Only data collected during the training routine with one match per week were utilized for the aims of the current study. To avoid any fatigue-induced variations in the technical and locomotor demands, only the SSGs completed on the match day +3 after a standardized warm-up were considered for the current investigation (match day +1 and +2 were a recovery low-intensity training session and a day off, respectively). All sessions were performed on grass pitches preserved by qualified operators and were conducted at the same time of day to limit the effects of circadian variation. A specialized and high-qualified physician recommended and monitored the diet regime of each player before and after every training session.

A total of 1332 individual observations across 24 different formats of SSGs were undertaken. SSGs ranged from 4 vs 4 to 10 vs 10 with an ApP from 60 m^2 to 488 m^2. A detailed description of the SSGs' characteristics is reported in Table 1. The ApP was calculated excluding the goalkeepers in SSGs. Each SSG lasted on average 4 minutes. The SSGs were performed under the supervision and motivation of several coaches to maintain a high work rate. For the same reason, a ball was always available by prompt replacement when it went out-of-play [6]. In SSGs, the corners were replaced by a prompt ball-in-game from the goalkeeper. The SSGs were completed after a standardized 20-min warm-up under the guidance of club staff. A total of 28.2 ± 5.4 official match individual samples were monitored. The official match pitch size was 105 × 66 m, with a grass surface.

Procedures

Video footage was recorded with high-definition dome cameras and high-resolution digital cameras (HDR-CX405, SONY Corporation, Minato, Tokyo, Japan). Each technical activity was counted by a specialized and high-qualified coaching staff with notational analysis during both training and match videos. To ensure the maximal accuracy in data collection, notational analysis was performed by three

TABLE 1. Pitch size during small-sided games with goalkeepers.

N° Players	m	Width:length ratio	m^2	$m^2 \cdot player^{-1}$	N° measures	N° individual samples
10 vs 10	65 × 52	0.800	3380	169	4	80
	65 × 60	0.923	3900	195	6	120
	105 × 65	0.619	6825	341	3	60
9 vs 9	40 × 36	0.900	1440	80	4	72
	52 × 40	0.769	2080	116	5	90
	65 × 45	0.962	2925	163	3	54
	65 × 52	0.800	3380	188	4	72
8 vs 8	35 × 30	0.857	1050	66	6	96
	65 × 40	0.615	2600	163	3	48
	65 × 45	0.692	2925	183	4	64
	65 × 60	0.923	3900	244	5	80
	70 × 65	0.929	4550	284	3	48
6 vs 6	40 × 36	0.900	1440	120	4	48
	52 × 36	0.692	1872	156	4	48
5 vs 5	30 × 20	0.667	600	60	5	50
	32 × 24	0.750	768	77	3	30
	30 × 30	1.000	900	90	5	50
	40 × 32	0.800	1280	128	4	40
	40 × 35	0.875	1400	140	5	50
	40 × 40	1.000	1600	160	3	30
	45 × 40	0.889	1800	180	3	30
4 vs 4	40 × 32	0.800	1280	160	6	48
	40 × 40	1.000	1600	200	3	24

The small-sided games with goalkeepers are split for the number of players and pitch size (length × width). **The width:length ratio**, the total pitch area (m^2) and area per player ($m^2 \cdot player^{-1}$) have been calculated. **The total number of measures for each SSG format and the number of the individual samples are also reported.**

TABLE 2. A brief description for each technical event is reported.

Technical events	Description
Total Activities	Number of technical activities that lead to any offensive or defensive actions carried out by the team in possession or non-possession of the ball. The total number of the technical activities was calculated as the combined number of the following activities and normalized by time (i.e. the number of technical activities per minute).
Shots	An attempt to score a goal, made with any (legal) part of the body either on or off target
Total passes	Number of an intentionally played ball from one player to another. All long, short, through passes and assists are considered.
Crosses	Number of long foot passes performed by a player from an offensive zone (last about 40 m of pitch between the short side of the penalty Area and the lateral side of the field) and direct to the penalty area.
Dribbling	Number of situations where a player tries to overcome another player with the ball possession.
Duels	Number of 1vs1 situations (with or without the ball) during with a player got in touch with the ball
Interceptions	Number of ball recoveries from an opponent's ball possession by interception (interruption of an opponent ball transmission)
Recoveries	Number of ball recoveries from an opponent's ball possession
Others	Any other voluntary ball touch during both possession or non-possession phases

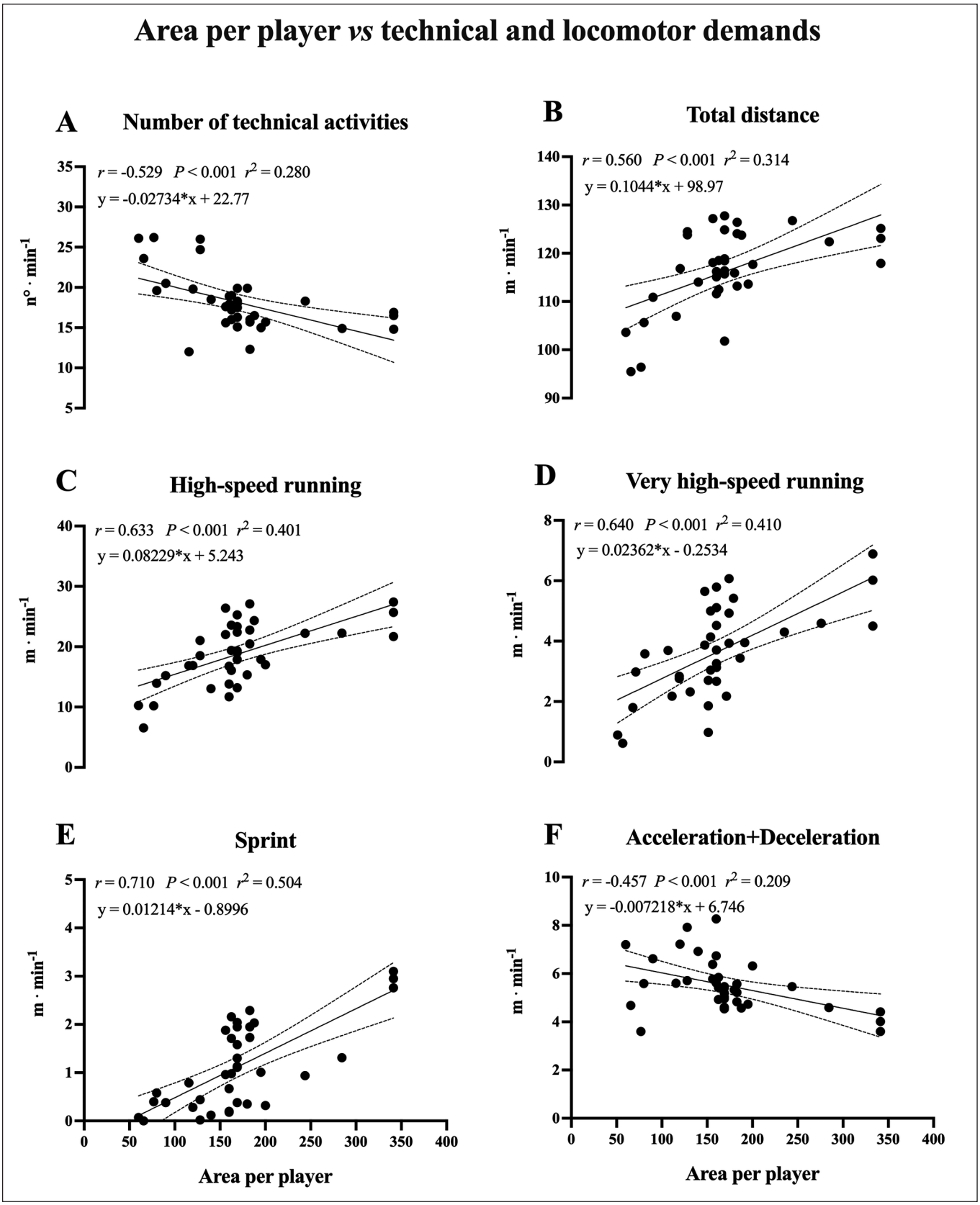


FIG. 1. The relationship between area per player ($m^2 \cdot$ player) and relative technical (technical activities $\cdot min^{-1}$) or locomotor ($m \cdot min^{-1}$) demands during small-sided games. The linear regression analysis with 95% confidence intervals and the correlation between the area per player and the relative technical or locomotor demands are reported for number of technical activities (Panel A), total distance (Panel B), high-speed running distance (Panel C), very high-speed running distance (Panel D), sprint distance (Panel E) and acceleration+deceleration distance (Panel F).

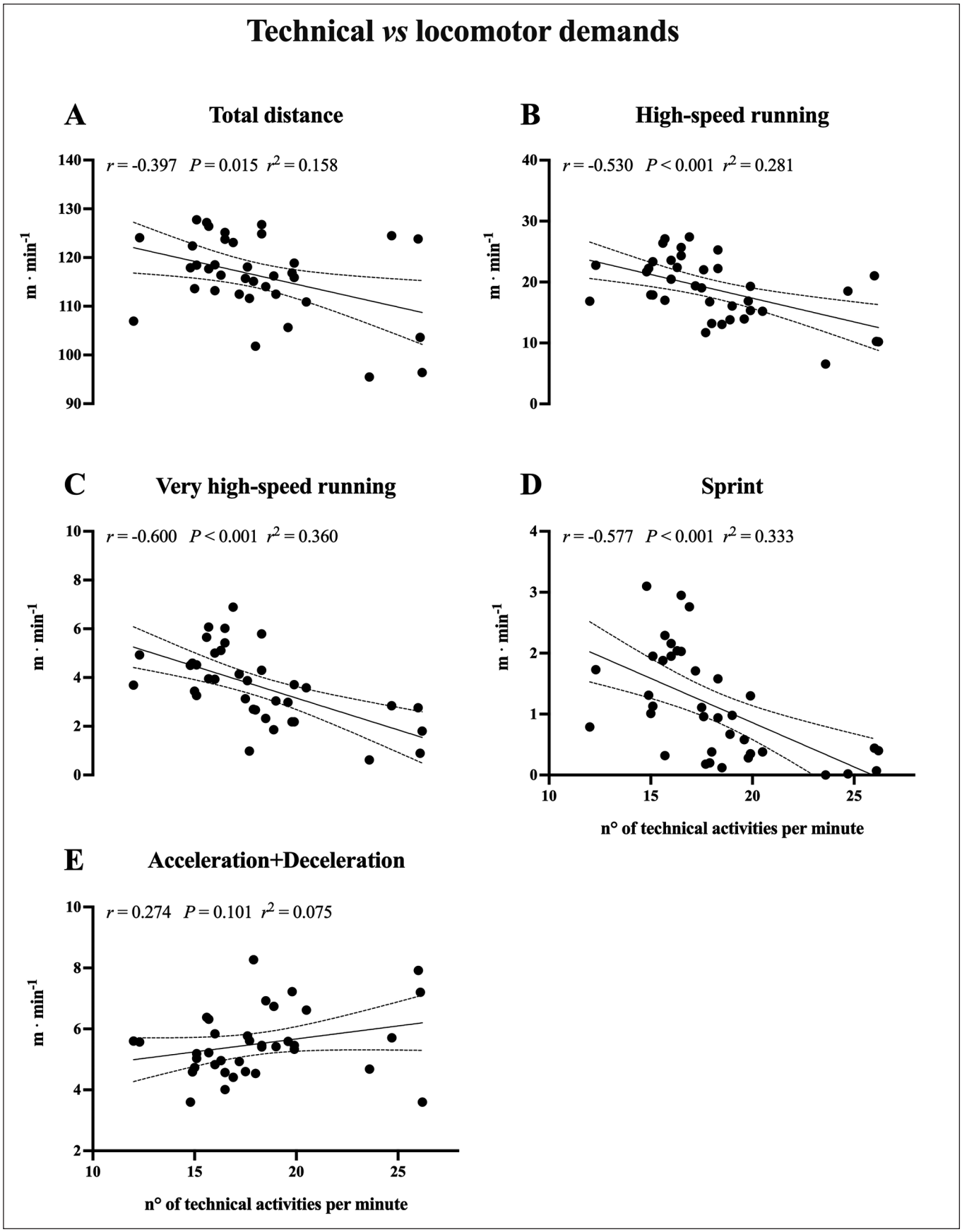


FIG. 2. The relationship between relative locomotor ($m \cdot min^{-1}$) and relative technical (technical activities$\cdot min^{-1}$) demands during small-sided games. The linear regression analysis with 95% confidence intervals and the correlation between the relative locomotor and technical demands are reported for total distance (Panel A), high-speed running distance (Panel B), very high-speed running distance (Panel C), sprint (Panel D) and acceleration+deceleration distance (Panel E).

different UEFA B coaches (operators). A brief description for each technical event is reported in Table 2. The total number of technical activities was calculated as the combined number of technical activities and normalized by time (i.e. the number of technical activities per minute). The combined number of technical activities per minute was calculated within each SSG or match and calculated as technical activities per minute per player. Thereafter, we averaged the individual notational analysis to determine the corrected number of technical activities per minute per player.

A 10 Hz global positioning system unit (K-sport, Montelabbate, Italy) was used to collect data during training [4]. Each device was turned on at least 15 minutes before each session to allow for acquisition of the satellite signal [4]. The minimum acceptable number of available satellite signals was 8 (range 8–11), as previously suggested [24–26]. To reduce the inter-unit differences, each player wore the same unit for every training session over the whole investigation [4]. The locomotor activities during the official matches were collected using a computerized semi-automated video-based multi-camera image system (Stats Perform, Chicago, Illinois, USA) and processed by dedicated software [4]. The systems have previously been shown to provide valid and reliable measurements of the match activity in soccer [4, 27]. The GPS and the video-based multi-camera image system were previoulsy detemined as interchangeable [4]. As previously reported [4], the magnitude of the bias between the GPS and the video-based multi-camera image system was *trivial* for each locomotor metric (about -3.0 to -3.9%, ES: -0.12 to -0.19).

During both training sessions and matches, total distance (TD), high-speed running distance (HSRD, 15 to 19.9 $km \times h^{-1}$), very-high speed running distance (VHSRD, 20 to 24 $km \times h^{-1}$), sprint distance (> 24 $km \times h^{-1}$) and acceleration+deceleration distance (Acc+Dec, > 3 $m \times s^{-1}$) were measured [4]. All data were normalized as meters covered in one minute ($m \cdot min^{-1}$) [4, 16].

To determine the ApP that replicates the normalized technical demands (technical activities $\times min^{-1}$), TD, HSRD, VHSRD, sprint and Acc+Dec ($m \times min^{-1}$) recorded during the official matches, we first recorded those variables during the official matches. Thereafter, we separately plotted each relationship between ApP and the normalized technical activities, TD, HSRD, VHSRD, sprint and Acc+Dec during SSGs. Then, the mean values recorded during the official matches were used to intersect each ApP/technical activity, TD, HSRD, VHSRD, sprint and Acc+Dec relationship recorded in SSGs to calculate the ApP that corresponded to the official match demands, as previously proposed [4, 5].

Statistical analysis

SPSS (version 26, IBM Corp., USA) was used to perform the statistical analysis. To check the normal distribution of the sampling, the Shapiro-Wilk test was used.

The validity and reliability of the operators to detect the total number of the technical activities during both SSGs and official matches were determined as the between-operators typical error calculated as the coefficient of variation (CV%). The between-measures reliability was calculated using the interclass correlation coefficient (ICC) and interpreted as follows: < 0.50 poor reliability, 0.50 to 0.75 moderate reliability, > 0.75: good reliability [23].

A linear mixed model analysis was used to calculate the individual relationship between technical and locomotor (TD, HSRD, VHSRD, sprint and Acc+Dec) demands and the ApP during SSGs. The correlation coefficient between ApP and technical demands, TD, HSRD, VHSRD, sprint and acceleration/deceleration was calculated and interpreted as follows: r = 0.00–0.09 (*trivial*), 0.10–0.29 (*small*), 0.30–0.49 (*moderate*), 0.50–0.69 (*large*), 0.70–0.89 (*very large*), 0.90–0.99 (*nearly perfect*). Thereafter, a linear mixed model analysis was used to calculate the difference in the minimal ApP required to replicate technical demands, TD, HSRD, VHSRD, sprint and Acc+Dec. A post-hoc analysis (Holm-Sidak correction) was used to calculate the differences in the independent factors. Cohen's d effect size with 95% confidence intervals (CI) was used to describe the magnitude of the pairwise differences and interpreted as follows: < 0.20 (*trivial*), 0.20–0.59 (*small*), 0.60–1.19 (*moderate*), 1.20–1.99 (*large*), ≥ 2.00 (*very large*). Statistical significance was set at $\alpha < 0.05$. Unless otherwise stated, all values are presented as mean ± standard deviation (SD).

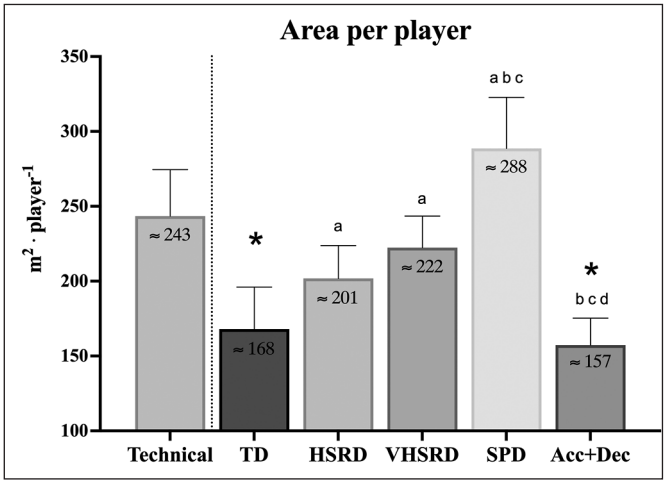


FIG. 3. The minimal area per player ($m^2 \cdot player$) to replicate technical (technical activities $\cdot min^{-1}$) or locomotor ($m \cdot min^{-1}$) match demands using small-sided games. Data are reported as mean (SD). Technical: number of technical activities per minute per player; TD: total distance; HSRD: high-speed running distance; VHSRD: very high-speed running distance; SPD: sprint distance; Acc+Dec: acceleration+deceleration distance. $^{*}P < 0.05$ vs Technical. $^{a}P < 0.05$ vs TD; $^{b}P < 0.05$ vs HSR; $^{c}P < 0.05$ vs VHSR; $^{d}P < 0.05$ vs SPR.

RESULTS

The reliability level of the operators to detect the total number of technical activities using video footage showed a ~2.1(0.4)% CV and *good* ICC [~0.891(0.032)].

For technical demands, an inverse *moderate* correlation with ApP was found (Figure 1, panel A). For locomotor demands, the correlations with ApP were *large* for TD, HSRD and VHSRD (Figure 1, panel B, C and D), *very large* for sprint (Figure 1, panels E) and inversely *moderate* for Acc+Dec (Figure 1, Panel F).

As presented in Figure 2, inverse *moderate* to *large* correlations ($P < 0.05$) between the number of technical activities per minute and locomotor demand were found for TD, HSRD, VHSRD and sprint.

As shown in Figure 3, ApP to replicate technical demands showed no differences compared to ApP for replicating HSRD, VHSRD and sprint; conversely, a higher ($P < 0.001$) ApP to replicate technical demands than TD (ES: 2.51; CI: 1.91 to 3.11) and Acc+Dec (ES: 3.36; CI: 2.66 to 4.06) was found. For locomotor demands, higher ($P < 0.05$) ApP for HSRD, VHSRD and sprint than TD (ES: 1.34 to 3.85) and Acc+Dec (ES: 2.22 to 4.80) were reported. Sprint required a higher ($P < 0.001$) ApP than each other locomotor metric (ES: 2.39 to 4.80).

DISCUSSION

The present study investigated for the first time the optimal ApP in SSGs to reproduce both the technical and the locomotor match demands in elite soccer players. The number of technical activities was inversely correlated with ApP. As concerns the locomotor demands, TD, HSRD, VHSRD and sprint increased with increments in the ApP, while Acc+Dec decreased when incrementing the ApP. The minimal ApP to replicate the technical demands was ~243 $m^2 \cdot$player. Interestingly, the ApP to reproduce the same number of technical demands recorded during official matches was similar to the ApP for replicating HSRD (~201 $m^2 \cdot$player), VHSRD (~222 $m^2 \cdot$player) and sprint (~288 $m^2 \cdot$player). These findings may help coaches and sport scientists to manipulate ApP during SSGs to replicate both technical and locomotor official match demands.

The present results demonstrated that the increments in ApP reduced the number of technical activities per minute, affecting the technical intensity. Moreover, these findings showed an inverse relationship between the technical demands and each locomotor metric. It was previously reported that ApP manipulation is useful to modify the technical learning environment [28–30]. Indeed, SSGs put physical, technical and tactical skills into play to cooperate with team members competing with the opponent towards offensive and defensive phases [3, 31, 32]. As such, the ApP manipulation should help performance staff to train skills within a highly specific soccer environment [4, 5]. A lower number of blocks, headers, interceptions, passes and receives but more dribbles, shots and tackles were reported using an ApP of ~125 $m^2 \cdot$player than ~166 $m^2 \cdot$player [30]. Similarly, a higher number of tackles and shots with no differences for passes, receives, turns, dribbles, headers and interceptions was reported using an ApP ~75 than ~150 or ~250 $m^2 \cdot$player in English Championship players [29]. In the real-life training routine, small pitch sizes are usually prescribed to increase the number of duels as well as to complicate the technical challenges [33]. The use of SSGs with a reduced pitch size was reported previously to effectively train players in the technical aspects by allowing greater exposure in the time with the ball without excessive physical demands [28]. The current findings also showed an inverse relationship between the technical and the locomotor demands when manipulating the ApP (i.e. the smaller ApP, the higher the technical demands and the lower the TD, HSRD, VHSRD and sprint). A highly contextualized training prescription based on the real-game model using a specific ApP may help to recreate soccer-specific tasks to improve technical, tactical and physical abilities and the decision-making process across soccer-specific locomotor outcomes [1, 2]. Interestingly, the current findings determined the ApP of ~243 $m^2 \cdot$player as the optimal pitch dimension to replicate the technical demands during official matches. Interestingly, such an ApP was quite close to the ApP required to replicate HSRD (~201 $m^2 \cdot$player), VHSRD (~222 $m^2 \cdot$player) and sprint (~288 $m^2 \cdot$player). Therefore, with the intention to increase the technical stimuli, lower ApP could be used. This would overload the number of individual involvements with the ball compared with the official matches. Indeed, previous studies suggested an ApP of ~91 $m^2 \cdot$player [4] or ~93 $m^2 \cdot$player [24] for technical purposes during SSGs. In contrast, when the purpose is recreating the match conditions, an ApP of ~250 $m^2 \cdot$player could be utilized to replicate both technical and locomotor official match demands. This would imply that the ApP during the SSGs should be manipulated depending on the aims of the session.

The present findings remark that a larger ApP is warranted for the high-speed demands [4, 5] as previously reported both in adult [4] and youth [5] elite soccer players. This mainly depends on the large space necessary to reach high speeds during SSGs, while a small pitch size is sufficient to reproduce Acc+Dec [4, 5]. It should be noted that the Acc+Dec do not change meaningfully across the different ApP [4, 5, 16], so a larger ApP can still be used for stimulating both high-speed demands and Acc+Dec. Therefore, to replicate the whole official match demand including the sprint distance, an ApP of ~288 $m^2 \times$ player appears to be needed. In line, a minimal ApP of ~311 $m^2 \times$ player or ~316 $m^2 \times$ player was indicated previously for sprinting in Italian Serie A [9] and French League One [4] soccer players. A specific ApP ~340 $m^2 \times$ player has been recently suggested to replicate the official match peak demands [16]. Additionally, playing SSGs in an ApP ~320 $m^2 \times$ player was also reported to enhance the players' tactical organization during attacking and defending actions [3] and to replicate the physiological match demands [14, 15]. Therefore, a larger ApP implies greater distance covered at very high-speed running and sprinting [4, 16], and influences the players' perception of space, conditioning its occupation and use, as well as the distances between players and their interactions [12] to

create scoring opportunities in offensive situations and to avoid the opponents' advance in defensive situations [3, 10].

Arguably, the exposure to the sprint activity occurring at a large ApP might be possibly protective against hamstring injuries [34], and should therefore be considered in practice. In this view, a large ApP appears most comprehensive in terms of the technical, tactical and physical official match demands [4, 5], preparing the players for the demands of the competition [31].

There are some limitations of the current investigation. Firstly, we would highlight that for replication purposes an individualized approach is required due to the typical soccer-specific variability (e.g., the athletes' characteristics, coaches' style of play) [23, 35], possibly affecting the current results both for the number of technical activities and locomotor demands; also the sample size of the measurements and the SSGs formats (different ApP, number of players, pitch size, width per length ratio, etc.) may affect both technical and locomotor demands during replicational studies. Secondly, for physical demands, the internal load parameters (e.g., heart rate) and the rate of perceived exertion were not examined. However, some technological limitations (e.g., the use of portable thoracic bands, especially during official matches) or some contextual limitations (e.g., athletes buy-in to collect rate of perceived exertion after each drill) affected the use of internal load assessment tools in the present study, especially during official matches. However, we acknowledge that coupling external load with internal load metrics may warrant a better understanding of drill demand. Thirdly, we would like to remark that to determine technical intensity the combined number of stops, passes, shots, crosses, tackles, etc. per min per player was utilized; however, future research could further investigate the effect of ApP on each single technical metric. Fourthly, individualizing the speed thresholds using the physiological individual profile [36–38] and/or individual maximal sprint speed [39] may help to further improve the understanding of the locomotor and physiological demands imposed on each player during different drills. Lastly, future studies may further investigate peak match demands [40] as a reference for SSGs, as recently proposed for the locomotor demands [16].

CONCLUSIONS

Technical demands increase when reducing ApP, while locomotor demands increase when enlarging ApP. An ApP ~243 $m^2 \cdot$ player is required to replicate the official match technical demands. Such an ApP was quite similar to the ApP required to replicate the official match high-speed locomotor demands. These findings might reinforce the knowledge about the use of specific ApP for soccer-specific training prescriptions using SSGs, and they might be useful to replicate, overload and underload both technical and locomotor demands using SSGs across the training routine.

Practical applications

An ApP of ~243 $m^2 \cdot$ player to ~288 $m^2 \cdot$ player could be utilized to replicate concurrently official match demands for both technical and locomotor purposes. A different number of players (e.g. 5 vs 5, 7 vs 7, 8 vs 8) within the same ApP (i.e. ~243 to ~288 $m^2 \cdot$ player) could be used to match both technical and physical demands accordingly with the technical-tactical aims of each drill. As a mere example, when training sessions aim to develop individual and team performance abilities (e.g., on match day -3 and/or -4), the use of a specific ApP may help to condition the players for match requirements towards different tactical learning environments.

Moreover, the present findings may also prove useful in congested-fixture periods [17], when time for training is lacking [41] and ball drills might be a viable conditioning option. For example, bouts of SSGs in specific large ApP should lead to higher external load demands than SSGs in a small ApP of similar time windows. This could enable an increase in either training volume or intensity, replicating the technical and locomotor official match demands in accordance with the distribution of official match intensities [42] without changes in the whole training session duration. Conversely, ApP < 243 $m^2 \cdot$ player may help to overload the technical actions, reducing the locomotor demands when conditioning purposes are not enhanced. Therefore, since ApP ~243 $m^2 \cdot$ player seems to be a good compromise between technical and locomotor activities to recreate the official match demands, practitioners could consistently utilize this specific ApP to recreate a highly contextualized training prescription based on the real-game model.

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Conflict of interest declaration

The authors declare no conflict of interest.

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An ecological investigation of average and peak external load intensities of basketball skills and game-based training drills

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ABSTRACT: This study quantified average and peak external intensities of various basketball training drills. Thirteen youth male basketball players (age: 15.2 ± 0.3 years) were monitored (BioHarness-3 devices) to obtain average and peak external load per minute (EL·min^{-1}; peak EL·min^{-1}) during team-based training sessions. Researchers coded the training sessions by analysing the drill type (skills, 1vs1, 2vs2, 3vs0, 3vs3, 4vs0, 4vs4, 5vs5, 5vs5-scrimmage), court area per player, player's involvement in the drill (in percentage), playing positions (backcourt; frontcourt) and competition rotation status (starter; rotation; bench). Separate linear mixed models were run to assess the influence of training and individual constraints on average and peak EL·min^{-1}. Drill type influenced average and peak EL·min^{-1} ($p < 0.05$), but with different directions of effects. EL·min^{-1} was higher in skills and 4vs0 drills, while higher peak EL·min^{-1} values were obtained in 5vs5 and 5vs5-scrimmage. Similarly, EL·min^{-1} was higher when involvement % increased ($p = 0.001$), while there was an opposite trend for peak EL·min^{-1} (lower with higher involvement %). Court area per player influenced peak ($p = 0.025$) but not average demands. No effects were found for playing position or competition rotation status (all $p > 0.05$), except for a moderately higher EL·min^{-1} in starters compared to bench players. The external load intensities of basketball training drills substantially vary depending on the load indicator chosen, the training content, and task and individual constraints. Practitioners should not interchangeably use average and peak external intensity indicators to design training but considering them as separate constructs could help to gain a better understanding of basketball training and competition demands.

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Constraints

INTRODUCTION

Game-based conditioning drills are an essential training mode in basketball and a preferred method for coaches to effectively train players [1–3]. Within a game-based drill, players can be exposed to the same multiple stimuli occurring during basketball games, such as sport-specific movements and technical actions (skills), tactical scenarios requiring cognitive processes and decision making, as well as high physical and physiological demands. Previous studies have demonstrated how training interventions focusing on small-sided games and ball drills can concurrently lead to physiological adaptations and improvements in physical performance as well as developing specific technical-tactical skills in basketball players [4, 5].

The effectiveness and time-efficiency of this training mode justify the increased interest shown by basketball researchers in the last decade. The possibility of manipulating an abundance of training constraints, such as number of players [1, 2], court area [1, 2] training regimes [1–3, 6], time pressure [7] rules [8, 9] and tactics [7], offers a unique possibility for coaches to design variable training scenarios, closely related to the stochastic nature of basketball game play. However, this growing body of literature on game-based conditioning in basketball presents some limitations. Indeed, previous works encompassed research designs where players were alternatively exposed to different ball drills for a limited number of sessions, which possess a low ecological perspective, limiting the finding's applicability in real-life training settings. By contrast, the analysis of performance during game-based conditioning drills and, more generally, team-based settings can vary [10, 11] due to the complex interactions among individual (e.g. physical capacities, fatigue), task (e.g. rules, court area, tactical content, playing positions) and environment (e.g. score line) constraints, which cannot be assessed in studies involving only a single or low number of game-based drills. Regarding individual constraints, for the same training drill different physical performances can be expected across players of different

age. While most research has focused on professional or adult players, physical demands in youth basketball players have been investigated less, possibly due to limited financial interests and the consequent unavailability of monitoring technologies [12, 13]. Furthermore, a player's involvement within a drill can vary significantly due to other variables not accounted for in the available literature, such as the number of players participating in the training session, interventions and breaks called by coaches, and other rules applied. Therefore, there is a need for a real-life context, ecological description of the demands of game-based conditioning drills during youth basketball training.

Another important aspect recently highlighted in basketball research is the analysis of peak demands, or most demanding scenarios [14, 16]. Studies across various team sports have suggested that quantifying external load intensities of training and competition based on classic average methods might underestimate the most demanding passages players have to engage in [14, 15]. These passages are defined as the most intense activity period (for an arbitrarily selected time frame, typically 1 minute) for a player within training or competition settings [14, 16, 17]. Examples of basketball scenarios characterized by peak external intensities could be multiple ball possessions with no basket or stoppages, or repeated basket-to-basket fast break actions. Importantly, these high-intensity moments have been suggested to be significantly influenced by contextual-related factors (e.g. technical-tactical aspects, score line, playing time, game quarter, game importance), that could be more frequently present during key competitions or game phases [14, 16, 17]. Therefore, these passages are of particular interest as they can be decisive to succeed in games. On the other hand, they might also indicate moments of very high physical loads imposed on the players' bodies, with potential consequences for load management and injury risk. In this perspective, the most common approach to calculating the average external intensity (e.g. external load per minute, $EL \cdot min^{-1}$) for a whole game, quarter or training drill might include stoppages, breaks called by the coach in training, as well as phases of less intense activity [14]. In contrast, a peak demands approach would allow practitioners to detect with more precision the most demanding passages of training and competition. For instance, Fox et al. [14] reported 3 to 4 times higher $EL \cdot min^{-1}$ in basketball training and games when considering peak indicators, compared to average ones. Notably, Garcia et al. [16] found that basketball training fails to match the peak external intensities of competition, which are 6 to 35% higher. Therefore, accurately quantifying the demands imposed on basketball players appears essential for accurate training design and performance optimization. To the best of our knowledge, only a few studies have evaluated the most demanding scenarios in basketball and mostly in competition settings [14–17], with less information available on training [14, 16] or youth players [19], calling for further research. Additionally, there has been recent criticism of the worst-case scenario approach and its interpretation in team sport training [18] with limitations identified in the high variability of these peak intensity moments, which derives from the multiple physical, technical and contextual factors that come into play during sport performance. There appears to be a need for a better understanding of the average and peak external intensity indicators in team sports, and especially for youth players, about which less information is available despite the crucial importance of the formative years for players' development. Therefore, the aim of this study was to evaluate the average and peak external load intensities of multiple basketball training drills in youth players, by using an ecological approach and considering different training (drill type, court area per player, player involvement percentage) and individual (playing position, competition rotation status) constraints.

MATERIALS AND METHODS

Participants

Fifteen youth male basketball players (backcourt [n = 6]: age: 15.1 ± 0.4 years; height: 173 ± 0.1 cm; body mass: 61.0 ± 6.3 kg; and training experience: 7.2 ± 2.5 years; frontcourt [n = 9]: age: 15.3 ± 0.2 years; height: 180 ± 0.5 cm; body mass: 69.8 ± 9.9 kg; and training experience: 7.8 ± 2.0 years) from a team participating in a highly ranked regional youth league organized by the Italian Basketball Federation (Federazione Italiana Pallacanestro, FIP) were recruited for this study. The team's weekly schedule featured 3 team-based training sessions (70–90 min) and 1 official game. Players and their parents/guardians were informed about the monitoring procedures, and one of their parents/guardians signed a consent form before the start of the data collection. Players monitored in < 4 training sessions were excluded from the study [12]. In total, 13 players (n = 6 backcourts, n = 7 frontcourts) were finally included, with 391 individual data points of distinct training drills collected.

Design

A descriptive design was adopted in this study to investigate the team's training sessions during 10 in-season weeks (October-December). The training content of the sessions monitored (match-day-5, MD-5, and MD-2) was mainly focused on game-based conditioning and tactical drills, played on different court areas (full-court, half-court, modified), and individual skills training. Physical conditioning without the ball was sparsely implemented across the monitoring period, and therefore was not included in the study. Additionally, warm-up and cool-down procedures were also excluded from the analyses.

Procedures

Players were monitored with BioHarness 3 microsensors (Zephyr Medtronic, Boulder, CO) to measure the average and peak external load intensity, by calculating the Impulse Load. This variable is calculated as the sum of areas under the 3-axis accelerometry curves (expressed in newtons per second ($N \cdot s$)). Impulse Load has shown robust agreement with other commonly used indicators of external load obtained by microsensors (such as PlayerLoad) in team sports [20], as well as recently used in basketball research [12, 21].

TABLE 1. Description of the factors included in the linear mixed models

Drill type	Skills training (dribbling, shooting, passing, post-moves); 1vs1; 2vs2; 3vs0; 3vs3; 4vs0; 4vs4; 5vs5; 5vs5-scrimmage
Court area per player	in m^2
Involvement %	% of involvement of players during the drill; e.g. 4vs4, 8 players in action, 4 players waiting outside the court = 66.7%
Playing position	Backcourt; frontcourt
Competition rotation status	Starter; rotation; bench

Average external intensities of each training drill were calculated as Impulse Load per minute. To avoid confusion, this variable will be referred in this article as EL · min^{-1}. Peak external intensity (peak EL · min^{-1}) was calculated as the most demanding 1-minute passage during a given training drill [14, 16].

A summary of the variables considered in this study is presented in Table 1. The research group accurately coded the training sessions of the team by analysing: 1) the duration of each drill, in minutes; 2) the drill type; 3) the number of players on (e.g. actively playing) and off the court (e.g. waiting for their turn) to calculate the percentage of participation during the drill, which was defined as involvement percentage (%); 4) the court area on which the drill was played [22] (half-court, full-court, quarter-court and other measures used by the coaching staff) to calculate the court area per player (in m^2). 5vs5-scrimmage refers to a 5vs5 played with competition-like rules and settings (court area, score count, fouls and free throws, shot clock). Additionally, playing position (backcourt; frontcourt) and competition rotation status were considered. Players were classified, according to the playing time registered by the coaching staff during official games, as starters (the five players starting the game and accumulating higher playing times), rotation (players who are on the bench at the start of the game but accumulate moderate playing times) or bench players (those with the lowest playing times). The data collection followed an ecological approach, with no interventions from the research team during the monitored training sessions.

Statistical analyses

Statistical analysis was performed using R version 4.0.3, RStudio version 1.4.1103, and the package *lmer* version 1.1–28. Two separate linear mixed models were used to evaluate the influence of drill type, court area per player, involvement %, playing position and competition rotation status on the average (EL · min^{-1}) and peak (peak EL · min^{-1}) physical demands encountered by basketball players (inserted in the model as a random effect) [12, 14]. Three variables are categorical, multi-level, having nine (drill type), three (competition rotation status) and two (playing position) factors, respectively. Therefore, a post-hoc Bonferroni correction was applied for p-values when performing all combinations of pairwise comparisons. Subsequently, a second linear mixed model was applied for each dependent variable to assess a possible interaction effect, by including only those variables which showed a significant main effect [23]. Data are presented as mean and standard error (SE).

Effect sizes (ES) were calculated using Cohen's *d*, and interpreted as: < 0.20, trivial; 0.20 to 0.59, small; 0.60 to 1.19, moderate; 1.20 to 1.99, large; and > 2.0, very large [24].

RESULTS

Significant effects on EL · min^{-1} were found for drill type ($p < 0.05$) and involvement % ($p = 0.001$) while no effects were found for playing positions, court area per player or competition rotation status (all $p > 0.05$). Regarding peak EL · min^{-1}, there were significant effects of drill type and court area per player (all $p < 0.05$), while no differences were found for involvement %, playing positions or competition rotation statuses (all $p > 0.05$).

Figures 1 and 2 present average and peak external intensities across different ball drills, court areas per player and involvement %. The drills leading to higher EL · min^{-1} were skills (220 ± 20 N · s) and 4vs0 (206 ± 13 N · s); conversely, higher peak EL · min^{-1} was registered in 5vs5 (369 ± 19 N · s) and 5vs5-scrimmage (378 ± 19 N · s). Table 2 presents pairwise comparisons between drills with significantly different average or peak EL · min^{-1}. Higher involvement % led to greater EL · min^{-1} ($p = 0.001$), while there was an opposite trend for peak EL · min^{-1} (lower with higher involvement %) (non-significant, $p = 0.140$). Larger court area per player elicited higher peak ($p = 0.025$) but not average external intensities. Regarding playing position, no significant differences were found for EL · min^{-1} (backcourts: 182 ± 23 N · s, frontcourt: 198 ± 24 N · s) ($p = 1$, ES: 0.38, small) and peak EL · min^{-1} (backcourt: 339 ± 39 N · s; frontcourt: 333 ± 38 N · s) ($p = 1$, ES: 0.06, trivial). Additionally, differences in EL · min^{-1} and peak EL · min^{-1} across competition rotation statuses were not statistically significant (all $p > 0.05$); however, there was a moderate (ES: 0.66) EL · min^{-1} difference between starters (203 ± 28 N · s) and bench players (177 ± 31 N · s), while small differences between starters and rotation players (187 ± 34 N · s) (ES: 0.50), and rotation vs bench (ES: 0.28) players were identified. The effects of competition rotation status on peak EL · min^{-1} were small and non-significant (starters: 320 ± 50 N · s; rotation: 337 ± 64 N · s; bench: 357 ± 53 N · s) (all $p > 0.05$, ESs: 0.27–0. 38, small).

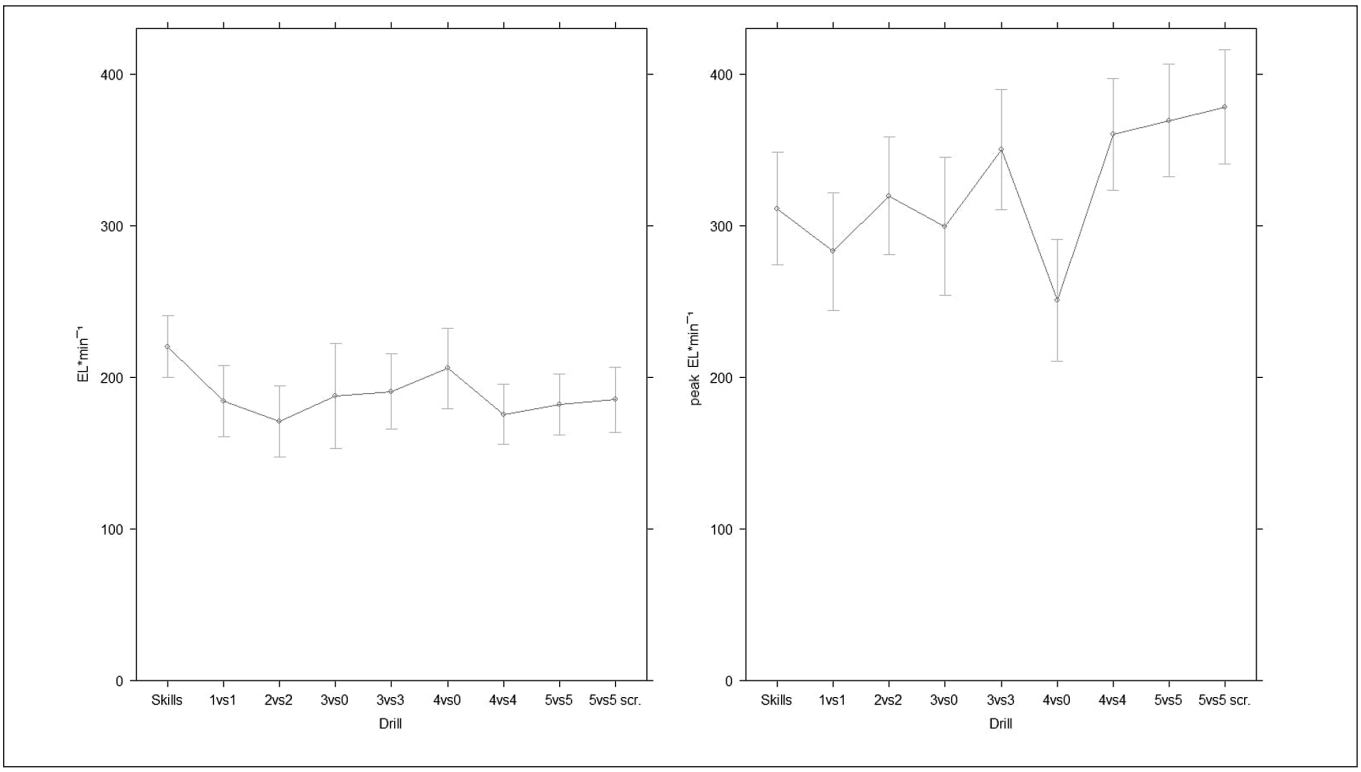


FIG. 1. Average and peak external intensities across drill types.

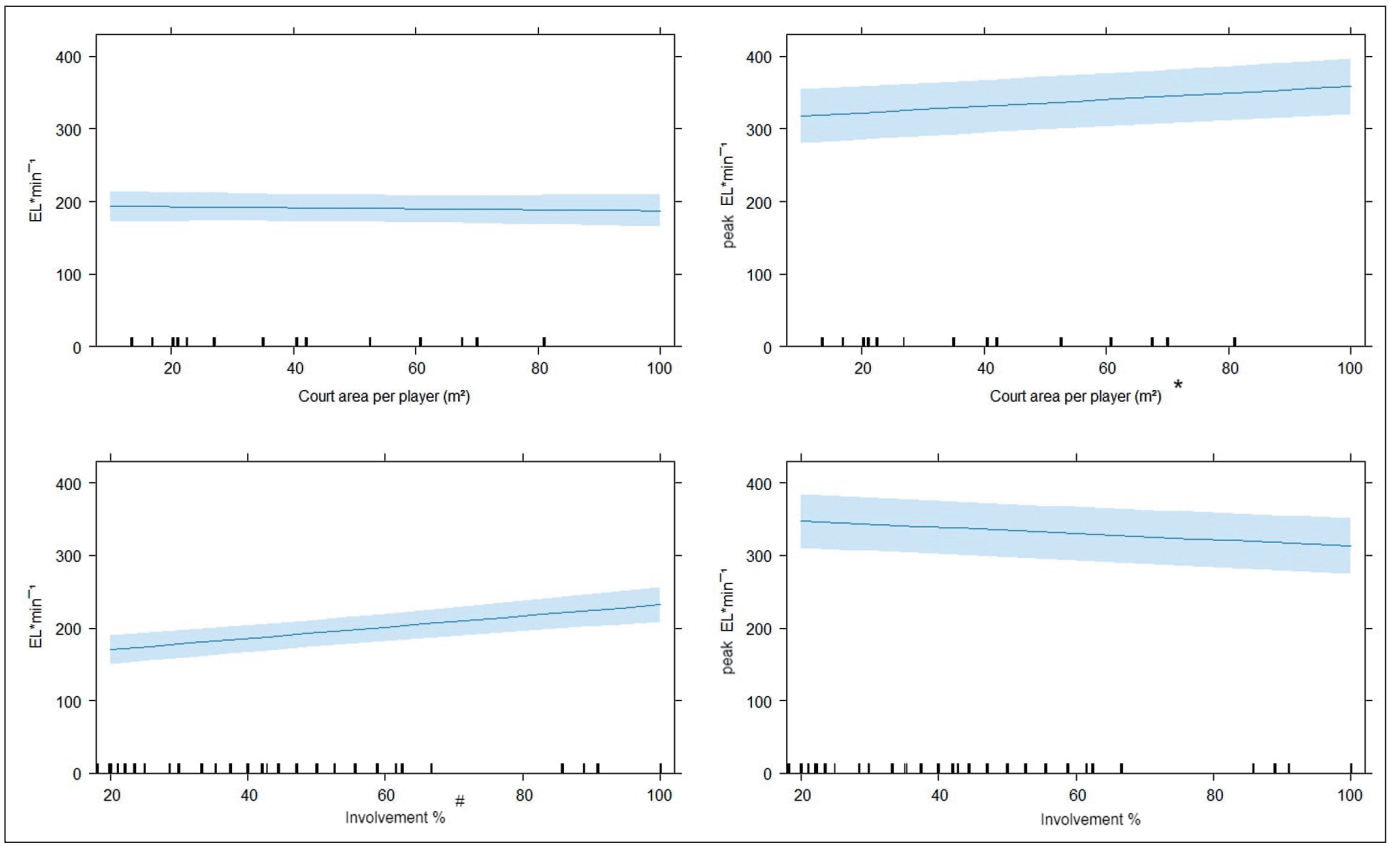


FIG. 2. Influence of court area per player and involvement % on average and peak external intensities. * significant main effect of court area per player ($p = 0.025$); # significant main effect of involvement % ($p = 0.001$).

TABLE 2. Pairwise comparisons between drill types with significant differences and effect size estimations.

EL·min^{-1}	p	ES	
Skills > 1vs1	< 0.001	0.46	Small
Skills > 2vs2	< 0.001	0.60	Moderate
Skills > 3vs0	< 0.05	0.22	Small
Skills > 4vs4	< 0.001	0.68	Moderate
Skills > 5vs5	< 0.001	0.54	Small
Skills > 5vs5 scr.	< 0.001	0.44	Small
Peak EL·min^{-1}	**p**	**ES**	
5vs5 scr. > skills	< 0.001	0.90	Moderate
5vs5 scr. > 1vs1	< 0.001	1.04	Moderate
5vs5 scr. > 2vs2	< 0.001	0.66	Moderate
5vs5 scr. > 3vs0	< 0.001	0.53	Small
5vs5 scr. > 4vs0	< 0.001	1.16	Moderate
5vs5 > skills	< 0.001	0.87	Moderate
5vs5 > 1vs1	< 0.001	1.00	Moderate
5vs5 > 2vs2	< 0.001	0.61	Moderate
5vs5 > 3vs0	< 0.001	0.48	Small
5vs5 > 4vs0	< 0.001	1.11	Moderate
4vs4 > skills	< 0.001	0.80	Moderate
4vs4 > 1vs1	< 0.001	0.98	Moderate
4vs4 > 2vs2	< 0.001	0.51	Small
4vs4 > 3vs0	< 0.001	0.43	Small
4vs4 > 4vs0	< 0.001	1.13	Moderate
3vs3 > skills	< 0.001	0.43	Small
3vs3 > 1vs1	< 0.001	0.62	Moderate
3vs3 > 4vs0	< 0.001	0.77	Moderate
2vs2 > 1vs1	< 0.05	0.38	Small
2vs > 4vs0	< 0.001	0.59	Small
1vs1 > skills	< 0.05	0.38	Small
Skills > 4vs0	< 0.001	0.65	Moderate

The second linear mixed models for interactions effects (EL·min^{-1}: drill type*involvement %; peak EL·min^{-1}: drill type*court area per player) showed no interaction (all $p > 0.05$), with all effect sizes between trivial and small.

DISCUSSION

In team sports, when monitoring training demands in game-based and collective drills, it is important to evaluate them in ecological conditions, considering their potentially high variability deriving from the complex interaction of individual, task and environmental constraints [10, 11, 18]. Through an ecological approach (no experimental conditions or interventions performed) this study described the average and peak physical demands of skills and game-based conditioning drills in youth basketball training. The main findings were: 1) the same training constraints have different effects depending on the external load indicator considered (average or peak intensity); 2) the drills closer to competition contexts (4vs4, 5vs5) led to higher peak, but not average external intensities; 3) the involvement of players has opposite effects on average (higher with higher involvement) and peak (higher with lower involvement) external intensities; and 4) higher average but not peak physical performances were registered in players with higher competition playing times.

One of the main focuses of this study was to investigate how average and peak external intensity indicators are influenced by basketball training drills. Although several previous studies have described average peak and demands in basketball competition, [14–17] only two have monitored them during training drills [14, 16], with no detailed information on training content. Peak external intensities in this study were 84% (± 50%) higher than average ones. Interestingly, we found how, for the same training constraint, their effects

on players' external intensities can be substantially different. For example, average external load was higher in skills drills, while for the same drill the peak external intensity was among the lowest; importantly, average external intensity was higher with higher involvement % (higher work:rest ratio). Oppositely, players had higher peak physical performances when involvement % was lower (lower work:rest ratios, thus more rest). Altogether, our findings suggest that average and peak external intensities should be considered as two separate constructs, and therefore team sport practitioners should not choose one over the other.

During game-based and skills training, a variety of drills is typically implemented by coaches. For example, 1vs1 drills can help players improve their ability to generate an advantage (offensively) and place stress on individual defence, while 4vs4 and 5vs5 drills can be focused more on replicating competition-like tactical scenarios. In this study, nine different training drills were described. Regarding the average external intensity, 4vs0 and skills drills showed significantly higher average intensities. This fact can be possibly explained by the absence of opposition in these drills; therefore players might have determined their pace more freely and possibly adopted a more continuous and sustainable intensity. In fact, pacing strategies are an important determinant of team sport athletes' performances during running-based training modes [25, 26], such as the ball drills monitored in this study. Differently, peak external intensities were registered in 4vs4 and 5vs5 drills, which resemble competition more (including in motivational aspects) and therefore stimulate players to reach higher peak performances. The 3vs3 drill, which is commonly implemented by basketball researchers and practitioners [3, 6, 7, 22], was also among the ones with higher peak $EL \cdot min^{-1}$. As our study involved youth players, it appears that this age group might be more stimulated by the ball and competition content of these drills, compared to those with no opposition, finally reaching higher peak intensities. On the other hand, adult professional players might approach the same training drills with a different mindset, leading to different average and peak external intensities. This is just a hypothesis, which we cannot confirm since basketball research on peak physical indicators is limited to competition studies. Our findings are in accordance with a recent study, which highlighted the considerable influence of tactical and contextual factors on peak external load indicators [18]. Figure 1 clearly shows how the influence of drill type on external intensity is quite divergent depending on whether average or peak indicators are taken into account. We therefore recommend practitioners to consider current findings when designing training drills for basketball players.

An important constraint coaches may manipulate in game-based conditioning drills is the court area on which the drill is performed. There is a general consensus that external loads are higher with larger court areas per player [2], and our findings partially confirm this. In fact, a significant main effect was found for peak external intensity, which was higher with increased m^2 per player (see Figure 2). Thus, on larger court areas players tend to make greater physical efforts; however, the same was not found for average external intensity. As suggested above, it is possible that across the whole drill duration players pace themselves to maintain their exertion level [3, 25, 26], while in a 1-minute window, substantially higher peak intensities can be found when the court area is larger.

As we hypothesized, findings for average and peak external intensity were divergent when considering players' involvement during training drills. Average external intensity was higher when players were more involved (higher involvement %) across the whole duration of the drill. Similarly, removing stoppages during 5v5 basketball drills has been shown to induce higher PlayerLoad per minute [27], possibly due to higher player involvement and less rest. When considering peak demands, the opposite appears to be true. Although the mixed model did not detect a statistically significant effect, a trend for higher peak external intensities with lower involvement % can be noticed (see Figure 2). Our findings support those of a recent basketball study [1], which showed how players reach higher peak external intensities when they accumulate lower playing times, both across the entire game and immediately before the peak intensity occurrence. More rest opportunities, or lower involvement %, such as in our study, can allow phosphocreatine resynthesis and reduce neuromuscular as well as perceptual fatigue [3, 26, 28], which can all help players to subsequently perform the multiple high-intensity actions [17] (sprints, decelerations, jumps) required for basketball performance. Therefore, the importance of manipulating work:rest ratios, controlling playing times and the use of substitutions to control training loads and to allow players to perform physically at their best during training and games is confirmed by our study.

We did not find any difference in either average or peak external intensity between backcourt and frontcourt players in this study. When comparing external loads of players of different positions, differences can be found when looking at specific load indicators, rather than global indicators such as Impulse Load (used in this study). For instance, backcourt players reach higher speeds [29] and cover greater distances [30], while frontcourt players perform more jumps and static exertions [31]. These differences are typically detected during game play, where players of different positions have to perform their specific tasks on court for a better collective performance. Differently, across multiple and varied training drills such as those monitored in this study, the influence of playing position and the players' tasks on court might be mitigated by the training setting. This might be especially relevant and explain the current findings considering the sample involved (youth players), for which the training goal might be to be exposed to a greater variety of basketball scenarios [12] for better motor learning, with less emphasis on position-specific tasks.

Regarding competition rotation status, the higher the player's importance [23], the greater was the average external intensity, especially when comparing starters and bench players (ES: moderate). However, there was no effect of competition rotation status on peak

physical demands. Considering our findings and those of previous research [17], it is possible that average external load indicators are more influenced by players' characteristics; for instance, starters might have better physical capacities and thus maintain higher physical intensities across the whole drill. By contrast, peak indicators are more variable [17, 18], and might be more influenced by other factors such as work:rest ratios, tactics and other contextual factors. Another possible explanations for the higher average external intensity of more important players (e.g. those who play more minutes) might be their more important roles in set plays during training drills. Specifically, these players can increase their activity on court and then their average external intensities, while at the same time they can reduce their rest on the court, and then limit their peak external performances.

Although this study provides useful insight for basketball practitioners, some limitations should be addressed. Firstly, only one external load measure (i.e. Impulse Load) was used in our study, limiting the generalization of our average and peak intensities to this measure. Furthermore, the comparison of our external intensity data is limited since this load indicator has not been extensively used in previous basketball studies. Secondly, no internal load responses (e.g. heart rate, sRPE) were adopted in our study, while their inclusion might be worthwhile since both average and peak external intensity phases have been suggested to elicit individualized internal responses in team sports [18] and youth athletes [32]. Therefore, future studies should focus on the analysis of average and peak intensity phases of other external load measures typically used in basketball training (e.g. accelerations, decelerations, jumps) and on the individual internal responses to both average and high-intensity phases.

CONCLUSIONS

The physical demands of basketball training drills can substantially vary depending on the training load indicator chosen, the training content, and task and individual constraints. Specifically, an effect of drill type and rotation % was found for average external intensity measures, while an effect of drill type and court area per players was observed for peak external intensity. Conversely, no effect was found for playing position or competition rotation status for both external intensity measures. Overall, practitioners cannot use interchangeably average and peak external intensity measures to monitor basketball training sessions.

This study has several practical applications for basketball practitioners. Firstly, we found that the external load of average and peak intensity phases are two different measures of the training intensity during basketball training due to different trends for the dependent variables in this study. Based on the measure used to monitor the external intensity during training, different results of either average or peak indicators can be expected. Specifically, basketball coaches can manipulate the drill type based on the number of players involved and the involvement % to modify the average external intensity. Differently, modification of the number of players involved and court area per player should be used to modify the peak external load intensity. Implementing drills more similar to competition contexts (4vs4, 5vs5) can be used to increase players' peak physical output intensity, while manipulation of work:rest ratios based on players' involvement in the drills influences both average (higher with higher involvement) and peak (higher with lower involvement) external intensities. Concluding, we recommend that coaches manipulate training constraints to increase peak external intensity during skills training considering that technical movements during competitions are often performed during demanding game passages.

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Conflict of interest declaration

The authors declare no conflict of interest.

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Is Stryd critical power a meaningful parameter for runners?

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ABSTRACT: Stryd is a foot pod that reliably estimates running power. Our objectives were to examine the efficacy of the website-generated Stryd critical power (CP_{STRYD}) as a meaningful parameter for runners. 20 runners performed their regular training while wearing Stryd for a minimum of 6 weeks to generate CP_{STRYD}. Runners completed laboratory graded exercise testing, and outdoor 1500 m and 5000 m time trails. CP_{STRYD} was most similar to the second ventilatory threshold (VT2) or the onset of blood lactate accumulation (OBLA) and is highly predictive of running performance. Stryd ground contact time (GCT) was a predictor of performance when comparing runners at the same submaximal treadmill speed. CP_{STRYD} generated from outdoor running is equivalent to that calculated using an established CP model. However, variance between different methods of CP estimation must be a consideration for runners and coaches. Stryd offers meaningful data for runners including a realistic estimate of CP.

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INTRODUCTION

Bicycle mounted power meters have revolutionised cycling racing and training by allowing real-time measures of a rider's power output. These bicycle power meters measure the direct force being applied to a component such as the pedal axle or crank arm using strain gauges. However, currently it is not possible to measure the power output of a runner using similar strain gauges. As an alternative, several manufacturers have developed devices to estimate running power using motion sensor units combined with complex power estimation algorithms [1]. One such running device is the Stryd power meter (Stryd Inc. Boulder CO, USA). The Stryd is a 9-gram foot pod that attaches to a running shoe and estimates power, pace, distance, vertical oscillation, cadence, leg spring stiffness and ground contact time (GCT). Stryd also estimates form power, and form power ratio which are estimates of running economy.

Stryd has been evaluated during treadmill running [2–5], track running [3] trail running [6] and walking [6, 7]. Stryd provides reliable measures for power [2–4, 7], though a minimum sampling time of 10 seconds is required at a constant speed [8]. Stryd also appears to offer reliable measurements of GCT [5, 9, 10]. Stryd compared with the OptoGait system exhibited greater precision for GCT at every speed examined [10]. Stryd was found to be valid for GCT during running when compared with RunScribe [5] though may underestimate GCT when compared with high-speed video analysis [5]. In contrast, when Stryd was compared at walking paces with the gold standard Optojump Next [7], Stryd overestimated GCT. While Stryd offers high reliability, bias between different sensor brands including Stryd are frequently noted.

Stryd offers its own website-based calculation of Critical power (CP). CP is a well-described endurance exercise concept: For any individual, time-to-exhaustion is highly predictable and directly related to the power output [11]. CP represents a boundary between steady-state and non-steady state exercise intensity [12] and may be related to skeletal muscle capillarity and proportions of slow twitch muscle fibre type in endurance-trained individuals [13, 14]. Essentially, CP is the highest intensity that can be sustained without accumulating significant fatigue from anaerobic metabolism. However, there is much controversy concerning CP as a threshold measure. CP values depend upon the trial protocols used and the mathematical models employed [15]. There is no accepted reference method for CP determination, however linear CP models that include trials of longer duration (> 10 minutes) are recommended [15]. A large range of exercise laboratory derived thresholds have been suggested to be comparable to CP intensity. These include ventilatory thresholds (VT1 and VT2), the lactate threshold (LT), the maximal metabolic steady-state (MLSS), the onset of blood lactate accumulation (OBLA) and even much higher intensities above VO_{2peak} (see [11, 16, 17] for reviews). Recent evidence suggest differences between CP and such thresholds may be due to discordance between the methods of determination [18]. Other authors have claimed that CP may differ significantly from other thresholds [16] and may be viewed controversially [19] as an independent physiological

threshold itself. It has also been suggested that CP is simply a mathematical artefact [17].

To our knowledge, no study has examined the efficacy of the website generated CP_{STRYD} as a meaningful parameter for runners. It is currently unknown what relationship CP_{STRYD} has with other validated physiological thresholds including CP nor its ability to predict running performance. We sought to provide evidence to accept or reject CP_{STRYD} as a method to estimate CP or other thresholds in running. Our primary aim was to compare CP_{STRYD} with a CP calculated using an established linear power-time^{-1} model. Specifically, we sought to establish if the two CP models were equivalent. Secondary aims were to establish which lactate or gas exchange threshold is most equivalent to CP_{STRYD} and to compare CP_{STRYD} with standard laboratory performance tests as predictors of running performance. If CP_{STRYD} is equivalent to an established CP linear power-time^{-1} model and allows training at individual physiological thresholds and / or prediction of running performance, it will provide evidence to accept CP_{STRYD} as a meaningful parameter for runners.

MATERIALS AND METHODS

Participants

Twenty participants provided written informed consent prior to participation in this study that was approved by the Institutional Ethics Committee. The cohort consisted of males (n = 16), and females (n = 4) and included internationally competitive runners (n = 2), national class runers (n = 3) and competive recreational runners (n = 15). Inclusion criteria of participants were regular running training for the previous 3 months at a minimum frequency of 3 days per week, and currently participating in competitive running events and free from injury and illness.

Laboratory testing with Stryd

All participants were familiar with treadmill running. Participants completed laboratory running tests in an environmentally controlled laboratory to minimise thermal strain [20] (temperature 15 ± 1°C: relative humidity 36 ± 4%) while wearing Stryd. Participants' heart rate was recorded during all testing with Polar OH1 (Polar Electro Oly, Kempele, Finland). Participants completed all testing using a motorised treadmill (Cosmos pulsar 3p, HP Cosmos Sports and Medical GMBH, Nussdorf Traunstein, Germany). Prior to laboratory testing, participants were instructed to prepare as if it was a competition, to avoid strenuous physical activity and performance altering supplements (e.g. caffeine).

Participants first completed a graded exercise test (GET) to volitional exhaustion. Participants supplied their recent (within 4 months) race times from flat course races. Starting pace was 70% of actual or predicted 10000 m pace as recommended [21]. Mean starting speed was 9.8 ± 1.8 km · h^{-1}. Stage increments were individualized to allow each participant to complete a minimum of five stages. 12.0 km · h^{-1} was one velocity that all runners maintained for one stage during testing. For this reason, the oxygen cost of running (VO_2 L min^{-1}) and Stryd economy estimates (form power and form power ratio) were examined for relationships at 12.0 km · h^{-1}.

The gradient was fixed at 1% in order to simulate on-road conditions [22]. Prior to the first stage all participants completed a 10-min warm-up at a self-selected submaximal intensity. Each stage lasted four minutes with one-minute passive rest between stages to allow for the collection of capillary blood samples. A 5 ul blood sample was collected via finger prick and was measured for lactate using a portable analyser (Lactate Pro 2, Arkray, Japan). LT was defined as the exercise intensity not associated with an elevation in blood lactate concentration above baseline [23]. OBLA was defined as the exercise intensity identified by interpolation across the 4.0 mmol · L^{-1} lactate point [24].

During testing, respiratory gases were continuously measured with a metabolic cart (Metalyser 3B, Cortex, Leipzig, Germany) calibrated in accordance with the manufacturer's instruction using Alpha gas standards. All participants maintained a respiratory exchange ratio (RER) < 0.85 at the first stage. All participants reached a stage where they achieved a failure to increase VO_2 by 150 mL/min with increased workload and a RER ≥ 1.10.

VT2 was determined using the criteria of an increase in both the VE/VO_2 and VE/VCO_2 and a decrease in PETCO2 as previously described [25]. VO_{2peak} was determined as the highest 30 s oxygen uptake value recorded. The average treadmill speed over the final 60 s was recorded as peak 1 minute GET.

After a passive recovery of 15 minutes each runner performed a Maximal Anaerobic Running Test (MART) [26]. The MART consists of repeated 20-second sprints on a treadmill with 100 second passive rest periods. The speed of the first run was 14.5 km · h^{-1} and the inclination 5 degrees. The speed was increased by 1.5 km · h^{-1} every run until volitional exhaustion. vMART was calculated as the speed of the last completed 20-second run, plus 0.216 km · h^{-1} for each 2 seconds over 8 seconds of the subsequent uncompleted sprint. An uncompleted sprint of 8 seconds receives no adjustment, an uncompleted sprint of 10 seconds receives a 0.216 km · h^{-1} adjustment and 12 seconds receives a 0.432 km · h^{-1} adjustment.

Outdoor running with Stryd

Each participant had a Stryd account set up for them by the researchers and access was shared between the researchers and participant. Participants were required wear Stryd for a minimum of 6 weeks for all their runs. This time frame was chosen from pilot testing on 5 individuals. While CP_{STRYD} is generated after only a few runs, it continues to update CP which becomes more stable with time. 6 weeks allowed for multiple estimates of CP for each participant. Laboratory testing procedures for each participant was also carried out within this same study period.

In addition to their usual running training, we referred participants to follow the advice given by Stryd for an accurate CP:

1. Long duration runs of 40–60 minutes at max effort or near max effort (time trial or 10k race) for those that are training for a half or full marathon distance.
2. Medium duration runs of 10–20 minutes at max effort or near max effort (time trial or 5k race)
3. A short max effort run that is 3–5 minutes in duration.
4. Short distance sprints or strides at max effort (10–30 seconds in duration).

To provide measures of running performance all participants were asked to compete at an outdoor 1500 m track race and / or a 5000 m track or flat road race. Participants were asked to race at their maximal effort and to race as close as possible to the period as they were running with Stryd. All events were official athletic track meets or on a measured and verified race courses. Race times were obtained from the individual event websites.

Data analysis and statistics

For each subject, the final 10 s of power at every stage of GET and vMART was analysed for linearity using linear regression.

Following the outdoor running period with Stryd, all power data from each participants Stryd account was downloaded to Golden Cheetah (GC, version 3.5, open source, https://www.goldencheetah.org/). Golden Cheetah was used to obtain details of the number of runs, distance, training speed, duration, and elevation for each subject over this period of training. Golden Cheetah was also used to collate maximum mean power (MMP) for 3, 5, 10 and 20 minutes for each runner.

CP_{STRYD} from each participants Stryd account was collated. CP_{STRYD} is an auto-calculated CP from the Stryd app/website and uses an undisclosed power estimation algorithm. CP_{STRYD} was compared with MMP durations and with for Stryd power at ventilatory threshold 1 (VT1), LT, OBLA, VT2, VO_{2peak} and vMART. CP_{STRYD} was also examined as a predictor of VT1, LT, OBLA, VT2, VO_{2peak} and vMART using linear regression.

The four MMP durations (3, 5, 10 and 20 minutes) were used to calculate a CP for each subject (CP_{CALC}). CP_{CALC} was calculated using the following linear power-time^{-1} model.

$$P = (W'/t) + CP_{CALC}$$

CP_{CALC} was then compared with CP_{STRYD} using Deming regression and a Bland-Altman plot to test for systematic bias. A two-one-sided t-tests (TOST) procedure was used to examine equivalence between CP_{STRYD} and CP_{CALC}. As day to day variation of individual CP measures of ~5% have been previously reported [27], 5% was chosen as a priori acceptable limit to determine equivalence.

Stryd power at VT2 from laboratory testing was examined as predictor of CP_{STRYD} using both linear and non-linear regression regression and a Bland-Altman plot was used to test for systematic bias.

The two outdoor runs, 1-minute peak speed from the GET and vMART were used as performance measures. Linear regression was used to examine if CP_{STRYD} or Stryd data at 12.0 km·h^{-1} could predict these four measures of performance. This was also compared with laboratory results to predict performance.

Distributions were tested for normality with descriptive statistics and the D'Agostino and Pearson omnibus normality test to examine suitability for parametric testing. Comparisons were made with the paired t test.

All regressions were examined with the runs test and graphs of the residuals.

All data were analysed using Prism version 4.0 (GraphPad Version 4.01, San Diego, CA, USA, www.graphpad.com).

RESULTS

20 participants completed laboratory testing procedures (Table 1). For all runners, linearity of Stryd power was excellent ($R^2 > 0.99$) at 1% for GET stage and 5% incline for MART stage ($R^2 > 0.99$).

TABLE 1. Participants and laboratory testing results.

	Age	Weight	Body Fat	VT1	LT	OBLA	VT2	Peak GET	VO_{2peak}	vMART
	years	Kg	%	Km·h^{-1}	Km·h^{-1}	Km·h^{-1}	Km·h^{-1}	Km·h^{-1}	L·min^{-1}	Km·h^{-1}
					All (n = 20)					
Mean	39.5	71.4	14.3	11.9	12.6	14.2	14.7	17.0	3.93	21.8
SD	14.6	9.9	6.7	2.2	2.4	2.8	3.0	3.2	0.73	3.4
					Male (n = 16)					
Mean	40.2	73.6	13.3	12.3	12.7	14.4	15.2	17.7	4.10	22.4
SD	14.7	9.5	6.7	2.1	2.4	2.9	2.8	3.1	0.70	3.3
					Female (n = 4)					
Mean	34	63.0	22.7	10.0	11.1	12.0	12.3	14.6	3.20	19.2
SD	11.7	7.1	6.1	2.4	2.5	2.5	3.0	2.9	0.37	2.8

Note: Participant characteristics and laboratory graded exercise testing results are presented. VT1 = first ventilatory threshold, LT = lactate threshold, OBLA = onset of blood lactate accumulation, VT2 = second ventilatory threshold, Peak GET = peak 1 minute from graded exercise test, VO_2 = maximum oxygen consumption, vMART = velocity maximal anaerobic running test, SD = standard deviation

TABLE 2. Stryd power from outdoor running compared with laboratory testing.

	Stryd Power (W) for runners during outdoor running					Stryd Power (W) for runners during laboratory testing					
	CP	3 min MMP	5 min MMP	10 min MMP	20 min MMP	VT1	LT	OBLA	VT2	Peak GET	MART
Min.	207	243	235	228	191	117	118	150	151	213	388
Mean	302	365	353	327	301	248	262	296	304	354	541
SD	58	78	74	65	69	51	46	56	65	66	108
Max.	393	512	487	422	406	320	325	369	393	449	703

Stryd power data for 20 runners completing 54 ± 46 runs, covering a distance of 464 ± 423 km with Stryd are compared with Stryd power from laboratory testing. CP = critical power, MMP = maximum mean power, SD = standard deviation, VT1 = first ventilatory threshold, LT = lactate threshold, OBLA = onset of blood lactate accumulation, VT2 = second ventilatory threshold, Peak GET = peak 1 minute from graded exercise test., MART = maximal anaerobic running test,

The oxygen cost of running (2.92 ± 0.35 VO_2 L min^{-1}) at 12.0 km·h^{-1} had no relationship with Stryd economy measures form power (76 ± 11 W) nor form power ratio (0.30 ± 0.03). Also, there was no relationship between oxygen cost and vertical oscillation (8.7 ± 1.5 cm), cadence (84 ± 5 steps min^{-1}), leg spring stiffness (11.5 ± 2.3 kN m-^{1}) or GCT (235 ± 22 ms) at this same velocity.

Within 6 weeks of laboratory testing runners completed 54 ± 46 outdoor runs with Stryd, covering a distance of 464 ± 423 km in 39 ± 28 hours with an elevation gain of 4862 ± 3376 m. Training speed with Stryd was 11.9 ± 1.9 km·h^{-1}. Stryd data from regular training was compared with Stryd data from laboratory testing which revealed OBLA and VT2 were the closest physiological thresholds to CP_{STRYD} (Table 2). CP_{STRYD} was not different ($p > 0.05$) from peak 20-minute power, power at OBLA or power at VT2. While speed at OBLA was slower ($p < 0.01$) compared with VT2 (Table 1), power at OBLA was not different ($p = 0.07$) compared with power at VT2 (Table 2).

CP_{STRYD} 302 ± 58 W was not different ($p = 0.34$) compared with CP_{CALC} 305 ± 60 W (Figure 1a). No bias was evident (Figure 1b). The TOST procedure ($CP_{CALC} - CP_{STRYD}$, $p = 0.34$, Cohen's $d = 0.09$ and $CP_{STRYD} - CP_{CALC}$, $p = 0.66$, Cohen's $d = 0.09$) confirmed that the two critical power estimates can be considered statistically equivalent (Figure 1c). The % differences between the two measures followed a normal distribution (0.8 ± 9.9%), ranged between -19.1 to 18.5%, 25th and 75th percentiles were -6.8 and 7.9%.

As VT2 had a stronger relationship with CP_{STRYD} ($R^2 = 0.75$) compared with OBLA ($R^2 = 0.72$), VT2 was chosen as the threshold to directly compare with CP_{STRYD}. While there was little difference between CP_{STRYD} and Stryd power at VT2 (figure 2a), the relationship may be best described as non-linear (2b) and individual differences of 20–40 W between CP_{STRYD} and power at VT2 were observed (Figure 2c).

13 participants ran a maximal 1500 m effort (320 ± 62 s) on a track or flat sealed surface within 33 ± 44 days of laboratory testing. 13 participants ran a maximal 5000 m effort (1174 ± 223 s)

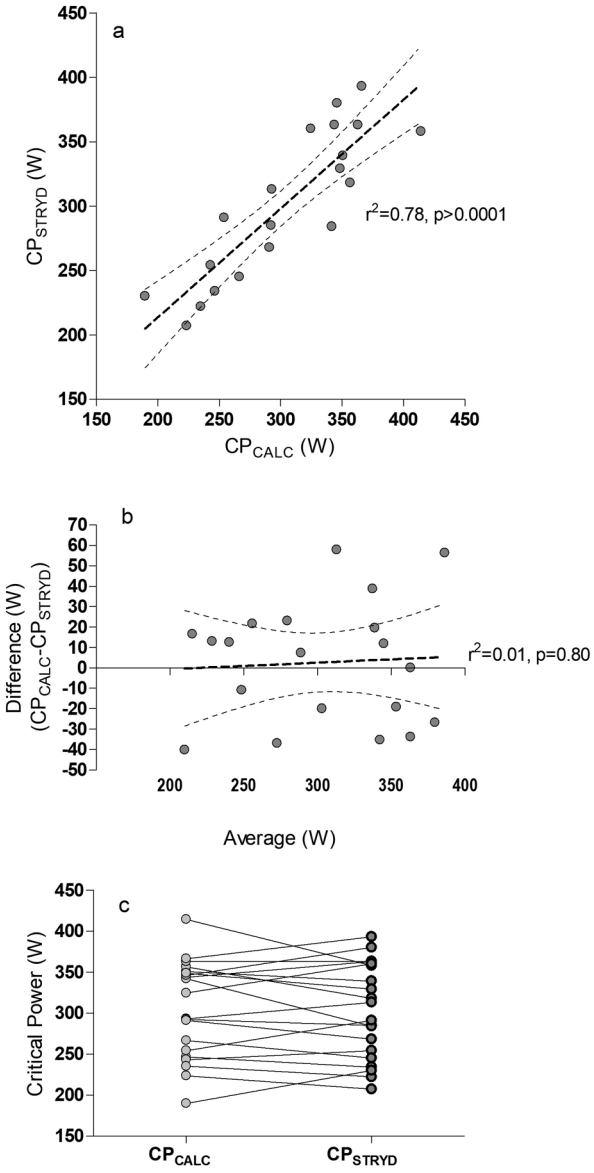


FIG. 1. 1a CPSTRYD is compared with vs CPCALC, Deming's Regression Results: Slope = 0.97 ± 0.13, Y-intercept = 7.48 ± 39.98, SD of the residuals = 30.18, $p<0.01$. 1b There was no bias evident on the Bland Altman plot. 1c The two measures of CP appeared equivalent. Runs test p value = 0.77.

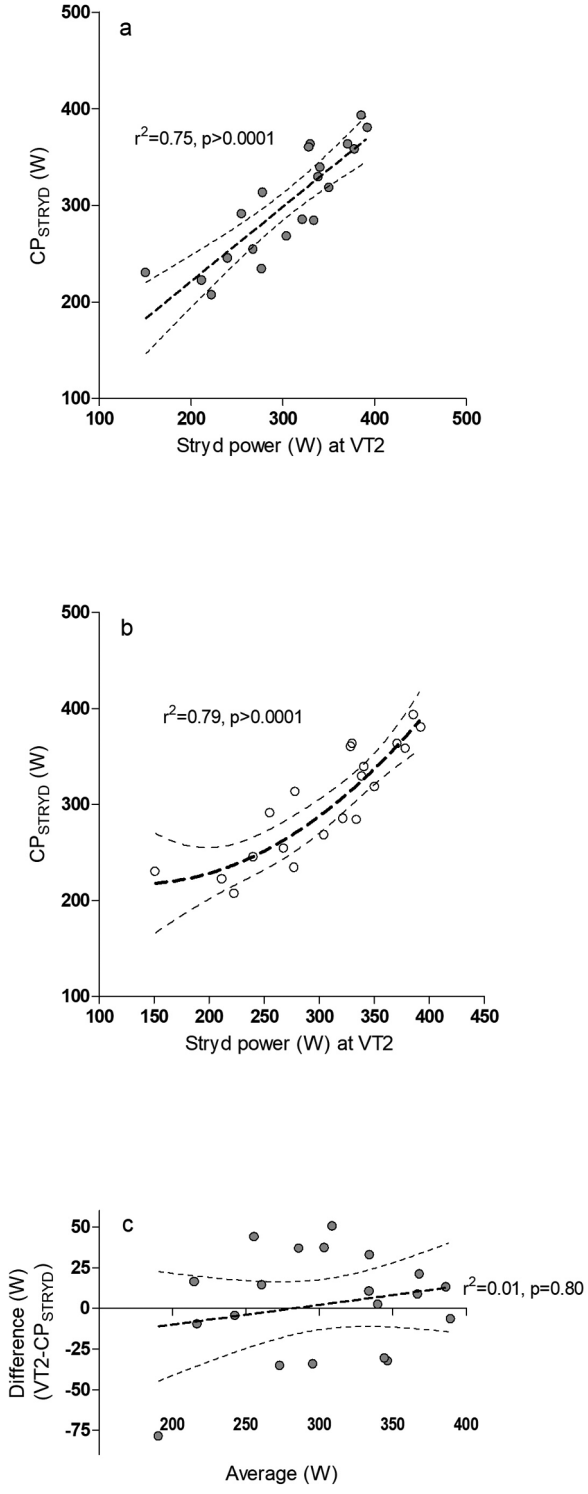


FIG. 2. Stryd CP is compared with power at VT2 with (2a) Linear regression (Best-fit values: Slope 0.77 ± 0.11, Y-intercept when X=0.0 66.70 ± 32.89, X-intercept when Y=0.-86.35) and (2b) non-linear regression (Polynomial: Second Order (Y=A + B*X + C*X^2), Best-fit values A = 265.2, B = -0.70, C = 0.00) are compared. 2c A Bland Altman plot was used to examine bias and individual athlete differences. Runs test p value = 0.87.

on a track or flat sealed surface within 34 ± 39 days of laboratory testing. 11 participants performed both distances. 7 participants could not compete at events because of COVID related event cancellations. These two outdoor runs and 1-minute peak speed from the GET and vMART were used as performance measures to compare Stryd data with laboratory tests (table 3).

While the two international class runners in our cohort had the lowest submaximal VO_2 at 12.0 km·h^{-1}, the oxygen cost of running was not predictive of performance. In contrast, Stryd GCT at 12.0 km·h^{-1} had an inverse relationship with performance and was predictive of 1-minute peak speed during GET, 1500 m time and was close to predicting (p = 0.07) 5000 m time. Further analysis revealed Stryd GCT at 12.0 km·h^{-1} also had inverse relationships with OBLA (r = -0.60. p = 0.04) and was close to significance with VO_{2peak} (r = -0.51. p = 0.05).

DISCUSSION

We found that CP_{STRYD} generated from regular training over a six week period was equivalent to that calculated using an established CP model. However, individual runner variance between CP_{STRYD} and other CP models must be a consideration for runners and coaches. CP_{STRYD} was most similar in intensity to VT2 and OBLA and was predictive of outdoor and laboratory running performance. However, laboratory-based data were superior predictors of running performance when compared with CP_{STRYD}. In addition, we found that Stryd running economy measures, form power and form power ratio, had little relationship with the oxygen cost of running. In contrast, GCT was inversely associated with performance when comparing runners at the same submaximal speed.

We found CP_{STRYD} (302 ± 58 W) was not different from CP_{CALC} (305 ± 60 W) estimated from a linear model using four MMP durations. In addition, we detected little bias between the two CP estimates. Day to day CP variation of ~5% has been previously reported for individual athletes [27]. As the differences between CP_{STRYD} and CP_{CALC} from our TOST procedure was not significant and is less (Cohen's d = 0.09) than 5% we suggest that the two CP estimates can be considered equivalent. It must be noted that some participants did record differences between the two CP estimates. While physiologically, CP supposedly represents a single boundary for an individual athlete between steady-state and non-steady state exercise intensity [12], different protocols and models are known to affect its determination [15]. CP_{STRYD} is an unknown unknown proprietary algorithm and the power time durations used in its estimation are not published for commercial reasons. Individual runner variance between the two CP estimates is somewhat an expected finding. Coaches and runners should be aware that any method of determining CP may not be interchangeable with other methods. However, CP_{STRYD} appears to be an acceptable method of determining CP in running when compared with previously published linear models.

CP_{STRYD} intensity closely resembles VT2 and OBLA which are thresholds frequently used as guides for training intensity

TABLE 3. Comparing laboratory, Stryd and outdoor running as predictors of running performance.

Performance Measure	Best laboratory predictor	Best Stryd Predictor	Stryd GCT at 12 km hr^{-1}	Running economy at 12 km h^{-1}
5000 m time (s)	OBLA (Km·h^{-1}) R^2 = 0.95 p < 0.01 (n = 13) Runs p = 0.76	CP (W/Kg) R^2 = 0.89 p < 0.01 (n = 13) Runs p = 0.87	NS	NS
1500 m time (s)	VT2 (Km·h^{-1}) R^2 = 0.91 p < 0.01 (n = 13) Runs p = 0.97	CP (W/Kg) R^2 = 0.86 p < 0.01 (n = 13) Runs p = 0.52	GCT (ms) R^2 = 0.52 P < 0.01 (n = 13) Runs p = 0.26	NS
1 minute peak speed during GET (Km·h^{-1})	VT2 (Km·h^{-1}) R^2 = 0.94 p < 0.01 (n = 20) Runs p = 0.07	CP (W/Kg) R^2 = 0.73 p < 0.01 (n = 20) Runs p = 0.43	GCT (ms) R^2 = 0.27 p = 0.03 (n = 20) Runs p = 0.55	NS
vMART speed (Km·h^{-1})	OBLA R^2 = 0.84 p = 0.01 (n = 20) Runs p = 0.95	20s PP (W) R^2 = 0.88 p < 0.01 (n = 20) Runs p = 0.68	NS	NS

The best laboratory-based data predictor of running performance is compared with the best Stryd data predictor for four performance measures. Stryd GCT is compared with running economy as a predictor. Each regression was examined with graphs of the residuals and the runs test. Runs test p values are included. PP = Peak Power. OBLA = onset of blood lactate accumulation, CP = critical power, VT2 = second ventilatory threshold,

distribution or "polarised training" in endurance athletes [28, 29]. CP_{STRYD} would thus appear to facilitate polarised training at recommend intensity distributions, without the need for laboratory testing. There may be limitations for using CP_{STRYD} as a threshold. Our results suggest for participants with lower CP_{STRYD} values (~220 W), VT2 may occur at a lower intensity compared with CP_{STRYD}. Also, individual subject differences of 20–40 W (7–13%) between CP_{STRYD} and power at VT2 were observed. Although CP_{STRYD} intensity may be similar to VT2, we cannot discount that it may be an independent physiological threshold. Also, it should be noted that we did not determine MLSS which has been suggested as a true representation of the boundary between steady-state and non-steady state exercise intensity [17, 18, 30]. In spite of these limitations, we speculate that individuals who experience an increase in CP_{STRYD} (W/kg) would also likely improve endurance performance. Although we did not specifically compare changes in CP_{STRYD} with changes in performance, some runners in our cohort did experience an increase in CP_{STRYD} over the training period that appeared to coincide with an increase in performance. Further research is required to confirm if changes in CP_{STRYD} with correlate with changes in performance.

We found no difference (p = 0.07) in Stryd power between OBLA and VT2 (296 vs 304 W), yet running speed at OBLA was slower (p < 0.01) than VT2 (14.2 vs 14.7 km h^{-1}). Similar OBLA and VT2 velocity differences have been reported previously in runners [25]. The fact that velocity and not power was different, might suggest that velocity is a more precise measure of intensity compared with Stryd power. However, even a 1% change in grade substantially changes the energetic cost of running [22], while Stryd power, unlike velocity, accounts for both elevation and wind. We found Stryd power linearity for flat and incline treadmill running was excellent (R^2 > 0.99). Thus, we speculate that Stryd power is likely to be superior compared with velocity for any individual runner seeking to measure running intensity where a change in grade result in changes in velocity.

CP_{STRYD} (W/Kg) was able to explain 73–89% of the variance in running performance for 1500 m, 5000 m and GET peak speed. However, for all three of these measures of running performance, laboratory testing was superior to Stryd CP and explained 91–95% of the variance. Treadmill velocities during GET were the most predictive of performance which is similar to previous research [31]. While the two international class runners in our cohort had lowest oxygen cost at submaximal speed, this was not predictive of any performance in this study. In contrast, Stryd GCT had significant inverse relationships with peak GET speed, VO_{2peak}, OBLA, and outdoor

running performance. Lower GCT has been associated with greater economical running in elite runners [32]. While laboratory exercise testing remains the gold standard to predict endurance performance, CP_{STRYD} is highly predictive of performance and Stryd GCT may also be a useful field-based parameter.

A major limitation from our study was that COVID restrictions prevented a single time trial. Thus, for our outdoor trials, participants encountered varying running conditions that we are unable to control for such as different weather, temperature and courses. Nevertheless, even with this limitation, CP_{STRYD} was highly predictive of outdoor performance. It must also be noted that our runners could not have feasibility raced one another in any meaningful way. Even a 1500 m track based time trail would result in some participants being lapped more than once. We believe this heterogeneity of our population can also be considered a strength as runners are not a homogenous group and running power will appeal to many runners of different abilities. Predictive measures such as VO_{2peak} are more predictive of performance in heterogenous populations [33]. A homogenous group such as elite runners would be likely to generate weaker relationships with Stryd than we have found. This also warrants further research. One possible limitation is that we did not determine MLSS and this also would be one area for further research. Also, a possible limitation is that while CP_{STRYD} was statistically equivalent to CP_{CALC}, some participants recorded differences between the two estimates. Coaches and runners need to remain aware that CP estimates are highly influenced by both trial protocols and the mathematical models employed [15]. Even when using the same protocol and model a ~5% day to day variance should be expected [27].

CONCLUSIONS

In conclusion, CP_{STRYD} generated from outdoor running is equivalent to that calculated using an established CP model. CP_{STRYD} appears to most similar in intensity to VT2 or OBLA and may offer a useful guide for training intensity distribution or polarised training. CP_{STRYD} is highly predictive of running performance although laboratory-based data are superior predictors. While Stryd was not predictive of the oxygen cost of running when comparing runners at the same submaximal speed, Stryd GCT is inversely associated with performance and may be a useful field-based parameter. Stryd offers meaningful data for runners including a realistic estimate of CP.

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Conflict of interest declaration

No potential conflict of interest was reported by the author(s).

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Increased brain ^{1}H-MRS glutamate and lactate signals following maximal aerobic capacity exercise in young healthy males: an exploratory study

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ABSTRACT: Physical exercise involves increased neuronal activity of many brain structures, but 1H-MRS investigations on the effects of human brain glutamate (Glu) concentrations on acute exercise have been sparse. Previous studies consistently found increases in brain lactate (Lac) concentrations following graded exercise up to 85% of the predicted maximal heart rate. However, the reported effects on brain concentrations of glutamine and glutamate were not consistent. This study aimed to determine the effect of acute intense graded maximal exercise on 1H-MRS signals related to concentrations of Glu, glutamate+glutamine (Glx), and Lac. Young adult males were randomly divided into two groups and subjected to 1H-MRS when resting (NE) or shortly after cessation of the intense graded exercise intended to pass the anaerobic threshold (E). 1H-MRS spectra were acquired from the large voxel encompassing the occipito-parietal cortex only once. Estimates of Glu, Glx, and Lac concentrations were calculated in institutional units by normalizing to a spectroscopic signal originating from creatine-containing compounds (Cr). Concentrations of Glu, Glx, and Lac were respectively 11%, 12.6%, and 48.5% higher in E than in NE ($p < 0.001$). The increased brain Lac signal in the exercising group indicated that in our experiment, vigorous exercise resulted in passing the anaerobic threshold and lactate apparently entered the brain. Concomitantly glutamate-related resonance signals from the vicinity of the occipito-parietal cortex were significantly increased; physiological mechanisms underlying these phenomena require further study. Future studies should evaluate whether the normalization rate of these concentrations is a marker of general physical fitness.

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INTRODUCTION

Exercise is a simple environmental intervention that profoundly modifies brain function by inducing a cascade of molecular and cellular processes that support brain plasticity. The effect on the exercise-induced plasticity of the brain may be driven from impulses generated outside the brain. The best-recognized evidence presented in human and animal studies shows an association between contraction-induced changes in working muscles of metabolic products and central nervous system (CNS) function by stimulation of group III and IV muscle afferents [1, 2, 3, 4]. Moreover, afferent signals from the lungs (increased ventilation) and the heart (increased heart rate) were found to affect brain function during exercise [5]. The onset of effects of exercise on the brain is rapid and evolves over time [6]. Initially, in response to exercise, neurotransmitter levels change, followed by upregulation of growth factors in the brain [e.g., brain-derived nerve growth factor (BDNF)] and the genesis of new neurons in the hippocampus [7, 8]. Acute normobaric hypoxia does not affect the simultaneous exercise-induced increase in circulating brain-derived neurotrophic factor (BDNF) and glial derived neurotrophic

factor (GDNF) in healthy young men [9]. It is well documented that dopaminergic and serotonergic pathways play a pivotal role in movement regulation, and their activity is strongly influenced by exercise [10] and would provide an input to the central governor, defined as the functional structure of the brain responsible for regulation of movement [11, 12].

Glutamate (Glu) is the main excitatory neurotransmitter in the mammalian central nervous system, and 60–80% of total energy consumption in the non-stimulated cerebral cortex is used by processes supporting glutamatergic neurotransmission [13]. A key part of the glutamatergic neurotransmission system is the so-called glutamate-glutamine cycle (Glu-Gln cycle), believed to efficiently recycle Glu released to synaptic clefts between synapses and presynaptic terminals. The cycle involves uptake of Glu from synapses by astrocytes, intra-astrocytic conversion of Glu to Gln, transport of Gln from astrocytes to neurons, and intraneuronal conversion of Gln back to Glu [14, 15].

Magnetic resonance spectroscopy (MRS) in vivo provides opportunities for noninvasively probing certain aspects of glutamatergic neurotransmission. Changes in brain proton magnetic resonance signals of these substances are only indirectly related to the rates of their metabolism, but certain information concerning the function of the glutamatergic neurotransmission system can be inferred from such observations. Although only a fraction of MRS-detectable glutamate is involved in neurotransmission, it has been argued that differences in MRS-visible glutamate, such as between healthy persons and patients suffering from mood disorders or schizophrenia, are likely related to changes in glutamatergic neurotransmission [16, 17].

Physical exercise involves markedly increased neuronal activity of many brain structures [18, 19], but investigations of the effects of acute exercise on estimated brain levels of Glx or Glu in humans have seldom been performed and the results obtained are not consistent. In a 1H-MRS study employing a 1.5T MR system, Maddock et al. [20] observed an 18% increase in the Glx signal from the visual cortex following graded exercise to approximately 85% of the predicted maximal heart rate. In a further study from the same laboratory, performed using a 3T MR system [21], an increase in glutamate resonance acquired following exercise from the visual cortex was confirmed, and a similar increase was noted in the anterior cingulate cortex. The authors interpreted these results as consistent with the exercise-induced expansion of the cortical pool of glutamate, seemingly in agreement with a marked increase in whole-brain nonoxidative glucose consumption [22]. However, other investigators [24], who employed a similar exercise paradigm but a 7T MR system and recorded 1H-MRS spectra from the occipital cortex, did not find a significant change in Glu or glutamine (Gln) following similar vigorous exercise when the metabolites were normalized to creatine. However, when the concentrations were scaled to a water signal, a decrease in both Glu and Gln was observed.

We hereby present the results of an exploratory study performed to evaluate the differences between brain 1H-MRS signals acquired from the brains of healthy young human volunteers at rest and following short-term acute exercise. We aimed to find out whether acute graded vigorous exercise continued until the subject reaches a predefined maximum heart rate limit is reflected in Glu-dependent resonance signals from the brain. We chose to collect H-MRS spectra from a large voxel encompassing the occipito-parietal cortex and vicinity because these areas are expected to be activated during exercise. The parietal cortex becomes activated with a diverse range of stimuli and tasks, including motion processing [24], and the occipito-parietal cortex is activated and becomes thickened following repeated exercise [25].

The other 1H-MRS-detectable effect of acute intense exercise in humans is the increase of the lactate (Lac) signal from the brain, which has been reported independently of whether the Glu signal was found to be increased [20, 21] or decreased/unchanged [23]. In the present experiments recording the brain lactate signal was not a primary goal, but it was performed in order to confirm the comparability of our experimental paradigm with those in the previous brain 1H-MRS exercise studies. We expected higher concentrations of Glu, Glx, and Lac in the exercising group (E) than in the resting (non-exercising, NE) group.

MATERIALS AND METHODS

Subjects

Twenty-eight young male candidate cadets taking the Polish Air Force University entrance exam volunteered for the study. They were aged 17–19 years, with a height of 177.8 ± 8.0 cm and a body weight of 76.5 ± 7.6 kg. As military cadets, participants had high physical fitness. They were randomly divided into two groups: collected at rest (NE group) and shortly after the end of the exercise in the exercise (E group). All participants had a current valid medical examination that excluded chronic diseases such as diabetes or epilepsy. They stated that for at least one month before testing they did take medications or dietary supplements. Participants were informed of the nature of the investigation, with a clear statement of the objective of the research and possible risk. They could withdraw at any time. The experimental protocol conformed to the principles presented in the Declaration of Helsinki and was approved by the ethical committee of the Military Institute of Aviation Medicine.

Exercise testing protocol

The participants were instructed to abstain from alcohol, coffee, tea, and strenuous exercise for at least two days before the study. Visits to the laboratory began at 10:00 AM after all-night sleep (i.e., the participants were not tired), 2–3 hours after a light breakfast composed of 50–60% carbohydrates, 15–20% protein, and 22–30% fat. The participants were randomly assigned to the non-exercising (control) group (NE, $n = 14$) and the exercising group (E, $n = 14$). For members of the exercising group, the MRI session started within 10 min after the end of the exercise.

The progressive exercise test was performed on a treadmill according to Mortara Qstress System guidelines (Mortara Instrument, Inc.,

Milwaukee, Wisconsin USA). Here we employed a routine procedure required by the Polish Ministry of National Defence for testing candidates for fighter pilots. Briefly, in the pre-exercise phase study, participants underwent short forced hyperventilation in the standing position (breaths as deep and rapid as possible for less than 1 min). During this phase, the Q-Stress system acquires ECG data to develop the patient's cardiac template used for heart rate limit calculation, ST-segment analysis, and possible arrhythmia detection. Three minutes later, a 1-minute warm-up was initiated with no treadmill inclination set at a velocity of 1.6 km/h, followed by the SIMULATOR treadmill protocol of graded exercise (Table 1). The test is continued until the subject reaches the age-dependent maximum heart rate limit, which is set as (220-age) beats per minute, as recommended for cardiovascular stress testing that uses exercise [26]. All participants fulfilled the conditions below, and none of the tests were interrupted for the following reasons: exhaustion; diastolic blood pressure increase (DBP) > 120 mmHg; systolic blood pressure (SBP) increase > 260 mmHg; sustained drop in SBP; clinical manifestation of intense typical chest pain; depression of the ST segment > 3 mm; elevation in the ST segment > 2 mm in the lead without the presence of the Q wave; complex ventricular arrhythmia; the appearance of sustained supraventricular tachycardia, atrial tachycardia, or atrial fibrillation; 2nd- or 3rd-degree atrioventricular block, signs of left ventricular failure; a failure in the monitoring or recording systems, or both. The presence of typical symptoms or symptoms of straightened or descending depression in the ST segment > 1.0 mm or ascending depression of the ST segment > 1.5 mm, 0.08 seconds from the J point, or even an elevation in the ST segment 1.0 mm, characterized a positive test. The test was considered successful if the patient reached at least 100% of the maximum heart rate recommended (220-age). Hypertension reactive to the effort was defined as SBP levels > 220 mmHg or an elevation of 15 mmHg or more in DBP, or both. Moreover, the indirect measure of maximum oxygen consumption (VO_2max), in METS, was automatically calculated by the software using the formula of the American College of Sports Medicine.

TABLE 1. SIMULATOR protocol: duration, velocity, and incline of the treadmill at every stage.

Stage	Time of duration	Velocity	Incline
1	1:00 min	4.0 km/h	12%
2	1:00 min	5.3 km/h	14%
3	1:00 min	6.8 km/h	14%
4	1:00 min	8.0 km/h	16%
5	1:00 min	8.9 km/h	18%
6	1:00 min	9.5 km/h	20%
7	1:00 min	11.1 km/h	22%
8	1:00 min	12.1 km/h	22%

Magnetic resonance sessions

In this cross-sectional study, MR studies were performed with a 3T GE Discovery 750w scanner with a 70 cm wide bore, using a body transmit coil for excitation and the eight-channel receiver coil (description available in the GE catalogue). Each MR session consisted of structural imaging performed for voxel placement and localized single-voxel proton MR spectroscopy. The structural scan was obtained using steady-state fast spin echo (SSFSE) with 3 slices in each orthogonal plane, with the following parameters: repetition time/echo

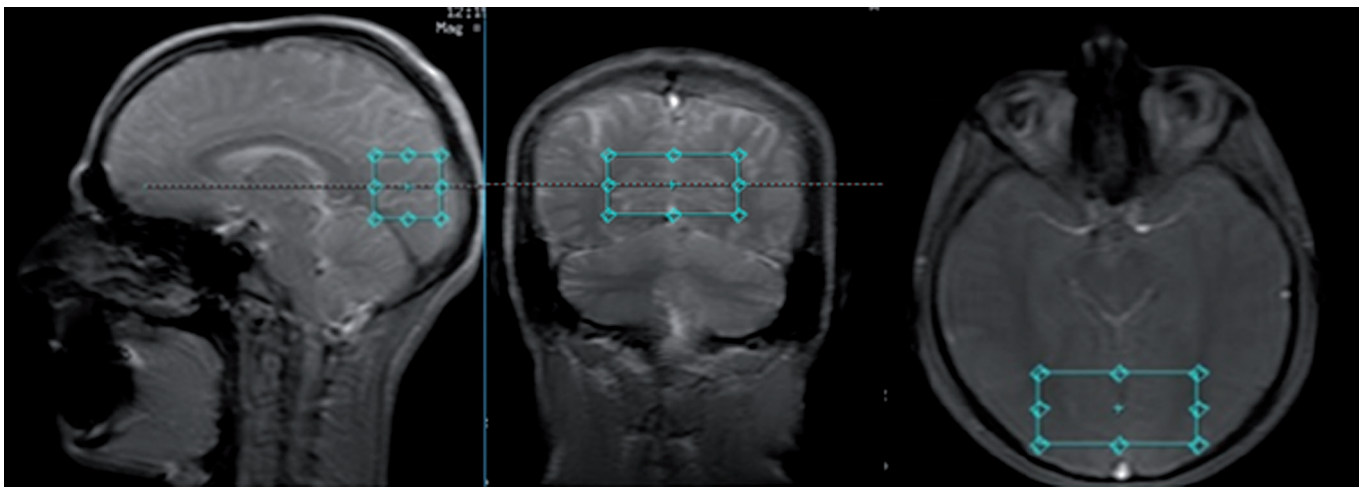


FIG. 1. Placement of the volume of interest ($30 \times 30 \times 60$ mm^3) in the area encompassing the occipito-parietal cortex of both hemispheres.

time (TR/TE) = 6.412/2.1 ms, duration 30 s. Spectroscopic data were acquired with a PRESS PROBE-P single voxel sequence (TR/TE = 1500/35 ms and TR/TE = 1500/288 ms, bandwidth = 2367 Hz, 128 acquisitions, duration 3 min 48 s), with chemical shift selective (CHESS) water suppression. The spectra were acquired with a short echo time (35 ms) to measure Glu and Glx and with a long echo time (288 ms) to measure Lac. Both spectra were acquired within the same volume of interest (VOI, $30 \times 30 \times 60$ mm = 54 cm^3), which was placed in the vicinity of the occipitoparietal grey matter area (Fig. 1). A large VOI was used to allow for monitoring of small signals from Glu and Glx within reasonable time.

Unsuppressed water signals were acquired for each sequence for eddy current compensation and phase correction. 4.096 complex points were acquired on the spectrum.

Spectra processing

Metabolite concentrations were estimated using the LCModel software [27], version 6.3.-1M. The default LCModel pre-processing pipeline was utilized, i.e., the sum of squares channel combined and phase cycle accumulation. The analysis window used with LCModel was 4.0 to 0.2 ppm. An example of the LCModel approximation of metabolite concentrations superimposed on the representative spectra obtained from the occipito-parietally localized VOI is shown in Fig. 2.

The 'standard' basis set for the 3T PRESS sequence with TE 35 ms or 288 ms was used, containing the following metabolites: alanine (Ala), aspartate, (Asp), creatine (Cr), phosphocreatine (PCr), glycerophosphocholine (GPC), phosphocholine (PCh), γ-aminobutyric acid (GABA), glucose (Glc), glutamine (Gln), glutamate (Glu), glutathione (GSH), lactate (Lac), myo-Inositol (Ins), N-acetyl aspartate (NAA), N-acetyl aspartate glutamate (NAAG), scyllo-Inositol (Scyllo) and taurine (Tau). The simulated basis set was provided by S. Provencher on request. Specified timings and ideal pulses were used for gamma simulation. The signal-to-noise ratio (SNR) was derived from the LCModel. Relative standard deviation estimates of the resonance signals (Cramér-Rao lower bounds, CRLB) were used to establish the criterion for further analysis. Resonance signals with mean CRLB ≤ 15% for metabolites and ≤ 30% for Lac (excluding

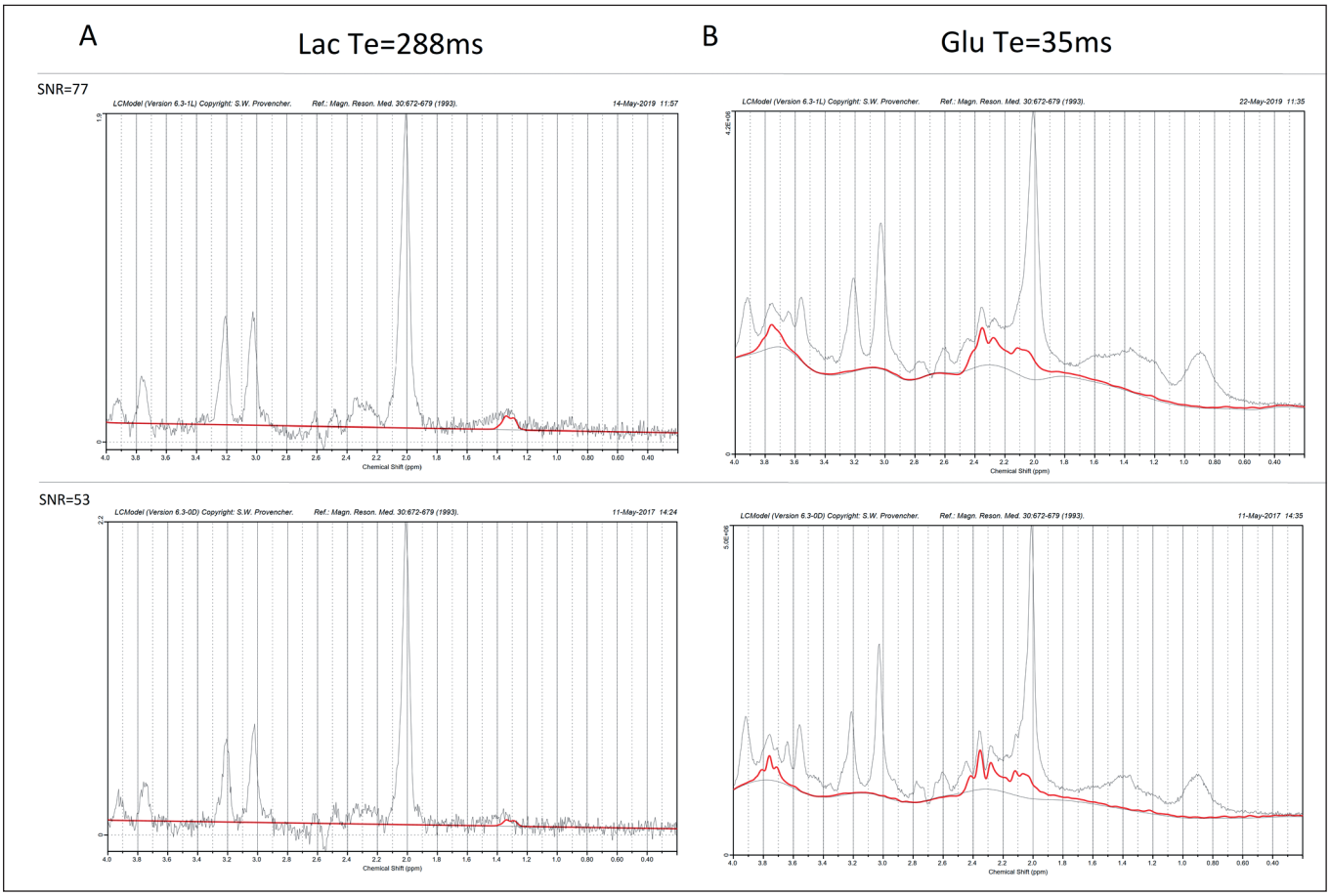


FIG. 2. Representative spectra (black line; the best SNR = 77 (upper graph) and the worst SNR = 53 (lower graph)) and LCModel approximation of metabolite signals (red line). A: Lac, TE = 288 ms, B: Glu, TE = 35 ms, Average CRLB: TE = 288 ms, Lac = 18.4, TE = 35 ms Glu = 4.7.

macromolecules) were identified and used to obtain estimates of their respective concentrations.

Metabolite signals in the acquired spectrum were scaled to the signal of the sum of creatine and phosphocreatine (tCr) [28]; i.e., the concentrations were measured in institutional units, not in moles/grams of the neurotransmitter of interest per unit volume of the brain. The term concentrations will refer to concentrations measured in institutional units throughout the manuscript. Spectral quality was comparable across groups (see Table S1).

Statistical analyses

The GraphPad Prism for Windows ver. 6.04 software package (GraphPad Software, San Diego, CA, USA) was used for statistical assessment of the data. The normality of distribution was assessed with D'Agostino–Pearson omnibus and Shapiro–Wilk normality tests. Because estimates of metabolite concentrations in the E group did not follow a normal distribution, non-parametric tests were used for data analysis. No correction for multiple comparisons was applied. The significance of differences between the data collected at rest (NE group) and exercise (E group) were tested using the Mann-Whitney test. Differences between groups were considered significant when $p \leq 0.05$.

RESULTS

Quantitative data concerning Glu Glx and Lac scaled tCr are presented on the graphs as individual data points and mean values for the NE and the E groups (Figs. 3–4). When 1H-MRS spectra recorded at rest and after exercise were compared, signals of Glu, Glx, and Lac were higher in the exercising group than in the resting group. Following exercise, the mean Lac was 49.5% higher than at rest ($p = 0.001$); the mean Glu was 11.0% higher than at rest ($p = 0.0001$); the mean Glx was 12.6% higher than at rest ($p = < 0.0001$). All measured metabolites (mean values and standard deviation) are presented in Table 2.

DISCUSSION

The major finding of the present study is that in young male volunteers, 1H-MRS signals of Glu and Glx recorded from the large voxel located in the vicinity of the occipito-parietal cortex shortly after the exercise were significantly higher than those recorded at rest. Our data confirm the findings of Maddock et al. [20], who observed an increase in Glx in the visual cortex of healthy volunteers following short strenuous exercise and attributed it to the exercise-induced expansion of the cortical pool of glutamate.

During recent years a body of evidence has accumulated indicating that both acute bouts of exercise and regular training contribute to the activation of numerous adaptive mechanisms of the human body. These exercise/training-induced adaptive changes increase the improvement in both health and exercise performance in sedentary subjects and athletes. The extent of these changes is primarily determined by the type of exercise/training, exercise/training loads, and the sports level of athletes [29, 30]. In recent years, a pivotal role in the regulation of these changes has been assigned to the brain, particularly the prefrontal cortex, which takes part in the regulation of many executive functions to prepare humans for situations demanding high levels of working memory, attention, and cognitive flexibility [31, 32]. Thus, the main contribution of this study was to provide new and relevant data on the effect of maximal exercise on glutamate and lactate signals in young, healthy men, which may be involved in the modulation of the above-mentioned functions in response to exercise. We chose these variables for our research because glutamate is one of the main neurotransmitters in the brain,

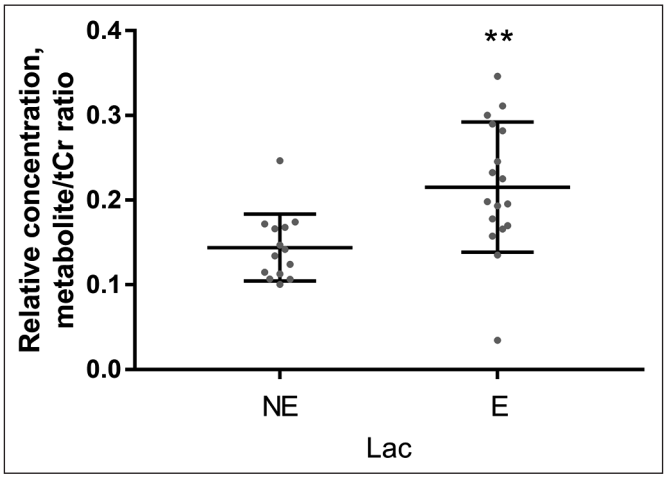


FIG. 3. Relative concentrations of Lac obtained from data recorded with TE = 288 ms, in the non-exercising group (NE) and in the exercising group (E). ****P < 0.0001.

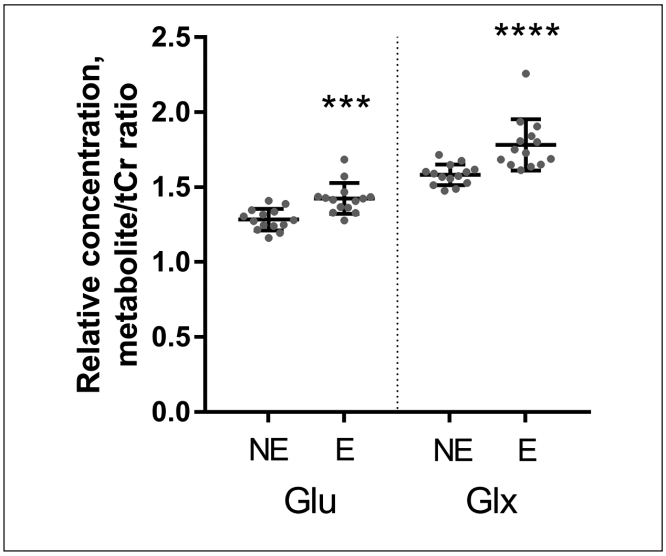


FIG. 4. Relative concentrations (mean values and standard deviations) of Glu and Glx obtained from data in the non-exercising group (NE) and in the exercising group (E). Individual values of metabolite concentrations scaled to total creatine (TE = 35 ms). *P < 0.0001.

TABLE 2. Average relative concentrations of measured metabolites for non-exercising group (NE) and exercising group (E).

X/tCr	NE Group		E Group		P value
	M	SD	M	SD	
Lac	0.14	0.04	0.22	0.08	0.001
Glu	1.28	0.07	1.42	0.10	0.0001
Glx	1.58	0.07	1.78	0.17	< 0.0001
NAA	1.42	0.05	1.49	0.11	0.08
NAA+NAAG	1.56	0.10	1.64	0.09	0.08
GPC+PCh	0.20	0.02	0.21	0.03	0.43
Ins	0.78	0.04	0.78	0.04	0.82
GPC	0.18	0.05	0.18	0.05	0.43
GSH	0.16	0.04	0.17	0.04	0.81
NAAG	0.14	0.06	0.15	0.05	0.94
Tau	0.19	0.04	0.23	0.08	0.01

Note: values are mean and standard deviations, X/ tCr - Metabolite scaled to the signal of the sum of creatine and phosphocreatine, Lac - Lactate, Glu - glutamate, Glx - glutamate and glutamine, NNA - N-acetylaspartate, NAA+NAAG - N-acetylaspartate and N-acetylaspartylglutamate, GPC+PCh - glycerophosphocholine and phosphocholine, Ins - inositol, GPC - glycerophosphocholine, GSH - glutathione, NAAG - acetylaspartylglutamate, Tau - Taurine.

and lactate, especially during exercise, is taken up by the brain and can significantly modify its functions [33]. Moreover, the role and contribution of glutamate is the least studied in response to exercise among the neurotransmitters.

According to the model presented by Fonnum and Hassel [34] there are four Glu pools in the brain: the transmitter pool, the glial pool, the GABA precursor pool, and the metabolic pool. These authors pointed out that different pools are housed by different compartments. The metabolic Glu pool resides in the neuronal bodies; the glial pool resides in the glial cells; the transmitter and GABA precursor pools reside in the presynaptic terminals, excitatory and inhibitory, respectively. Whereas the average brain Glu concentration (determined by chemical methods) is approximately 10 mM [35], its concentration in glutamatergic synaptic terminals is much higher. Presynaptic glutamate is stored in synaptic vesicles, from which it is released upon stimulation [36], and Glu concentration in the vesicles is thought to reach 100 mM [37].

The 1H-MRS technique provides information on the average Glu concentration in the chosen volume of interest, and the aforementioned glutamate pools in the brain are usually not mentioned in interpretations of the spectroscopic data. When an increase in the average Glu pool in brain tissues is detected using 1H-MRS technique, information is provided neither about relative sizes of the various Glu pools nor about which pool/s of Glu is/are responsible for the overall change detected. However, the concentrations of Glu and Gln are higher in the brain than in any other tissue [38]. Considering that 85% of the energy consumed by the resting brain is used for support of glutamatergic neurotransmission, we may be rather certain that an increase in the average brain Glu content during exercise is related to the enhancement of excitatory neurotransmission and neurotransmitter Glu recycling through Gln. The other important functions of Glu in the brain served by its metabolic pool are nitrogen buffering (ammonia detoxification) and providing an input into the tricarboxylic acid cycle (TCA) [39]. However, ammonia is released from the working muscles to blood; in rat experiments, the requirement for NH_3 removal from the brain during exercise was increased, and glutamine synthesis was stimulated as a mechanism of detoxication, resulting in brain Glu decrease [40]. Also, supporting enhanced neurotransmission is the only additional work performed in the brain during exercise compared with rest, and it would be very impractical to use Glu to fuel the TCA cycle. Considering all the above, it seems rather certain that the exercise-induced expansion of the total brain Glu pool is caused mostly, if not totally, by the expansion of the Glu pool serving neurotransmission.

The other finding of the present study concerns the exercise-induced increase in the lactate signal. This observation is also in agreement with the findings of Maddock et al. [20, 21], who attributed increased Lac resonance to the entry of lactate from the blood to the brain during exercise. Such an interpretation agrees with the prevailing view that during intense exercise, when lactate is released into the blood by the working muscles, blood lactacidaemia makes it available to the brain, which switches from a net producer to a net importer of lactate [41]. An increase in 1H-MRS Lac signal recorded from the brain has been reported following sodium lactate infusion in healthy volunteers [42]; this result indicates that increased brain activity is not a prerequisite for lactate entering the brain from the blood. On the other hand, in an fMRI experiment, a significant increase of the lactate signal (by an average of 8.6%) was observed in the motor cortex following the standard finger-tapping paradigm [43]. It is possible that a part of the increased Lac signal from

the brain following the exercise bout reflects the intensification of the aforementioned increase of glucose metabolism to lactate and subsequent anaplerotic metabolites, including glutamate. However, in our data, there was no correlation between Glu and Lac signals, the correlation coefficients being r = 0.004 and r = 0.06 for resting and post-exercise groups, respectively (data not shown).

Our study has several limitations. Some of them are typical for clinical studies employing 1H-MRS. Clinical MR scanners are frequently employed to estimate Glu concentrations in the human brain, but values obtained vary among the studies. For example, average values of Glu concentrations in predominantly grey matter (GM) of adult human brain estimated from H-MRS spectra acquired using 1.5, 3 or 7T magnets published prior to 2003 ranged from 7.1 to 12.5 mmol/L; see Table 5 in [44]. More recently, a comparison of 1H-MRS of 3 regions of the human brain at 3 and 7 T, using the same subjects and similar methodology, revealed significant differences in the estimates of the concentration of some metabolites, e.g. Glx [45]. Although the aforementioned dispersion of the data seems to indicate a rather high inaccuracy of the 1H-MRS technique as a tool for estimation of brain metabolite concentrations, such a situation is not unusual in neurochemistry. In a landmark study concerning the *in vivo* neurochemical profile of rat brain [46], estimates of metabolite concentrations obtained from ultra-short echo time 1H-MRS were compiled with data obtained using non-resonance analytical techniques, published in the neurochemical literature, including reference textbooks. For Glu, the resonance-derived estimate was 8.3 mmol/g brain, while the classical data ranged from 7.3 to 12.5 mmol/g brain. This comparison shows that resonance-derived estimates of brain metabolite concentrations may not be less accurate than the data obtained with other techniques.

Further limitations are related to the exploratory character of our study. We chose to compare the proton magnetic resonance data collected at rest and shortly after the end of a bout of strenuous exercise from a large voxel located around the occipito-parietal cortex area and subjected to minimal processing. Our main aim was to determine whether the estimates of Glx and Glu concentration are different between the resting and post-exercising group, while the accuracy of the measurements was of secondary importance. We did not perform frequency drift correction, but magnetic resonance spectra acquisitions lasted only 4 min, and over this time, no significant drift is expected [47]. Also, we did not record non-averaged data and did not apply a correction for actual volume fractions of grey matter, white matter, and fluid spaces. We assumed that, since the study participants were highly homogeneous with respect to age and general health conditions, the composition of voxels from which the spectra were collected are also highly similar in all of them. In agreement with this expectation, there was no difference between the NE and the E group with respect to SNR, FWHM (full width at half maximum), and CRLB values for all quantifiable metabolites. When the estimates of metabolite concentrations were obtained with LCModel, statistically significant differences between the NE and the E group were observed for Glx, Glu, and Lac, and also taurine. However, the taurine signal displayed a high CRLB value, and the difference disappeared after correction for multiple comparisons was applied.

CONCLUSIONS

In summary, our exploratory experiment showed that resonance signals of Lac, Glu, and Glx recorded from the large voxel around the occipito-parietal cerebral cortex of young, healthy volunteers after a single episode of vigorous exercise were higher than those recorded at rest. The present data do not provide an explanation for the physiological mechanisms underlying these effects. In particular, further studies are needed to understand the relation between the increased rate of glutamate neurotransmission and the concomitant increase in glutamate-dependent resonance signals from the brain.

Conflict of interest declaration

The authors declare no conflict of interest.

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Supplemental material

Table S1. Spectral quality for each metabolite.

	NE Group		E Group		p Value
	M	SD	M	SD	
Snr	61.14	4.96	64.57	4.31	0.062
FWHM [Hz]	5.68	1.37	5.69	0.99	0.933
CRLB [%] Cr+PCr	1.93	0.27	1.93	0.26	> 0.99
CRLB [%] NAA	2.00	0.00	2.00	0.50	> 0.99
CRLB [%] NAA+NAAG	2.17	0.39	2.07	0.48	0.797
CRLB [%] GPC+PCh	2.75	0.45	2.64	0.50	0.574
CRLB [%] Ins	3.75	0.45	3.89	0.33	0.509
CRLB [%] GPC	6.08	5.79	8.71	8.99	0.946
CRLB [%] NAAG	17.8	6.80	16.67	3.75	0.634

Note: Values are mean and standard deviations. Data collected at rest (NE group) and exercise (E group). FWHM - Full width at half maximum herc [Hz] , CRLB - cramer-rao lower bound percentage [%] , Cr+PCr - creatine and phosphocreatine, NAA - N-acetylaspartate, NAA+NAAG - N-acetylaspartate and N-acetylaspartylglutamate, GPC+PCh - glycerophosphocholine and phosphocholine, Ins - inositol, GPC - glycerophosphocholine, NAAG - acetylaspartylglutamate.

Association between internal training load and muscle injuries in Brazilian professional soccer players

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ABSTRACT: The training load is associated with injury risk in a variety of sports. This study aimed to evaluate the association between the internal training load and injury risk in Brazilian professional soccer players. The data were collected from 32 soccer players across two full seasons (2017 and 2018). The rating of perceived exertion (RPE) for every training/match session was used as an internal load variable. The cumulative training load from 3 and 4 weeks (C3 and C4) and the acute:chronic workload ratio (ACWR) were calculated. A generalized estimating equation analysis was applied to examine associations of non-contact muscle injuries with C3, C4 and ACWR. A total of 33 injuries were recorded across the two full seasons. A significant association was found between cumulative training load for three (C3, $p = 0.003$) and four weeks (C4, $p = 0.023$) and the occurrence of injuries. Players in the "high load" group presented greater injury risk in relation to the "moderate load" group (C4: OR = 4.5; IC 95% 1.5–13.3; C3: OR = 3.7; IC 95% 1.7–8.1). There was no association between ACWR and injury occurrence. The athletes exposed to a high cumulative load in a period of 3 to 4 weeks presented higher injury risk in comparison to those who had moderate cumulative training loads. Besides that, there was no association between ACWR and injury occurrence.

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INTRODUCTION

Training load monitoring has become a common practice in sports, whereby the practitioners can assess whether an athlete is receiving a suitable training load [1]. It can be ascribed as internal or external workload, depending on the parameter assessed, as being internal or external to the athlete [2]. In the team sports context, there is increasing interest in the applicability of internal training load, which represents the perceptual and/or physiological responses of players from an external load. In soccer, the rating of perceived exertion (RPE) has been considered as a valid tool for measuring the internal load [3] and can be utilised for a variety of training sessions [4].

In the last few years, a topic of debate which has arisen is the possible relationship between training load and non-contact injury risk in different sports and athlete levels. Briefly, most of the studies have analysed this association by two different training load approaches. One consists of the association between the cumulated training load during a certain period of time (e.g., the absolute workload from one week, one month, etc) and the occurrence of injuries [5]. Another approach involves utilising the acute:chronic workload ratio (ACWR) (i.e., the magnitude of the current week's training load in relation to a longer term training load, usually 3–6 weeks) [6]. Although it has been largely used in the field, it is noteworthy that ACWR has also been criticized because its causal relation to injury has not been established, lacking a conceptual basis and showing inconsistent results [7, 8].

According to the International Olympic Committee statement about load in sport and risk of injury, both acute and cumulated workload should receive special consideration [9]. Indeed, this association between training load and injury risk has been reported in elite soccer players from Europe [4, 8, 10] and Australia [11] by using RPE assessed following every training session.

Also, regional characteristics of soccer could influence the training/match demands and consequently the injury incidence [12]. For instance, lower injury incidence has been observed in professional Asian players than European players [13]. Regarding the relationship between workload and injury, even in the population of European players, there have been reported different results [4, 14]. To the best of our knowledge, there are no data reporting these relationships in professional Brazilian soccer players from a consistent period of time. Hence, the aim of the present study was to examine the association between absolute and relative internal training load and non-contact muscle injury risk in Brazilian professional soccer players.

MATERIALS AND METHODS

Participants

Data were collected from 32 professional soccer players from the same team (mean ± SD age: 27.5 ± 4.8 years, body mass 77 ± 8 kg, height 181 ± 7 cm) during two consecutive seasons (i.e., 2017 and

2018). Ten out of 32 players participated in both seasons, resulting in a total of 42 individual observations.

The team played in the Brazilian First Division Championship in 2017 and the Brazilian Second Division Championship in 2018. Only players who stayed in the club for at least 6 months took part in the analysis for the purpose of this research. The study was approved by the Human Research Ethics Committee of the local university, was performed in accordance with the ethical standards of the Helsinki Declaration, and participants signed an informed written consent form.

Quantification of training load

The intensity of every session was quantified by the sRPE method [15]. The RPE score was collected approximately 30 minutes after every single training session (field and gym sessions) or match, always by the same staff member. Thus, the internal training load was derived from each player by multiplying the RPE score and the duration of training or match, and it was expressed as arbitrary units (AU). All data were gathered in a Microsoft Excel spreadsheet. Cumulative workloads were calculated considering blocks of 3 (C3) and 4 (C4) weeks (sum of daily training load, from Monday to Sunday), independently. To determine ACWR, the value of the last week (i.e., acute workload) was divided by the rolling average from the last 4 weeks (i.e., chronic workload) [1]. In the week of injury occurrence, the workload data from that week were not considered for calculations, regardless of the day of occurrence.

Injury data collection

The occurrence of injuries was diagnosed by the team physician. An injury was considered when the player was unable to fully participate in future soccer training or a match due to any physical complaint [16]. Only acute (sudden-onset) non-contact muscle injuries were considered for analysis of the current study [17]. Muscle injury incidence was obtained by dividing the total number of muscle injuries by the exposure time (the sum of each session duration), and it was reported as the rate of injury per 1000 hours.

Statistical analyses

Generalized estimating equations (GEE) were used to model the univariate association between load variables (ACWR, cumulated 3 and 4 weeks) and muscle injury occurrence in the subsequent week (i.e., the week of the injury was not included). The GEE analysis was chosen because it takes into account the correlated nature of the data [18]. To analyse the longitudinal data of a dichotomous response variable (i.e., injury: yes/no) the logit link function was used, with an exchangeable working correlation matrix [19]. When GEE analysis was significant ($p < 0.05$) the data were divided into tertiles, obtaining the following groups: "low load", "moderate load" and "high load". The "moderate load" group served as the reference for subsequent analysis. Odds ratios (OR) and 95% confidence intervals (CI) were calculated for comparison among injury risks in different load groups. All analyses were performed using the software SPSS v. 21.0 (IBM, USA).

RESULTS

During the period of the study, a total of 501 training sessions and 124 matches were recorded. A total of 33 non-contact muscle injuries were detected over the two seasons (Season 2017, n = 14; Season 2018, n = 19). From the total, 17 occurred during matches and 16 during training sessions. The average incidence of non-contact muscle injury was 3.9/1000 h (2017, 3.6/1000 h; 2018, 4.2/1000 h).

The average cumulated training load during 4- and 3-week blocks was 4930 ± 1289 AU and 3672 ± 971 AU, respectively. There were significant associations of C4 and C3 with injury risk (C4: $p = 0.023$; C3: $p = 0.003$) (Table 1).

For both variables, the "high load" group showed greater injury risk than the "moderate load" group (C4: OR = 4.5; CI 95% 1.5–13.3; C3: OR = 3.7; CI 95% 1.7–8.1) (Figure 1). There was no difference in the injury risk between the "low load" group and "moderate load" group ($p > 0.05$).

No significant association was found between ACWR and injury occurrence ($p = 0.569$). Figure 2 depicts the frequency and percentage of observations according to the reference zones as suggested elsewhere[1].

DISCUSSION

The present study aimed to analyse the relationship between internal training load and the risk of acute non-contact muscle injuries in a group of Brazilian professional soccer players. We found an association between accumulated training load and injury occurrence, for the two entire seasons analysed herein. Specifically, the high-cumulated workload during 4 and 3 weeks raised the injury risk in relation to the moderate cumulated workload, for the same period.

According to our results, the high-cumulated workload (above 5335 and 3980 AU for 4 and 3 weeks, respectively) raises the

TABLE 1. Odds ratio (OR), 95% confidence interval (CI95%) and p-value between the cumulative training load, and binary outcome (injury: yes/no).

Cumulative workload	OR (IC 95%)	p-value
4 Weeks Workload > 5335	4.5 (1.5–13.3)	0.006*
4 Weeks Workload < 4260	2.5 (0.95–6.6)	0.062
3 Weeks Workload > 3980	3.7 (1.7–8.1)	< 0.001*
3 Weeks Workload < 3150	2.1 (0.8–5.4)	0.135

The reference workload range for the 4-weeks load: 4260 to 5335 AU; and for the 3-weeks load: 3150 to 3980 AU. * Significant effect ($p < 0.05$)

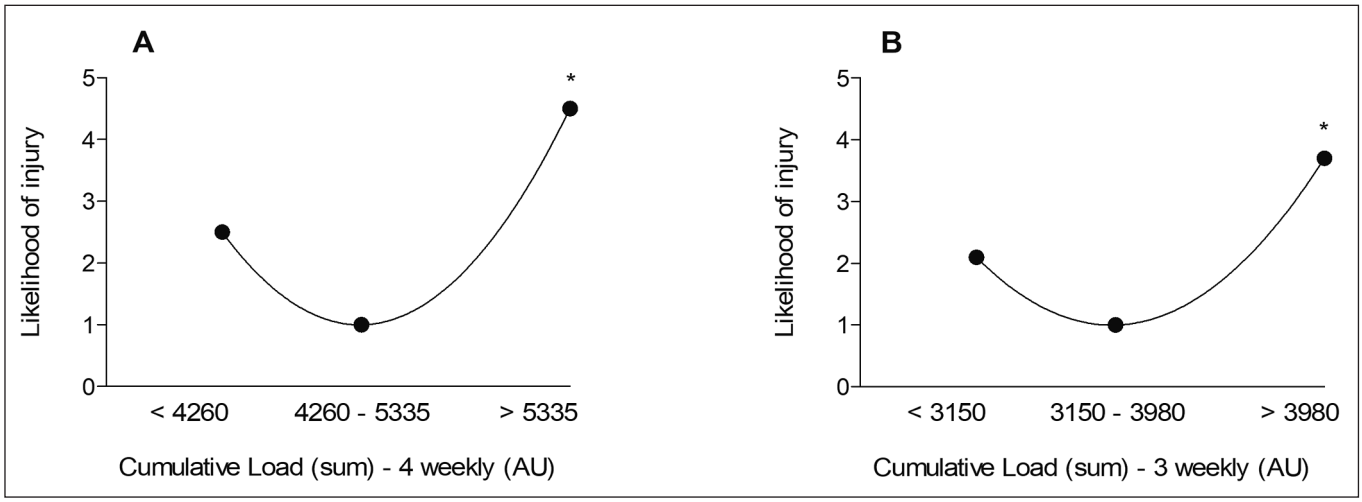


FIG. 1. Cumulated workload and likelihood of injury for 4 weeks (Panel A) and 3 weeks (Panel B).
* Likelihood of injury significantly greater than the reference group ($p<0.05$).

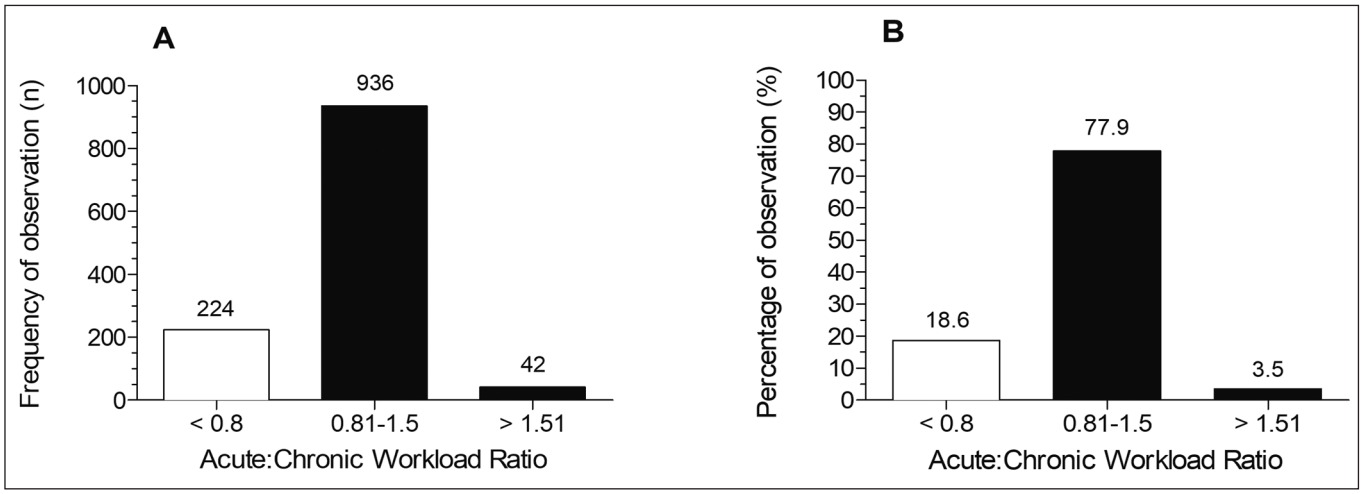


FIG. 2. Frequency (Panel A) e percentage of observations (Panel B) according to acute:chronic workload ratio.

injury risk by 4.5 and 3.7 times compared to the moderate workload group. This U-shaped relationship between training load and injury, as observed in Figure 1, has been previously reported in the literature [20]. In soccer players, a decreased injury risk was found for moderate values of external load [21, 22]. Regarding the internal training load, it was also found that a high-cumulated training load was associated with a higher injury risk than the moderate training load [23]. It is well understood that augmented load is an important factor for improving physical fitness [24]. Indeed, cardiovascular and neuromuscular adaptations are triggered through a high training load, acquired by the manipulation of training intensity, volume and frequency [24, 25]. However, if the intensity or volume is above the capacity of the psychophysiological system to endure, supposedly it could produce a likely overload, triggering a subsequent soft tissue injury.

In relation to the low-cumulated workload, despite the tendency for an increased injury risk in this condition (Figure 1), a significant association was not found. It has been reported in female soccer players that a low average weekly exposure was associated with a higher risk of injury [26]. In other sports, this relationship has also been established [27, 28], which could be associated with undertraining. Therefore, it is important to recognise the "ideal" workload zone, in order that the psychophysiological adaptations can occur without high exposure to injury occurrence [29].

Contrary to the present results, Malone et al. [10] found a linear association between injury risk and training load in soccer players from European teams. During the competitive period, the group with higher cumulated training load showed a lower injury risk than the group with low cumulated load. However, the 95% confidence interval of the OR included the value 1 (OR = 0.91; IC 95% 0.26–3.14),

so the relationship is not reliable. Other studies have not found an association between cumulated training load and injury risk [4, 30]. Features such as competitive level, number of seasons analysed and the number of injuries can explain these disagreements. Also, the statistical model approach and the way the data categorization is arranged can challenge the comparison among studies [31].

The average weekly training load observed in the present study was slightly lower than previously reported in the literature [8, 23, 32]. A possible explanation is the massive number of games played in a continental-size country such as Brazil. In this way, the logistics of travelling have an impact on the number of training sessions, which could at least partly explain the lower weekly training load.

The use of ACWR for controlling the training load has spread in the last few years [9]. Its use is intended to identify the injury risk, consequently reducing the likelihood of a player presenting a soft tissue injury, which should be under the control of staff [33]. However, the ACWR has been criticised regarding the lack of a conceptual basis and inconsistent results [7, 8]. The ACWR is an extension of Banister's fatigue-fitness model used to predict performance (which has been criticised for the lack of a physiological underpinning), without a clear link to mechanisms of injuries. Also, its relationship with risk of injuries often could appear in different directions [7]. In the present study, the ACWR was not significantly associated with the injury incidence, agreeing with part of the literature [14, 30]. While some authors have found an association between the ACWR and injury risk [4, 8, 21, 23], others did not observe a significant relationship [14, 30]. According to Gabbett [1], values above 1.5 represent a "danger zone" for the occurrence of a non-contact injury. In the present study, only 3.5% of injuries occurred at an ACWR above 1.5. Thus, based on the low occurrence of injuries within this zone, one could suggest that this metric is not sufficient to detect greater risk.

Regarding the studies in the literature about the relationship between training load and injury risk, it is important to mention that there has not been a distinction among injury types (e.g., an injury with an acute or repetitive mechanism). However, it is unlikely that the load-injury relationship is the same regardless of the nature of the injury [34]. Therefore, defining clearly which type of injury is being discussed can help in the understanding of this relationship.

Beyond injury risk management, a well-designed training programme should positively impact performance [35]. For example, a negative association was observed between low season injury rates and team performance (i.e., points won per league match) [36], Thus, the training load monitoring could assist in obtaining the most effective training "dose" for maximising the improvement of physical fitness (i.e., athlete's resilience), while minimising injury risk, with a resultant increased player availability.

Based on the results of the present study, the monitoring of internal training load could be utilised for identifying soccer players with increased risk of muscle injury. The present data suggest that a high 3- and 4-week cumulative training load increases the muscle injury risk by at least 3 times. By using cumulative training load data, coaches could take better decisions in daily practice in order to increase player availability for training and competitions.

The fact that subjects belonged to the same soccer team should be considered as a strength of the current study, although extrapolation of the results should be done with caution. In addition, it is important to highlight that the team's staff used the workload data to eventually adapt the training programming, and it may have impacted the outcomes. On the other hand, the present study could be considered as a 'real world' observation, with respect to the relationship among training prescription, training load and injury incidence in a high-level soccer team. As stressed elsewhere, the risk (and subsequent injury) management in elite sport should be supported by robust longitudinal data, such as the current study has presented [37]. Additionally, the injury definition utilised herein may differ from others studies, making comparison among them difficult. Finally, the complex system approach is rising in popularity, and future studies should take into account the multifactorial nature of sports injuries [38].

CONCLUSIONS

In conclusion, cumulative training loads are associated with increased risk of acute non-contact muscle injury in professional Brazilian soccer players. Soccer players exposed to greater internal training loads in a period of 3 or 4 weeks are more susceptible to suffer from muscle injuries, while ACWR presented no significant association with injury risk. Thus, one should highlight the importance of monitoring the internal training load, in order to reduce injury risk in professional soccer players. Additionally, this reduction in injury risk can also help achieve a better performance.

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Conflict of interest declaration

The authors declare no conflict of interest.

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A post-exercise infrared sauna session improves recovery of neuromuscular performance and muscle soreness after resistance exercise training

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ABSTRACT: The aim of this study was to investigate effects of a single infrared sauna (IRS) session on post-exercise recovery of neuromuscular performance, autonomic nervous system function, subjective sleep quality, and muscle soreness. Male basketball players (n = 16) performed two trials consisting of a complex resistance exercise protocol (maximal strength with plyometrics), followed by either 20 min passive recovery (PAS) or IRS (temperature 43 ± 5°C), in a randomized crossover design, with trials separated by one week. Recovery of neuromuscular performance was assessed using 20 m maximal sprint, maximal countermovement-jump (CMJ), and isometric leg press tests, performed 14 hours after exercise. Heart rate (HR), heart rate variability (HRV), sleep diary, muscle soreness, and indirect muscle damage markers were measured pre and post exercise. The decrease in CMJ performance from pre- to post-exercise was attenuated after IRS compared to PAS ($p < 0.01$). The IRS session resulted in higher HR and lower root mean square of successive differences between normal heartbeats (RMSSD), and high and low frequency power, compared to PAS ($p < 0.002$). Post-exercise night-time HR and HRV did not differ following IRS vs. PAS. Muscle soreness was less severe, and perceived recovery was higher after IRS compared to PAS ($p < 0.01$). Post-exercise IRS attenuated the drop in explosive performance and decreased subjective muscle soreness after resistance training, which may enhance mood, readiness, and physical performance of an athlete. A single IRS session had no detrimental effects on recovery of the autonomic nervous system.

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INTRODUCTION

Infrared radiation (IR) is a subdivision of the electromagnetic spectrum with wavelengths between 750 nm –1 mm [1]. The IR-region is often divided into IR-A (0.78–1.4 μm), IR-B (1.4–3 μm), and IR-C (3 μm–1 mm), the latter of which is also termed far-infrared radiation (FIR) [1]. IR radiates energy in the form of heat [1]. Thermal radiation has effectively been used to alleviate certain diseases and discomforts, such as musculoskeletal disorders, and IR-emitting saunas (IRS) and heat lamps are gaining popularity [1]. In line with these technological developments, the use of IR for relaxation and recovery is becoming more widespread. An IRS heats the air to approximately 40–60°C and radiates heat at wavelengths between 1–12 μm [2, 3]. The manufacturers of IRS advertise numerous therapeutic effects, including weight loss, improved cardiovascular health, reduced pain, and fatigue. However, the scientific evidence to support these claims is limited due to low number of studies and conflicting results [2].

Research evidence is also lacking on whether IRS can influence recovery of physical performance. A post-exercise IRS session has been found to improve recovery of countermovement jump (CMJ) performance [3]. Exposure to a IR-lamp has been found to reduce muscle soreness but had no effect on creatine kinase (CK) activity, an indirect biomarker of exercise-induced muscle damage [4]. The beneficial effects of IR during recovery may be attributed to increased peripheral blood flow due to vasodilatation [5], which could accelerate the clearance of edema, limit inflammation and perceived pain, and improve muscle repair [4]. As IR heat penetrates deeper under the skin than warm air, it may transmit heat to muscles, blood vessels, and nerves more effectively [2, 6], which may attenuate tissue temperature loss, facilitate muscle circulation and metabolism, and reduce peripheral nerve excitability [7].

Heart rate variability (HRV) is a tool for monitoring autonomic nervous system balance [8, 9]. A post-exercise IRS session has been found to decrease HRV and increase heart rate (HR) indicating prolonged sympathetic activity after exercise [10]. On the other hand, a IRS session without prior exercise did not affect HRV and HR [10].

Furthermore, repeated use of IRS has been found to improve sleep quality in patients with chronic pain [11]. However, the effects of post-exercise IRS on subsequent nocturnal HRV and sleep quality have not been studied. It would be important to verify that post-exercise IRS does not place additional stress on autonomic function after exercise. Hormonal concentrations in blood samples can provide additional information about the physiology underlying the recovery process by indicating stress responses and anabolic-catabolic balance [12].

The aim of the present study was to investigate effects of a single post-exercise full-spectrum IRS session on recovery of neuromuscular performance, autonomic nervous system balance, subjective sleep quality, muscle soreness, biomarkers of muscle damage, and hormonal responses. We hypothesized that IRS after resistance training may enhance recovery of neuromuscular performance, increase nocturnal HRV, and attenuate muscle soreness, as well as biomarkers of muscle damage.

MATERIALS AND METHODS

Participants

Sixteen healthy and injury-free male basketball players (mean ± SD: age 18.9 ± 2.3 years, height 189 ± 8 cm, body mass 83.4 ± 11.1 kg, body fat 13.3 ± 5.7%) provided written informed consent to take part in the study. For participants who were under the age of 18 years, written consent from a guardian was also obtained. Participants represented two different teams from same club: the first team (n = 7), playing in the second highest league in Finland, and the second team (n = 9), playing in the third highest league in Finland. Ethical approval for the study was obtained from the University of Jyväskylä Ethical Committee. The study was conducted in accordance with the Declaration of Helsinki.

Research Design

Participants performed two experimental trials that each took place over two days, separated by one week. First, participants performed a resistance exercise protocol. IRS (43 ± 5°C, 20 min) and passive recovery (PAS, room temperature, 20 min) were used after exercise in a randomized order. A schematic representation of the protocol is provided in Figure 1.

Participants performed 20 m maximal sprint, maximal countermovement-jump (CMJ), and isometric leg press tests before (pre) and 14 h after exercise (post14h). The CMJ test was also performed immediately after exercise (postEX). We collected blood samples in the morning (pre) and at post14h. Participants completed sleep diaries in the mornings before and after the exercise protocol, and muscle soreness questionnaires (Visual Analog Scale, VAS) at pre, postEX,

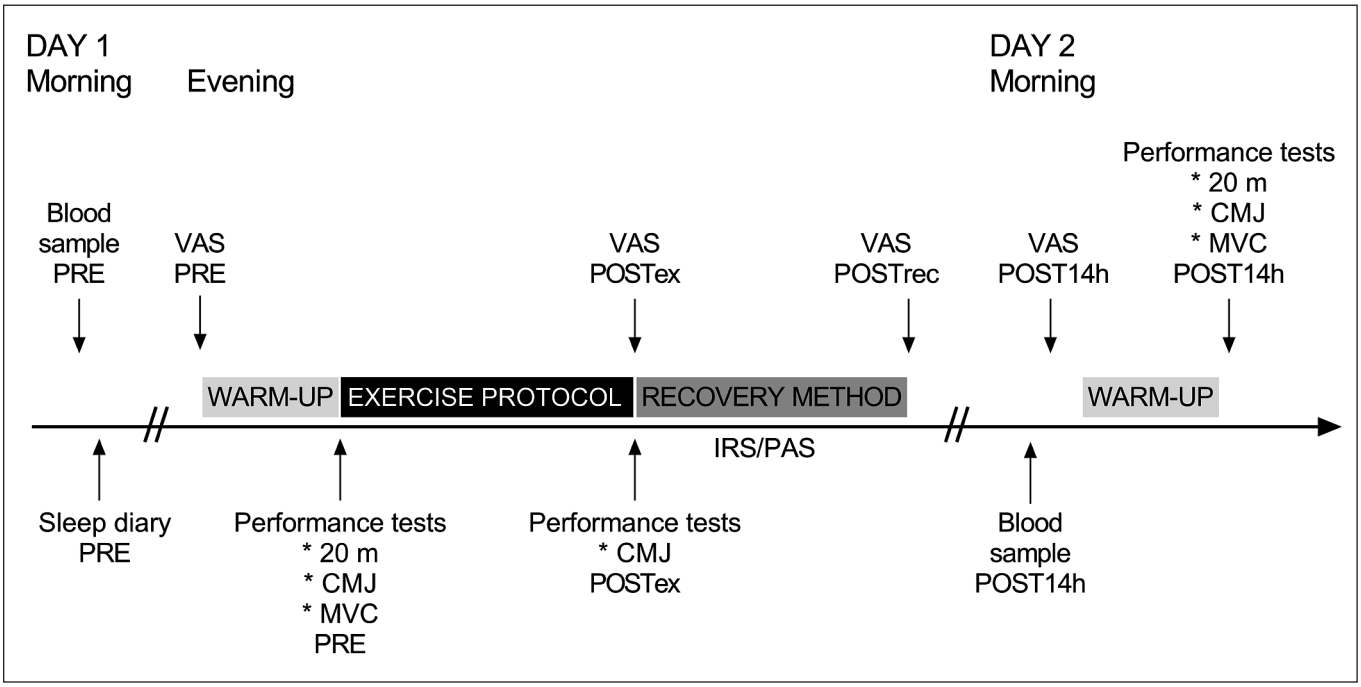


FIG. 1. Schematic view of study design. Participants completed a standardized exercise protocol followed by a recovery protocol, involving sitting in infrared sauna (IRS) or in room temperature (PAS, passive recovery). Follow-up measurements were obtained the morning after exercise protocol. PRE = before the exercise protocol; POSTex = after the exercise protocol; POSTrec = after the recovery method; POST14h = after 14 hours recovery; 20 m = 20 m sprint; CMJ = countermovement jump; MVC = isometric leg press; VAS = visual analog scale by muscle soreness.

immediately after the recovery intervention (postREC), and post14h. HRV was assessed during the nights before and after exercise, as well as during IRS and PAS.

Fluid intake was controlled during the experimental trials. Participants were provided with 0.5 l water during the exercise protocol and 0.5 l water during IRS or PAS. Participants consumed a recovery beverage (8 g carbohydrates and 28 g protein, Teho Sport, Olvi Oyj, Iisalmi, Finland) before IRS and PAS. Furthermore, participants completed food diaries during the first recovery period to track nutritional intake during the first recovery period and ensure replication of it during the second recovery period. The use of nonsteroidal anti-inflammatory drugs and other recovery methods was prohibited.

Procedures

Exercise protocol

Participants performed a complex resistance exercise protocol (total duration 60 min), which participants were accustomed to performing, as follows:

1. Back squat 3 × 3 + CMJ 3 × 3 (90–95% 1RM; 1 min rest between squat and jump, 3 min rest between sets)
2. Nordic hamstring curl 3 × 5 + standing long jump 3 × 3 (maximal effort; 1 min rest between curl and jump, 3 min rest between sets)
3. Leg press 3 × 3 + box jump (90–95% 1RM; 1 min rest between leg press and jump, 3 min rest between sets)

During the first trial, participants performed the exercises in a randomised order and completed warm-up sets as they felt was appropriate. The exercise order, weights, and warm-up sets were then replicated for each participant during the second trial. During the exercise protocol, participants reported their Rating of Perceived Exertion (RPE, scale 1–10) after the last set of each exercise, and the mean RPE value was calculated.

Performance tests

To assess acute fatigue, a CMJ-test was performed 3 minutes after completion of the exercise protocol. Furthermore, pre-, and post-performance tests included a CMJ, 20 m maximal sprint, and isometric leg press. The CMJ flight time, determined using photocells (University of Jyväskylä, Finland), was used as a measure of maximal muscle power output. Participants kept their hands on their hips and jumped as high as possible, with three attempts to achieve their best performance (1 min rest between attempts). A self-determined range of motion was permitted. In the 20 m sprint test, we used photocells (University of Jyväskylä, Finland) to obtain sprint times. Participants had three attempts to achieve their best sprint performance, with 3 min rest between attempts. We used an isometric leg press device (University of Jyväskylä, Finland) to measure maximal voluntary contraction, performed with a knee angle of 110°, which has been reported previously [13]. Participants had three attempts to achieve their best performance with 1 min rest between attempts.

Infrared sauna session

Participants sat for 20 min in an infrared sauna (VitaMy, Sentiotec GmbH, Vöcklabruck, Austria), or engaged in passive recovery by sitting in room temperature for 20 min. The sauna had two seats with IR-emitting panels (radiation: IR-A 24%, IR-B 55%, IR-C 24%) at the front (distance: about 55 cm from the chest of the participant) and back (distance: 7–15 cm from the back of the participant). Temperature of the sauna was set to 50°C, but the measured air temperature was 43 ± 5°C and relative humidity 21 ± 1% in the sauna.

Heart rate and heart rate variability monitoring

A wearable sensor (Bodyguard2, BG2, Firstbeat Technologies Ltd, Jyväskylä, Finland) was used to record HR and HRV. The sensor uses two spot electrodes, which were placed under the right collarbone and on the left rib cage. Participants attached the monitor before going to bed on the day before the exercise protocol and wore the monitor continuously until the morning after the exercise protocol. The monitor records an electrocardiogram and converts the signal into R-R intervals using an algorithm with an accuracy of 1 ms. The BG2 sensor has been found to be accurate and reliable for HRV analysis [14]. We transferred data from the sensor to the validated [15] Kubios software (Kubios Oy, Kuopio, Finland) for further analysis. Average HR, the root mean square of successive differences between normal heartbeats (RMSSD), power of high frequency (HF-power) and low frequency (LF-power) heart rate variability, and ratio of low and high frequency heart rate variability (LF/HF-ratio) were analyzed (Table 1).

HRV data were analyzed from each night over a four-hour period, commencing 30 min after bedtime. Furthermore, HRV data were analyzed over 16 min during the recovery sessions. The raw HRV data required little artifact correction; the average percentage of corrected beats was 1.3% (117 beats) during the night and 0.5% (6 beats) during the recovery sessions.

TABLE 1. Heart rate variability variables analyzed.

Variable	Explanation
HR (l/min)	Average heart rate
RMSSD (ms)	The root mean square of successive differences between normal heartbeats
HF-power (ms^2)	Average power of high frequency heart rate variability (0.15–0.40 Hz)
LF-power (ms^2)	Average power of low frequency heart rate variability (0.04–0.15 Hz)
LF/HF-ratio	Ratio of low and high frequency heart rate variability (LF-power/HF-power)

Sleep diaries and muscle soreness

Sleep diaries were used to evaluate participants' bedtimes, as well as the duration and quality (on a scale of 1–5) of sleep. Furthermore, participants reported perceived recovery (on a scale of 1–5). We used a VAS scale to evaluate muscle soreness; reported on a 12 cm line with "no pain" at one end (0 cm) and "the worst possible pain" at the other end (12 cm).

Collection and analysis of blood samples

Blood samples were collected to analyze serum hormone and myoglobin concentrations and CK activity in the mornings (7:30–9:15 a.m.), after 10 h of fasting. Blood samples were taken from the antecubital vein into serum tubes (Vacuette, Greiner Bio One International GmbH, Kremsmünster, Austria). Whole blood was centrifuged at 3600 rpm (Megafuge 1.0 R, Heraeus, Germany) for 10 min. After separation of serum, samples were frozen at -80°C until analysis. To assess anabolic versus catabolic status and muscle damage, we measured serum cortisol, total testosterone, sex hormone binding globulin (SHBG), growth hormone, and myoglobin levels with chemiluminescence immunoassays (IMMULITE 2000 XPi, Siemens Healthcare Diagnostics, UK) and hormone-specific immunoassay kits (Siemens, New York City, USA). CK activity was assessed with a photometric test (Indiko Plus, Thermo Fisher, Massachusetts, USA). The inter-assay coefficients of variation were 5.1% for cortisol, 4.1% for growth hormone, 2.1% for myoglobin, 6.3% for SHBG, and 13.1% for testosterone.

Serum free testosterone was calculated using Anderson's formula: Free testosterone (pmol/l) = Total testosterone (nmol/l) × (2.28–1.38 × log(SHBG (nmol/l) /10)) × 10 [16]. Hemoglobin and hematocrit were determined with an automated hematological analyzer (Sysmex XP300, Sysmex Corporation, Kobe, Japan), and plasma volume change from pre was determined from hemoglobin and hematocrit concentrations using the equation by Dill and Costill [17]. The plasma volume corrected values were used in analyses.

Data processing

One participant (A) could not participate in all the CMJ measurements, two participants (A, B) could not complete all 20 m sprints, and three participants (A, C, D) could not complete all the isometric leg press measurements. Absences were due to personal scheduling problems (A) and soft tissue pain/discomfort (B, C, D). The physical performance results from one participant (D) deviated above mean + 2SD and were not included in the analyses. Thus, the number of participants included in the analysis of physical performance were: 20 m sprint: n = 13; CMJ: n = 14; and isometric leg press: n = 12.

HRV data from four participants were not obtained for the entire four-hour periods and in some cases (6 participants) the period began later than 30 min after bedtime, because of missing data or longer sleep onset latency reported in the sleep diary. In these cases, participants' data were analyzed in the same way for both experimental conditions. A total of 5 participants had missing data from one or more nights. Thus, nocturnal HRV data were analyzed from 11 participants. Furthermore, HRV data during the recovery methods was not obtained from 5 participants, thus 11 participants were included in the analysis. One participant ate before collection of a fasted blood sample. His results were not taken into account in the statistical analyses of the blood samples.

Statistical Analyses

Data were analyzed using IBM SPSS Statistics 26 (IBM Corp. Armonk, NY, USA). Two-way repeated measures analysis of variance (ANOVA) followed by Bonferroni post hoc tests, as well as Friedman and

TABLE 2. Mean (SD) results and relative changes from pre- to post-measurement for countermovement jump, 20 m sprint, and isometric leg press in the infrared sauna and passive recovery.

		IRS	PAS	%Δ IRS	%Δ PAS
CMJ (cm)					
	Pre	41.5 (5.5)	41.8 (5.6)		
	Post 14 h	40.9 (4.8)	39.8 (5.7)$^{\#\#}$	-1.1 (4.5)**	-5.0 (3.8)
20 m sprint (s)					
	Pre	2.95 (0.11)	2.96 (0.11)		
	Post 14 h	3.03 (0.12)$^{\#\#\#}$	3.04 (0.10) $^{\#\#\#}$	2.5 (1.4)	2.7 (1.2)
Isometric leg press (kg)					
	Pre	673 (221)	700 (218)		
	Post 14 h	678 (240)	692 (234)	0.0 (10.0)	-2.2 (6.7)

Abbreviation: CMJ = countermovement jump; IRS = infrared sauna; PAS = passive recovery; %Δ = percentage changes from pre- to post-measurement. ** Indicates difference compared to passive recovery ($p < 0.01$). $^{\#\#\#}$ Indicates difference from pre-value ($p < 0.001$). $^{\#\#}$ Indicates difference from pre-value ($p < 0.01$).

Wilcoxon tests were used in the statistical analysis. Paired t-tests were used to analyze absolute or relative (physical performance) changes (pre-post) between the recovery methods. Data are presented as mean ± SD. Statistical significance was set at $p < 0.05$. Effect sizes were calculated (ES; Cohen's d) to determine meaningful differences. CK and myoglobin were analyzed as natural logarithms (ln). The change between the pre- and post-measurements was calculated as: lnChange = ln(post/pre).

RESULTS

Exercise effort and acute fatigue

The relative decrease in CMJ performance from pre- to post-exercise did not differ ($p = 0.158$) between IRS (-6.0 ± 4.6%) and PAS (-7.9 ± 3.7%). Neither did mean RPE differ between the exercise protocols that preceded IRS and PAS (IRS: 8.1 ± 0.9; PAS: 8.3 ± 0.8, $p = 0.248$).

Neuromuscular performance

IRS attenuated the relative reduction in CMJ performance from pre- to post14h ($p = 0.009$, ES = 0.76) compared to PAS (Table 2). However, there was no difference in CMJ performance at post14h between IRS and PAS ($p = 0.129$, ES = 0.65). The post-exercise decrease in CMJ height was statistically significant in the PAS trial ($p = 0.002$, ES = 1.28), but not the IRS trial ($p = 1.000$).

The relative changes in sprint time and isometric leg press performance did not differ between trials from pre- to post14h ($p = 0.631$ and $p = 0.545$, respectively; Table 2). Furthermore, there were no differences in 20 m sprint and isometric leg press performance 14 h after recovery with IRS or PAS ($p = 1.000$). However, there was an increase in 20 m sprint time at post14h in both trials ($p < 0.001$).

Heart rate and heart rate variability

HR and LF/HF-ratio were higher ($p < 0.001$, ES = 2.39; $p = 0.002$, ES = 1.23), and RMSSD, HF-power and LF-power were lower ($p < 0.001$, ES = 2.08; $p = 0.001$; ES = 1.50; $p = 0.002$, ES = 1.24) during IRS compared to PAS recovery (Table 3). No differences in the changes from night before to night after values were observed between the recovery protocols. There was no significant time or treatment effect on nocturnal HR and HRV (Table 3).

Hormonal responses

The change in cortisol from pre- to post14h did not differ between IRS and PAS ($p = 0.306$; Table 4). However, higher cortisol values ($p = 0.005$, ES = 0.518) were found at post14h following IRS compared to PAS. Furthermore, there was a decrease in cortisol values from pre to post14h after PAS ($p = 0.001$, ES = 0.61), but not after IRS ($p = 0.256$). There were no differences in other hormone values (Table 4).

Muscle soreness, creatine kinase, and myoglobin

The change in muscle soreness from pre- to post14h-values was smaller after IRS compared to PAS ($p = 0.032$, ES = 0.58; Table 5). Furthermore, muscle soreness was significantly affected by the recovery protocols and varied over the time course of recovery. Post-exercise muscle soreness was higher following both protocols compared to pre-values (IRS: $p = 0.002$, ES = 0.54; PAS: $p = 0.001$, ES = 0.56). Absolute muscle soreness scores were lower after IRS compared to PAS at the postREC- ($p = 0.003$, ES = 0.53) and post14h-measurements ($p = 0.005$, ES = 0.50).

TABLE 3. Mean (SD) heart rate and heart rate variability variables in the infrared sauna and passive during recovery conditions, during the night before and after the exercise protocol, and change from the night before to the night after values.

	IRS	PAS
During recovery method		
RMSSD (ms)	26.7 (8.9)***	53.4 (15.0)
HR (1/min)	85 (6)***	72 (5)
HF-power (ms^2)	295 (180)**	1027 (545)
LF-power (ms^2)	1214 (623)**	2649 (1600)
LF/HF-ratio	4.83 (2.13)**	2.82 (1.27)
Night before		
RMSSD (ms)	84.7 (41.2)	77.7 (32.2)
HR (1/min)	53 (7)	52 (7)
HF-power (ms^2)	2372 (1768)	1947 (1333)
LF-power (ms^2)	2813 (1929)	2296 (1151)
LF/HF-ratio	1.34 (0.57)	1.41 (0.51)
Night after		
RMSSD (ms)	77.2 (37.4)	76.6 (36.4)
HR (1/min)	53 (5)	52 (5)
HF-power (ms^2)	2021 (1449)	1940 (1499)
LF-power (ms^2)	2472 (1723)	2294 (1199)
LF/HF-ratio	1.40 (0.51)	1.48 (0.65)
Δ		
RMSSD (ms)	-7.5 (8.7)	-1.0 (15.8)
HR (1/min)	-0.1 (3.1)	-0.4 (3.2)
HF-power (ms^2)	-351 (477)	-6 (1148)
LF-power (ms^2)	-342 (513)	-2 (530)
LF/HF-ratio	0.1 (0.3)	0.1 (0.6)

Abbreviation: IRS = infrared sauna; PAS = passive recovery; Δ = changes from night before to night after measurement; RMSSD = root mean square of successive differences; HR = heart rate; HF-power = average power of high frequency heart rate variability; LF-power = average power of low frequency heart rate variability; LF/HF-ratio = ratio of low and high frequency heart rate variability. *** Indicates difference compared to passive recovery ($p < 0.001$). ** Indicates difference compared to passive recovery ($p < 0.01$).

TABLE 4. Mean (SD) hormonal values and changes from pre- to post-measurement in the infrared sauna and passive recovery conditions.

		IRS	PAS	Δ IRS	Δ PAS
Cortisol (nmol/L)					
	Pre	445 (98)	432 (59)		
	Post 14 h	423 (58)**	390 (57)##	-21 (64)	-42 (39)
Total testosterone (nmol/L)					
	Pre	17.1 (4.2)	17.3 (3.7)		
	Post 14 h	16.8 (4.7)	15.9 (2.9)	-0.2 (2.5)	-1.4 (2.4)
Free testosterone (pmol/L)					
	Pre	265 (43)	267 (42)		
	Post 14 h	261 (51)	252 (38)	-3 (33)	-15 (32)
Growth hormone (ug/L)					
	Pre	0.256 (0.217)	0.118 (0.102)		
	Post 14 h	0.231 (0.279)	0.105 (0.077)	-0.025 (0.344)	-0.013 (0.126)

Abbreviation: IRS = infrared sauna; PAS = passive recovery; Δ = changes from pre- to post-measurement. ** Indicates difference compared to passive recovery ($p < 0.01$). ## Indicates difference from pre-value ($p < 0.01$).

TABLE 5. Mean (SD) muscle soreness and changes from pre- to post-measurement in the infrared sauna and passive recovery conditions.

	IRS	PAS	Δ IRS	Δ PAS
Pre	2.0 (1.7)	3.1 (2.3)		
Post exercise	4.7 (2.2)##	5.8 (3.0) ##	2.8 (2.6)	2.8 (2.5)
Post recovery method	3.0 (2.0)**, §§	5.3 (2.8) ##	1.1 (2.7)	2.2 (2.3)
Post 14 h	2.9 (2.0)**, §§	5.2 (3.0) ##	0.9 (2.3)*	2.1 (1.8)

Abbreviation: IRS = infrared sauna; PAS = passive recovery; Δ = changes from pre- to post-measurement. ** Indicates difference compared to passive recovery ($p < 0.01$). * Indicates difference compared to passive recovery ($p < 0.05$). ## Indicates difference from pre-value ($p < 0.01$). §§ Indicates difference from post exercise value ($p < 0.01$).

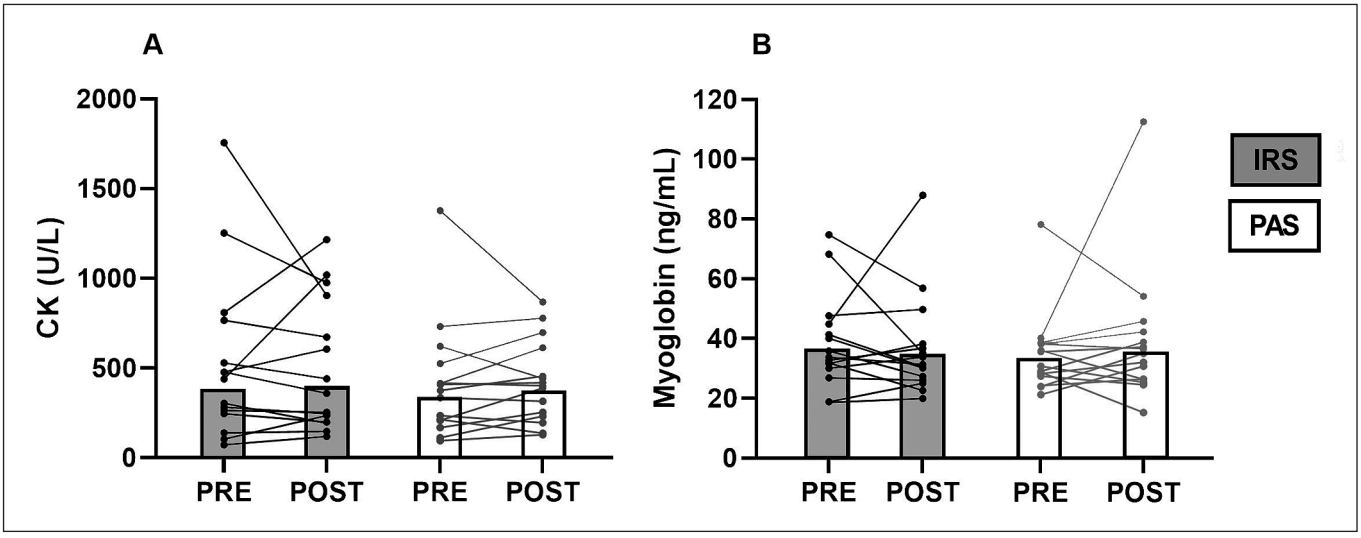


FIG. 2. Geometric means and individual values of CK (A) and myoglobin (B). IRS = infrared sauna method; PAS = passive recovery; Pre = before exercise protocol; Post = 14 h after exercise protocol.

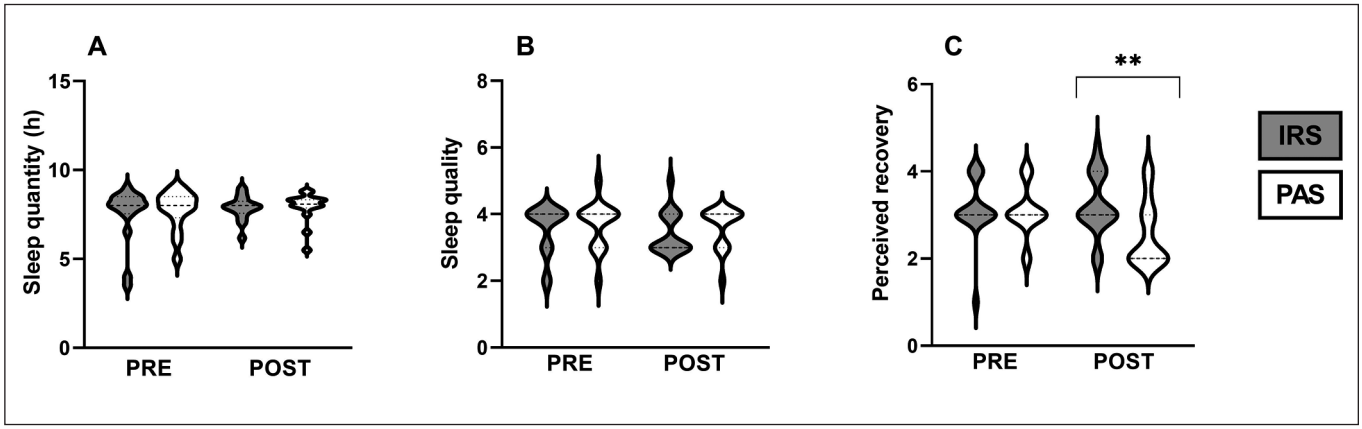


FIG. 3. Violin plots of sleep quantity (A), sleep quality (B), and perceived recovery (C). ** Statistically significant ($p < 0.01$) difference between far-infrared sauna and passive recovery. IRS = infrared sauna method; PAS = passive recovery; Pre = before exercise protocol; Post = 14 h after exercise protocol.

There were no differences in CK and myoglobin between IRS and PAS in either the change from the pre- to post14h-values (CK: $p = 0.640$; Myoglobin: $p = 0.446$); or the absolute values (CK: $p = 1.000$; Myoglobin: $p = 0.955$; Figure 2).

Sleep quantity, sleep quality, and perceived recovery

Sleep duration and quality did not differ between IRS and PAS (duration: $p = 0.377$, Figure 3A; quality: $p = 0.632$, Figure 3B), or between the two nights (duration: IRS: $p = 0.727$, PAS: $p = 0.201$; quality: IRS: $p = 0.480$; PAS: $p = 0.705$). However, the change in perceived recovery from pre to post14h was greater in IRS (0.1 ± 0.7) compared to PAS (-0.5 ± 0.7; $p = 0.009$, ES = 0.47). Perceived recovery the morning after exercise was also higher at post14h in IRS (3.2 ± 0.7) compared to PAS (2.6 ± 0.8; $p = 0.007$, ES = 0.48, Figure 3C). Furthermore, following PAS, the perceived recovery at post14h was lower compared to pre ($p = 0.027$, ES = 0.392). This reduction was not noticed after IRS ($p = 0.527$).

DISCUSSION

The main finding of this study was that an IRS session improves recovery of power capacity in the lower extremities, assessed by CMJ, and attenuates muscle soreness, as we hypothesized. Contrary to our hypothesis, IRS had no effect on nocturnal HRV and subjective sleep quality.

In the present study, the deterioration of CMJ performance during recovery was attenuated by IRS compared to PAS. IRS during recovery has previously been found to improve CMJ performance after a single endurance training session, but not after a strength training session [3]. In that study, however, participants were not athletes and performed a hypertrophic strength training session [3]. Furthermore, recovery of power capacity improved after using a far-infrared 'sleeping' bag four times during a five-day training period [6]. Because relatively little research has been conducted on IRS and recovery of physical performance, it may also be important to compare our findings with studies that have examined recovery after traditional sauna bathing. Traditional saunas heat the air to approximately 70–100°C, which then heats the occupant primarily by convection [2, 3]. In other words, heat is transferred by the movement of the heated air to the occupant. In contrast, IRS radiates heat [2, 3]. It is believed that radiated infrared heat penetrates deeper into human tissues, such as muscle tissue, than convection of heated air [2]. A traditional sauna bathing session with and without prior exercise was found to decrease strength capacities for 24 h during recovery [18]. In addition, taking a traditional sauna after swimming was found to impair swimming performance the following morning [19]. These negative effects have not been found with IRS [3, 6].

Previous studies have speculated that the positive effect of IR on neuromuscular performance can be attributed to deeper heat penetration, that upon reaching the neuromuscular system [3] elicits positive effects on the function of fast-twitch muscle fibers [6], located predominantly in the superficial layers of the muscle [20]. Furthermore, it has been speculated that IR could alter cell membrane potentials [1], but this has not been studied with IRS while the similar radiators and wavelengths has been used. However, we found no differences between the recovery protocols in 20 m sprint and isometric leg press performance, in line with previous studies [3, 6]. Others have observed improved CMJ performance following recovery interventions, but no effects on isometric maximal strength tests [21, 22]. This discrepancy in results from different performance tests may be attributed to heterogenous demands on neuromuscular mechanisms during the stretch-shortening cycle [22] or enhanced recovery of fast-twitch muscle fibers [21]. Sprint performance predominantly depends on muscle strength capacity and neuromuscular coordination [23],

so it may not be sufficiently sensitive to minor differences in physiological recovery.

During the IRS session, we found decreased parasympathetic activity compared to passive recovery, indicating that the IRS session may have increased stress in the body. However, nocturnal HR and HRV-values did not differ between recovery protocols. Thus, the stress caused by IRS is likely short-lived. In a previous study, post-exercise IRS was found to acutely decrease RMSSD and increase HR compared to pre-exercise values, but RMSSD-values were higher after IRS compared to after exercise [10]. Because of missing data, the number of participants in HRV analyses were low, and the effect of IRS on HRV should be studied with larger number of participants. Nonetheless, it appears that a post-exercise IRS does not affect restoration of autonomic modulation during sleep, even after an evening training session. Moreover, there were no differences in subjectively assessed sleep quality and quantity in this study. However, after IRS, participants reported improved perceived recovery the following morning. Thus, it appears that IRS may have positive effects on subjective recovery, but the effect of IRS on post-exercise sleep quality is not clear.

We found higher cortisol concentrations after post IRS compared to passive recovery the following morning. Nonetheless, the change in cortisol from pre- to post-intervention was not statistically significant between protocols, and the post14h concentration was not higher than pre-concentration after IRS. There were neither changes over time nor differences between IRS and passive recovery in other hormone variables. Similarly, in one previous study, it was found that repeated use of an FIR 'sleeping' bag during recovery had no effect on cortisol and testosterone concentrations [6]. Contrary, growth hormone has been shown to increase following a traditional sauna session after resistance exercise, while testosterone was elevated 24 hours after a sauna session [18]. Because hormonal changes were observed at different time points and with different exercise protocols, it cannot be concluded from the present study whether traditional sauna and IRS may exert different effects on hormonal responses. In the present study, IRS did not appear to influence hormonal balance during the follow-up period. However, it would be important to study the effect of IRS on hormonal responses in the first few minutes and hours after exercise, because testosterone [24, 25], cortisol, and growth hormone levels [26] have been found to increase immediately after exercise and return to or below baseline within one hour.

IRS reduced muscle soreness compared to pre-exercise and passive recovery in the present study. In previous study, the use of a IR-lamp has been found to decrease perceived pain after 48 hours recovery compared to passive recovery [4]. Furthermore, meta-analytical data show that the use of post-exercise heat therapy after exercise can relieve pain for more than 24 hours [7]. It has been speculated that post-exercise heat therapy may reduce muscle tissue temperature loss, thereby facilitating circulation and energy metabolism in the muscle, which reduces accumulation of inflammatory cytokines and metabolic waste in muscles [7]. In addition, heat may decrease the excitability of peripheral nerves, and a combination of these factors may contribute to pain relief [7]. Nevertheless, markers of muscle damage did not differ between IRS and passive recovery. CK activity and myoglobin values were already elevated at the start of each trial, possibly because participants performed the trials during the competitive or preparatory phase of their season, which may have influenced the results of CK activity and myoglobin concentration. On the other hand, in previous studies CK activity did not decrease after the use of IR-lamps [4], IR-clothes [27, 28], and a IR-bag [6] compared to control conditions. Thus, based on this study and previous studies, it seems that IR might not affect CK activity and myoglobin concentration.

It should be noted that because of the nature of IRS, it is not possible to provide a placebo condition within such experimental trials. Therefore, it is possible that participants expected a positive outcome from IRS, which may have influenced the results of the subjectively-assessed variables. The improved perception of recovery and muscle soreness may also lead to an improvement in athletes' mood and readiness, which in turn may enhance physical performance [29]. On the other hand, the effectiveness of IRS could be investigated by including another heat condition as a placebo in the future. It should be considered that the participants in this study were competitive athletes who were familiar with the exercise modalities employed during the exercise session. Therefore, generalization of the results to athletes from other sports is more applicable, although only for short recovery periods.

CONCLUSIONS

A single post-exercise IRS session improved recovery of explosive strength capacities and decreased subjective muscle soreness one day after resistance exercise. In addition, a single IRS session had no detrimental effects on acute recovery of the autonomic nervous system or sleep quality, but conversely increased subjective perceived recovery the following morning. An adequate balance between training and competition load and recovery is essential for athletes to achieve continuous high-level performance. The improved recovery could indicate a better readiness to train and compete. Thus, IRS could be a practically useful recovery method for athletes since it is safe and relatively easy to integrate into athletes' training routines. Further studies should investigate the mechanisms that may underpin the performance enhancement and reduced muscle soreness following post-exercise IRS.

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Conflict of interest declaration

The authors declare no conflict of interest.

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Effects of *Eurycoma longifolia Jack* supplementation on eccentric leg press exercise-induced muscle damage in rugby players

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ABSTRACT: *Eurycoma longifolia* Jack (ELJ) is a herbal plant that has androgenic and antioxidant effects. We investigated the short-term effect of ELJ supplementation on muscle damage induced by eccentric exercise. Eighteen young (19–25 years), well-trained rugby 7s players were assigned to an ELJ or a placebo (PLA) group (n = 9/group). Each participant took four 100-mg capsules a day for seven days prior to performing a leg press eccentric exercise to failure in a double-blind fashion. Peak force, peak power and jump height in countermovement jump (CMJ), drop jump reactive strength index (RSI), muscle soreness assessed by a 100-mm visual analogue scale, plasma creatine kinase (CK) activity, and salivary hormones were measured at 24 h before and 0.5, 24, 48, 72, and 96 h after the exercise. Changes in the variables over time were compared between the groups by two-factor mixed-design ANOVA. The number of eccentric contractions performed was similar ($P = 0.984$) between the ELJ (21 ± 5) and PLA groups (21 ± 5). Salivary testosterone and cortisol concentrations did not change ($P > 0.05$) after the supplementation for both groups. CMJ peak power ($-9.4 \pm 5.6\%$) and height ($-10.6 \pm 4.9\%$), and RSI ($-15.2 \pm 16.2\%$) decreased at 24 h after exercise ($P < 0.05$), and muscle soreness (peak: 89 ± 10 mm) and plasma CK activity (peak: 739 ± 420 IU/L) increased after exercise ($P < 0.05$) without significant differences between groups. These results showed that 7-day ELJ supplementation prior to the leg press eccentric exercise had no significant effects on hormones, performance and muscle damage markers for the athletes.

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INTRODUCTION

Eurycoma longifolia Jack (ELJ), also known as Malaysian ginseng or tongkat ali, is a herbal species that has been used for medical purposes for thousands of years mainly in Southeast Asian countries. The root of ELJ contains several compounds (e.g., glycoprotein, eurycomanone) that are purported to be effective for anti-aging [1] and increasing androgen hormones such as testosterone [2, 3]. It was reported that consuming 200 mg/day of ELJ for one month increased serum testosterone concentration by 47% [2], and a dosage of 400 mg/day did not affect the urinary testosterone:epitestosterone ratio to the level that the World Anti-Doping Agency (WADA) considers as doping [3]. A dose of 600 mg/day ELJ ingestion was still found to be non-toxic [4]. However, potentially beneficial effects of ELJ on exercise are not well explored [3], although some studies have examined its effects on exercise performance [5, 6, 7]. Importantly, some athletes are taking an ELJ supplement in the belief that it improves performance. Thus, the effects of ELJ supplementation on athletic performance should be scrutinised.

Ooi et al. [8] found that supplementation of ELJ in the form of a drink containing 0.3 mg/kg body weight consumed every 20 min during a cycle ergometer trial until exhaustion did not change maximal oxygen consumption. Muhamad et al. [7] reported that a dosage of 150 mg/day ELJ for 7 days taken by recreational athletes did not show any beneficial effect on 20-min time trial running. However, ELJ supplementation that was consumed at a dosage of 100 mg/day for 5 weeks increased fat free mass by 4.1%, muscle strength of bench press by 6.8% and arm circumference by 5.8% in healthy adult men [5]. It appears that dosage and duration of ELJ supplementation are important factors when evaluating the ELJ ergogenic effects [3], and its effects on skeletal muscle are more promising than those on aerobic performance.

To the best of our knowledge, no previous study has investigated the effects of ELJ supplementation on exercise-induced muscle damage that is indicated by delayed onset muscle soreness (DOMS) and a prolonged loss of muscle function. Howatson et al. [9] investigated the anti-inflammatory and/or antioxidant effects of tart cherry juice. They reported that ingesting a commercially available tart cherry juice blend (473 ml) for 5 days before and for 2 days after a marathon run enhanced the recovery of muscle strength, and reduced

increases in inflammation markers such as interleukin-6, C-reactive protein, and uric acid. Since ELJ contains antioxidants such as flavonoids [10], it is possible that ELJ supplementation affects the extent of muscle damage induced by eccentric exercise. Additionally, Talbott [11] reported that ELJ compounds (e.g., eurycomanone, flavonoids) improved hormonal profiles such as cortisol/testosterone ratio, mood, and wellbeing, while reducing stress and fatigue. Thus, it seems possible that ELJ compounds prevent overtraining syndrome, alleviate muscle soreness, and improve post-exercise recovery [11, 12]. However, these effects of ELJ have not been investigated.

Therefore, the present study examined the effects of ELJ supplementation for one week prior to exercise in comparison to the placebo (PLA) condition on changes in testosterone and some indirect markers of muscle damage after leg press eccentric exercise performed by elite athletes. We hypothesized that muscle function would recover faster and there would be less DOMS after exercise when ELJ was supplemented in comparison to the placebo condition.

MATERIALS AND METHODS

Participants

The present study recruited 18 elite male rugby 7s players who had represented Malaysia for major international tournaments such as the Commonwealth Games. Their mean ± SD (range) age, height, body mass, and competitive experience were 22 ± 2 (19–25) years, 1.73 ± 0.06 (1.63–1.85) m, 85 ± 10 (68–110) kg, and 5 ± 1 (3–7) years, respectively. The participants were ranked by the countermovement jump (CMJ) height, and assigned to one of the two groups, ELJ (n = 9) or PLA (n = 9), based on an ABBA procedure (block randomisation). In this format, a player with the best CMJ height was assigned to the ELJ group, players with the second and third best height to the PLA group, the fourth best player to the ELJ group, and so on. The inclusion criteria were male, international-level players, having at least three years of resistance training experience, and 100% commitment to the study including taking supplements as instructed, and reporting to a laboratory for all data collection sessions. Players with musculoskeletal injuries and/or illnesses in the previous month prior to data collection were excluded. Based on a study design of repeated measures, a priori sample size analysis using G*Power revealed that achieving an effect size of 0.50 (arbitrarily) with an alpha level of 0.05 and power of 0.90 would require a total sample size of 16.

Their physical characteristics shown above were not significantly ($P > 0.05$) different between groups. They were not allowed to use any supplements other than that provided to them during the study period. They rested for 48 hours prior to the first testing session, and were not allowed to engage in any physically demanding activities until the end of the experiment period (i.e., for 7 days before exercise and for 4 days after exercise). Specifically, no resistance training was conducted during this period; only light to moderate field training sessions (i.e., maintenance) focusing on tactical and strategy were performed by the players. Written informed consent was obtained from all participants, and this study was approved by the Institutional Research Committee (077–2018), in agreement with the Declaration of Helsinki.

Study design

This double-blind, parallel design study was conducted at the National Sports Institute of Malaysia (Kuala Lumpur, Malaysia). The independent variable was the supplementation (ELJ vs PLA) and the dependent variables included the number of eccentric contractions performed in the leg press exercise to failure, peak force (PF), peak power (PP), and jump height in CMJ, reactive strength index (RSI) in drop jump (DJ), plasma creatine kinase (CK) activity, muscle soreness assessed by a visual analogue scale (VAS), and hormones in saliva (testosterone, cortisol). The eccentric exercise (leg press) was preceded by one-week daily supplementation of either ELJ or placebo (maltodextrin), and the dependent variables were measured at 24 hours before, 0.5, 24, 48, 72 and 96 hours after the exercise. The diet was standardised throughout the study period, and participants were instructed not to change their diet but to consume similar foods to what they ate prior to the study.

Supplementation

The participants in the ELJ group ingested 4 capsules (1 capsule = 100 mg) of ELJ supplement, while the PLA group ingested the same amount of maltodextrin. The capsule was designed by the manufacturer (Biotropics Malaysia Berhad, Malaysia) to have the same shape, size, taste and colour; thus no one, including the investigators, knew which was which until the end of the study. All athletes were briefed regarding the study's protocol including how the supplement should be consumed. The amount of the supplement was 400 mg per day for 7 days, and the participants took 200 mg (2 capsules) in the morning and 200 mg (2 capsules) in the afternoon with 250 ml of water for each occasion. This amount was chosen as it has been shown to increase testosterone and muscular strength [13], and has been demonstrated to be safe for long-term use [3].

Exercise

All participants performed a bout of exercise consisting of repeated 5-s eccentric contractions of the knee extensors using a leg press machine with a 350-kg load to failure. For the eccentric phase (lowering the weight), the tempo was indicated to each participant by "verbal counting" along with a stopwatch. This phase was carried out in a controlled and balanced manner throughout the range of motion from a fully extended knee to a knee angle of ~90^{o}. A brief pause of 1 second was inserted at the end of this movement before the weight was pushed back to the knee extended position by spotters; thus the participants performed the concentric phase without a load. One-repetition maximum (1-RM) strength of the leg press exercise was between 420 kg and 570 kg (average ± SD: 509 ± 53 kg) including the carriage's mass of ~50 kg among the

participants, which was determined prior to the study. Thus, the 350-kg weight was 61–83% (70 ± 8%) of the conventional 1-RM strength among the players. A repetition was deemed to be 'failed' if the lowering phase was less than 5 seconds, which was observed when each participant was no longer able to execute the next repetition. None of the participants had done the leg press eccentric exercise using this protocol prior to this study.

Dependent variables

All dependent variables were measured at 24 hours prior to the exercise, and 24, 48, 72, and 96 hours after exercise. Additionally, CMJ and DJ measures were taken and muscle soreness assessment was performed at 30 minutes after exercise.

(a) Hormones

Saliva was collected to analyse testosterone and cortisol according to a standard procedure [12]. This required washing the mouth, resting and relaxing in a seated position for 10 min prior to the sample collection. One hour before the collection, the participants were instructed to avoid intake of any food or beverages including coffee. All samples were stored at -80°C for future analysis. The salivary testosterone and cortisol concentrations were determined using commercially available ELISA kits (Salimetrics LLC, Philadelphia, PA, USA). The assays were performed in duplicate, and the average value was used for further analysis. The intra-assay coefficient of variation was 8.4% and 10.0% for testosterone and cortisol, respectively.

(b) Peak force, peak power and height in CMJ, and reactive strength index in DJ

The lower limb muscle function was assessed by CMJ and DJ performed on a force platform (Fitness Technology, Adelaide, Australia), and the force data were sampled at 600 Hz. Each test procedure required each participant to perform four jumps with a 60-s rest between trials. During the CMJ, each participant placed his hands on his waist, and was instructed to jump as high as possible. Custom-designed software interfaced with the force plate provided PF, PP, and jump height. For the DJ, each participant was instructed to drop from a 30-cm box with his hands on the waist to eliminate arm swing, and to jump as high as possible after landing from the box by minimising the contact time. RSI was calculated by dividing the jump height by the ground contact time. For all tests, the highest value was used for further analysis [14, 15].

(c)Plasma CK activity

Blood (1 ml) was obtained by venepuncture from the antecubital vein, 30 μl of blood was pipetted onto a test strip, and CK activity was determined by an analyser (Reflotron Plus Chemistry Analyser, Roche Diagnostics, Indianapolis, IN, USA). The samples were analysed in duplicate and the average of the two measures was used for further analysis. The calculated inter-assay coefficient of variation was 6.4%.

(d) Muscle soreness

A VAS with a 100-mm line with "no pain" on one end (0) and "extremely painful" on the other end (100) was used to evaluate the extent of muscle soreness. This was assessed after stretching of the quadriceps, and each athlete was asked to indicate the level of pain on the scale.

Statistical analyses

Shapiro-Wilk's test of normality showed that each set of data was normally distributed ($p > 0.05$). The independent t-test was used to compare between groups for the number of eccentric contractions performed to failure. Two-factor mixed-design ANOVA was used to compare between the groups (ELJ, PLA) for changes in the dependent variables over time. Mauchly's test of sphericity was used to check homogeneity of variance, and any violations of the assumption were corrected using the Greenhouse-Geisser or Huynh-Feldt adjustment. Additionally, Hedges' *g* was calculated, and classified as trivial ($g \leq 0.20$), small ($0.20 < g \leq 0.60$), moderate ($0.60 < g \leq 1.20$), large ($1.20 < g \leq 2.0$), very large ($2.0 < g \leq 4.0$), or extremely large ($g > 4.0$) [16]. All data were presented as mean ± standard deviation (SD). The accepted level of significance was set at $p < 0.05$. All data were

TABLE 1. Changes (mean ± SD) in salivary testosterone and cortisol concentrations and testosterone:cortisol ratio (T:C ratio) before (Pre), and 24, 48, 72 and 96 hours after eccentric leg press exercise for placebo (PLA) and *Eurycoma longifolia* Jack (ELJ) supplementation conditions.

		Pre	Post 24 h	Post 48 h	Post 72 h	Post 96 h
Testosterone (pmol/L)	PLA	505 ± 229	376 ± 208	478 ± 162	494 ± 214	440 ± 256
	ELJ	488 ± 313	414 ± 197	467 ± 210	570 ± 170	511 ± 222
Cortisol (nmol/L)	PLA	5.6 ± 3.1	6.1 ± 1.9	5.3 ± 1.8	6.0 ± 3.7	5.4 ± 2.7
	ELJ	5.6 ± 3.9	5.7 ± 3.1	5.7 ± 1.9	5.6 ± 1.9	5.7 ± 2.1
T:C Ratio	PLA	97 ± 33	78 ± 41	84 ± 35	107 ± 75	97 ± 64
	ELJ	103 ± 56	94 ± 65	83 ± 30	113 ± 55	105 ± 83

analysed using IBM SPSS Statistics for Windows, version 26.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Exercise

The number of eccentric contractions performed in the exercise to failure was similar between ELJ (21 ± 5) and PLA (21 ± 5) groups ($p = 0.984$).

Hormones

No significant changes ($p > 0.05$) in testosterone, cortisol, and testosterone:cortisol ratio were found for both groups, and no significant interaction effect was evident (Table 1).

Muscle damage markers

Figure 1 shows changes in PF, PP and jump height in CMJ, and RSI from DJ over time. No significant differences ($p > 0.05$) were found for changes in any of the variables between groups. Compared to the baseline, significant ($P < 0.01$) decreases in PP (-9.4 ± 5.6%, $g = -1.13$, *moderate*), jump height (-10.6 ± 4.9%, $g = -1.04$, *moderate*), and RSI (-15.2 ± 16.2%, $g = -0.88$, *moderate*) were observed at 24 hours after exercise.

Plasma CK activity increased ($P < 0.05$) from the baseline (512 ± 265 IU/L) at 24 (49 ± 55%, $g = 0.62$, *moderate*) and 48 hours (21 ± 36%, $g = 0.31$, *small*) after exercise. However, no significant interaction effect ($p > 0.05$) was evident (Figure 2).

Muscle soreness increased ($p < 0.05$) at 0.5 (69 ± 12 mm, $g = 7.35$, *extremely large*), 24 (43 ± 14 mm, $g = 4.50$, *extremely large*) and 48 hours after exercise (43 ± 15 mm, $g = 3.85$, *extremely large*), and returned to the baseline by 72 hours after exercise (Figure 3). No significant ($p > 0.05$) difference was evident for the changes between groups.

DISCUSSION

The results showed that the supplementation did not affect the salivary testosterone and cortisol concentrations (Table 1) nor the number of eccentric contractions performed to failure. Muscle damage was induced by the eccentric exercise indicated by significant decreases (*moderate* changes) in muscle function shown by the CMJ and DJ parameters at 24 hours after exercise, and increases in DOMS and plasma CK activity (*small* to *moderate* changes) as shown in Figures 1–3. However, the changes were not significantly different between the ELJ and placebo groups. These results did not support the hypotheses and suggest that the ELJ supplementation does not attenuate muscle damage.

Tambi et al. [2] found that serum testosterone concentration increased 47% when individuals (50 ± 10 years) with testosterone deficiency (late-onset hypogonadism) consumed 200 mg of ELJ for one month. However, the present study did not find any changes in salivary testosterone and cortisol concentrations after the 7-day ELJ supplementation or following the eccentric exercise (Table 1). This may be due to a shorter supplementation period than the previous study (one month vs one week) and/or the sensitivity of the measurement (blood vs saliva). It is also possible that the hormonal responses to the ELJ supplementation are affected by the age and athletic status of the participants. The age of the athletes in the present study (19 to 25 years) was concomitant with the peak production of testosterone [17]; thus it is possible that the ELJ supplementation did not increase the testosterone further due to a ceiling effect. Furthermore, the participants of the current study were athletes who were well trained and exposed to high-intensity training regularly, allowing them to recover quicker from the strenuous exercise [18]. With the same number of eccentric contractions performed in the exercise between the ELJ and placebo groups (~21 repetitions), similar levels of hormones after the exercise between groups were also anticipated. Talbott et al. [1] stated that ELJ was a 'maintainer' or 'restorer' of normal testosterone levels, rather than a testosterone 'booster'; thus the ELJ supplementation effect on testosterone is likely more relevant to middle-age and older adults whose testosterone levels are lower.

Decreases in CMJ and DJ variables were observed following the leg press eccentric exercise, but they returned to the baseline values by 48 hours after exercise (Figure 1). A prolonged decrease in muscle function indicates muscle damage [19]; thus the decreases in the variables at 24 hours after exercise are likely to indicate muscle damage. However, the magnitude of muscle damage appeared to be minor, since the decreases after exercise were relatively small, and no longer seen at 48 hours after exercise. This may be due to the 'single set' eccentric protocol (even though it was performed 'to failure') that might not have been intensive enough for the 'well-built' athletes to get severe muscle damage. Another potential explanation for the minor muscle damage in the present study may be related to the muscle group used. Some studies have detected less muscle damage in leg muscles, especially for the knee extensors, when compared with arm muscles [20, 21, 22]. The quadriceps have a pennate architecture, presenting an angular orientation of fibres relative to the force-generating axis [23]. Pennate muscles (e.g., quadriceps) are characterised by large cross-sectional areas, providing lower specific tension (or mechanical strain) per muscle unit during a maximal voluntary contraction, as compared to fusiform muscles (e.g., elbow flexors), which are composed of fibres that extend parallel to the muscle's force-generating axis [21].

It was expected that the recovery of muscle function would be enhanced by the anti-inflammatory and antioxidant effects of the ELJ supplementation. Howatson et al. [9] claimed that tart cherry juice, which is rich in antioxidants, enhanced recovery following marathon running due to increased total antioxidative capacity, and reduced inflammation and lipid peroxidation. A recent review concluded that acute administration of antioxidants immediately before or during an exercise session delays fatigue and reduces muscle damage and oxidative stress markers [24]. However, such findings were not confirmed in the present study. It is possible that because of the minor muscle damage, and the fact that the muscles recovered within

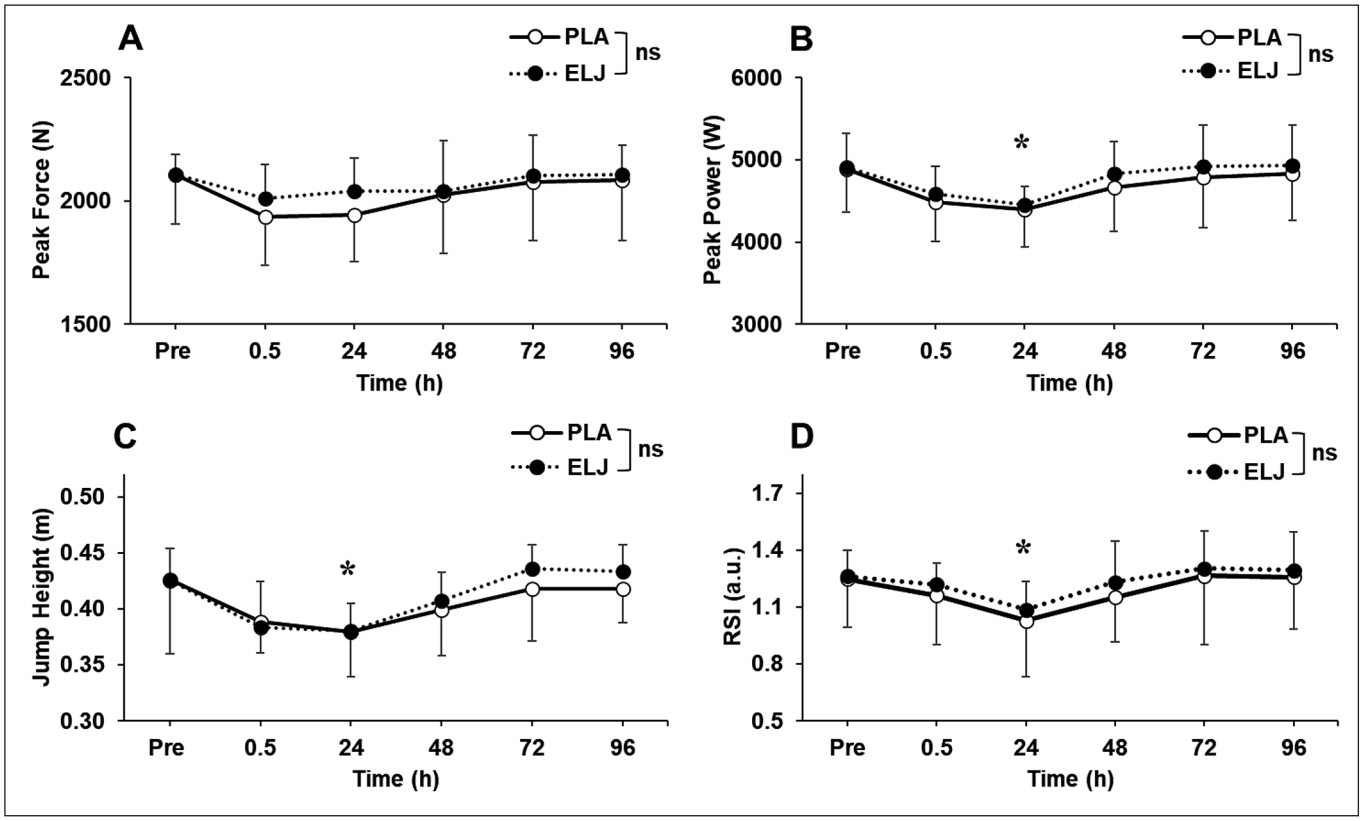


FIG. 1. Changes (mean ± SD) in peak force (A), peak power (B) and jump height (C) during countermovement jump, and drop jump reactive strength index (D) before (Pre), and 0.5, 24, 48, 72 and 96 hours after eccentric leg press exercise for placebo (PLA) and *Eurycoma longifolia* Jack (ELJ) supplementation conditions. ns: not significantly different; *: significantly ($P < 0.05$) different from the Pre value.

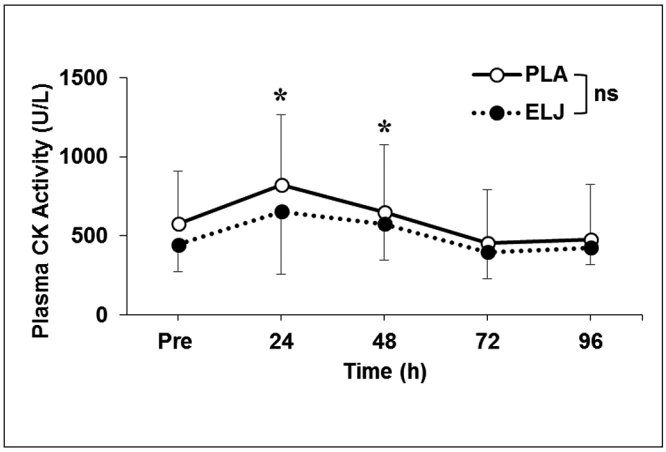


FIG. 2. Changes (mean ± SD) in plasma creatine kinase (CK) activity before (Pre), and 24, 48, 72 and 96 hours after eccentric leg press exercise for placebo (PLA) and *Eurycoma longifolia* Jack (ELJ) supplementation conditions. ns: not significantly different; *: significantly ($P < 0.05$) different from the Pre value.

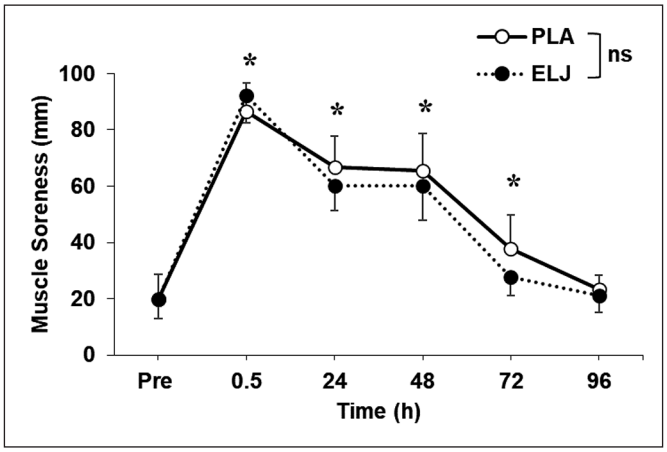


FIG. 3. Changes (mean ± SD) in muscle soreness quantified by a 100-mm visual analogue scale before (Pre), and 24, 48, 72 and 96 hours after eccentric leg press exercise for placebo (PLA) and *Eurycoma longifolia* Jack (ELJ) supplementation conditions. ns: not significantly different; *: significantly ($P < 0.05$) different from the Pre value.

48 hours after exercise, any anti-inflammatory and antioxidant effects of the ELJ on muscle damage markers were not clearly detected.

Increased plasma CK activity resulted from plasma membrane disruption [25], which was evident at 24 and 48 hours after exercise similarly in both ELJ and placebo groups, but the magnitude of increase was small (Figure 2). As discussed above, this suggests that the magnitude of muscle fibre damage was relatively low. Hicks et al. [26] reported that pre-damage CK is < 150 IU/L for recreationally active males, while the current study obtained a baseline CK of ~500 IU/L, which was considered to be still a normal level for most athletes [27]. The relatively high baseline CK activity was probably due to the larger muscle mass and greater daily activities of the participants in the study. In a study among active individuals, Hicks et al. [26] reported that serum CK activity increased > 10 times at 96 hours following an eccentric knee extension protocol (6 sets × 12 repetitions at $60° \cdot s^{-1}$). The magnitude of the increases in CK activity in the current study (~50% at 24 hours after exercise) indicate that muscle fibre damage was minor.

Muscle soreness developed at a similar extent in both ELJ and PLA groups, and subsided by 72 hours after exercise (Figure 3). It has been shown that muscle soreness is more associated with connective tissue (endomysium, perimysium, epimysium) damage and inflammation than muscle fibre damage [28]. Thus, the anti-inflammatory effect of the ELJ was expected to alleviate damage and inflammation of the connective tissue. Vitamin C antioxidant effects have been shown to attenuate muscle soreness when prescribed before and after eccentric exercise [29, 30]. A similar effect was observed when tart cherry antioxidant was taken before, during, and after a marathon run [9]. Thus, it is possible that continuous ELJ supplementation after the eccentric exercise would have attenuated DOMS. It is important to note that the magnitude of changes in the indirect markers of muscle damage varied. Thus, it is necessary to include both physiological and psychological markers when investigating the effect of exercises on muscle damage.

The current study had some limitations. First, the supplementation period was relatively short (one week) in comparison with previous studies in which the supplementation period was more than 4 weeks [5, 13]. This could have restricted potential positive results of the supplement. However, it should be noted that a short-term intervention is desirable for most athletes and coaches. We did not quantify dietary intake of our participants; however, they were training and living in the same national training centre, and were provided with a similar quality of meals across all athletes during the data collection sessions, although specific caloric intake may be different among individuals. As mentioned previously, the magnitude of muscle damage was minor in the present study, and therefore the potential effects of ELJ supplementation might have been masked. It is interesting to examine the effects of the ELJ supplementation on more severe muscle damage conditions. The present study did not include assessment of sleep quality [31], although all players were encouraged to preserve their night sleep duration and bed timing during the study period, and no sleep issue was reported by them. Finally, the present study used elite male athletes, so the results of the present study cannot be generalised to other populations such as female athletes, older adults, and sedentary individuals. Since it is known that the magnitude of muscle damage is greater for non-resistance-trained than resistance-trained individuals [32, 33], it is possible that the effects of ELJ supplementation on eccentric exercise-induced muscle damage are better clarified by using different populations. As a final note, many different supplements without strong scientific evidence are used by athletes; therefore it is important to scrutinise their effects and report the facts even if no positive effects are found. This will help the athletes and create a "healthy" environment in sports communities.

CONCLUSIONS

In conclusion, ELJ supplementation (400 mg daily for seven days) had no effects on muscle functions, hormones, and muscle damage markers among elite rugby players. A longitudinal study to observe ergogenic effects of ELJ supplementation is warranted.

Practical applications

- *Eurycoma longifolia* Jack (ELJ) supplementation has been reported to enhance testosterone level, but 400-mg supplementation for a week did not affect salivary testosterone and cortisol concentrations in young male athletes.
- The ELJ supplementation did not affect the number of eccentric contractions in a leg press exercise to failure performed by young male athletes.
- Muscle damage induced by the leg press eccentric exercise was not attenuated by the ELJ supplementation.

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Author contributions

AZZ, JAW, and KN designed the study, AZZ and JAW participated in the data collection and analyses and drafting the manuscript, and JAW and KN edited the manuscript. All authors read and approved the final version of the manuscript.

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Competing interest statement

The authors declare there are no competing interests.

Data availability statement

Data associated with the study are available from the corresponding author upon reasonable request.

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The effect of two sessions of combined jump and sprint training per week on fitness parameters in soccer players. A randomized controlled trial

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ABSTRACT: This study aimed to investigate the effect of a combined jump and sprint training program, two sessions a week for 6 weeks, on sprinting, change of directions (COD) and jumping performance in semi-professional soccer players. Twenty soccer players were enrolled in this randomized controlled trial (age 20 ± 2 years, body mass 74.3 ± 5.9 kg). Players were randomized into two groups such as training group (TG, n = 10 players) or control group (CG, n = 10 players). Physical tests were performed before and after 6 weeks of training such as sprint 10 m, sprint 30 m, 505-COD test and standing long jump (LJ). The two groups performed the same training except for the combined jump and sprint training performed twice a week by TG. After 6 weeks of training, between-group analysis reported statistical difference in favor of the TG in sprint 10 m ($p = 0.015$, $\eta^2 = 0.295$, *large*), sprint 30 m ($p < 0.001$, $\eta^2 = 0.599$, *large*), in 505-COD ($p = 0.026$, $\eta^2 = 0.154$, *large*), and LJ ($p = 0.025$, $\eta^2 = 0.027$, *small*). These data indicate that combined sprint and jump training, when performed twice a week, for the duration of 6 weeks, in addition to the regular team training, can improve specific physical performance in male soccer players. This study has shown that a volume increment of 10% after 3 weeks of training can be a suitable training dose progression and that a combination of 64–70 jumps and 675–738 m of sprinting training per session can yield benefits in sprint, COD and jump performance.

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INTRODUCTION

Soccer is an intermittent sport where brief bouts of high-intensity linear and multi-directional activity are superimposed on a larger background of low-intensity exercise [1–3]. The physical demands of soccer match play have been well investigated, with players typically covering distances of 10–13 km and performing approximately 1,350 high-intensity actions, such as sprints, accelerations, decelerations, and changes of direction (COD) [1]. Such high-intensity movements are an important ability to acquire to improve performance as they are related to playing standard and high-reward situations in soccer match play (e.g., scoring a goal, defending a goal) [4, 5]. Moreover, high-intensity demands have evolved over time with distances and actions increasing from 2006–2013 in the English Premier League [6], which highlights the importance of football-specific training [2, 7].

The development of short-distance sprint performance and COD are a vital component of athletic performance within the football codes [8–10]. Sprint training exposes the body to large forces, which may elicit coordinative and neuromuscular adaptations [11–13]. Although regular sprint training exposure is expected to facilitate adaptations to improve sprinting performance in athletes, sprint training alone seems not so effective in developing short sprint performance in football code athletes [8]. This could be due to the high sprint demands of the game eliciting players' high chronic adaptations. Therefore, soccer practitioners should research the most suitable training method combinations to perform alongside sprint training in order to achieve their aims [14–17]. For instance, previous research reported that combining both sprint and jumping training in youth soccer players elicits positive fitness adaptations [18] as well as the combination of jump and COD training [14]. This is further supported from a recent meta-analysis that has identified that primary methods alone (e.g., sprint technique, sprinting) are ineffective in eliciting adaptations (i.e., sprint < 20 m) [8], while combining primary methods with either secondary (e.g., resisted, or assisted sprinting) or tertiary (e.g., strength training and plyometrics) can induce positive adaptative responses.

Jump training is a popular and effective method to improve power and sprint performance [19]. It involves jumping exercises that elicits the stretch-shortening cycle (SSC) muscle action and enhances the ability of the neural and musculoskeletal system to produce maximal force in the shortest possible time [19, 20]. SSC based

movements are a natural part of most sporting movements and are regularly performed within soccer training and match play [19, 21]. A previous systematic review has showed clear benefits of implementing jump (plyometric) training into the increasing muscle power in 13 out of 16 studies analyzed, with positive effects ranging between 2.4 and 31.3% [19]. Additionally, research found that jump training when performed once and twice a week can increase sport specific physical capacities in soccer players such as horizontal and vertical jump and short distance sprint performance [22]. Therefore, the implementation of jump training, as a standalone method or combined within a training program, is a valid training method to elicit sport specific physical adaptations in soccer players [23], however, to maximize soccer specific capacities, utilizing a combination of jumping, sprinting and COD exercises in an integrated program seems worthwhile [14, 19, 24, 25].

Previous research combining sprinting and other training methods into a soccer training program produced meaningful fitness adaptations [8], which cannot be achieved with only sprint training or regular soccer training, however, the current evidence available in the scientific literature is limited, in particular when training programs are implemented in season [24], and with a robust research design (i.e., randomized controlled trial) [21]. Therefore, this study aimed to investigate the effect of a combined jump and sprint training program, two session a week for 6 weeks (within regular team training), on players sprinting, COD and jumping performance in semi-professional soccer players. We hypothesize that the addition of this training program would improve the players' sport specific performance indicators compared to the control group, which performed the usual soccer training program.

MATERIALS AND METHODS

Participants

Twenty semi-professional male soccer players were enrolled in this study (mean ± SD; age 20 ± 2 (range 18–22) years, body mass 74.3 ± 5.9 kg, height 1.77 ± 6.1 m). Only outfield players were included in this study, while goalkeepers and under 18 players were excluded as well injured players. The Ethics Committee of the University of Suffolk (UK) approved this study (RETH19/020). All procedures were conducted according to the Declaration of Helsinki for human studies. All subjects were informed about the potential risks and benefits of the study and signed a written informed consent.

Experimental design

Using a randomized controlled design, this study examined the effect of 6 weeks of combined jump and sprint training (twice a week) on sprint, COD and jump performance in a sample of semi-professional male soccer players. Authors calculated *a priori* the statistical power of this study using G*Power (version 3.1.9.7, Heinrich Heine University Düsseldorf, Germany). A sample size of 20 participants was necessary to have a sufficient power (> 0.80) based on alpha selected (5%) and *moderate* effect size (f = 0.35). For such a reason, 20 players were enrolled in this study with an actual power of 0.841. Before the beginning of the protocol, researchers performed a randomization according to a computer-generated sequence (https: // www.sealedenvelope.com/simple-randomiser/v1/lists). As reported in the CONSORT flow (Figure 1), after the randomization, players were allocated to either a training group (TG, n = 10 players) or control group (CG, n = 10 players).

Nineteen players finished the protocol, while one player of the CG did not because of an injury that occurred during a match. An intention to treat analysis was used in this study, therefore researchers included in the statistical analysis all the players (n = 20) initially enrolled in this study therefore the final actual power of the study was > 0.8 [26, 27].

Experimental procedure

The players enrolled in this study had prior experience of the test battery being used as it was part of their normal evaluation routine with the club, so specific testing familiarization was not required. A standard warm-up routine was performed before each testing session (duration 10 min), which included low-intensity running, dynamic stretching (static stretching was avoided) and sport-specific movements that allowed for the preparation of the players to perform jump and spring sessions. Players performed sprint tests of 10 m and

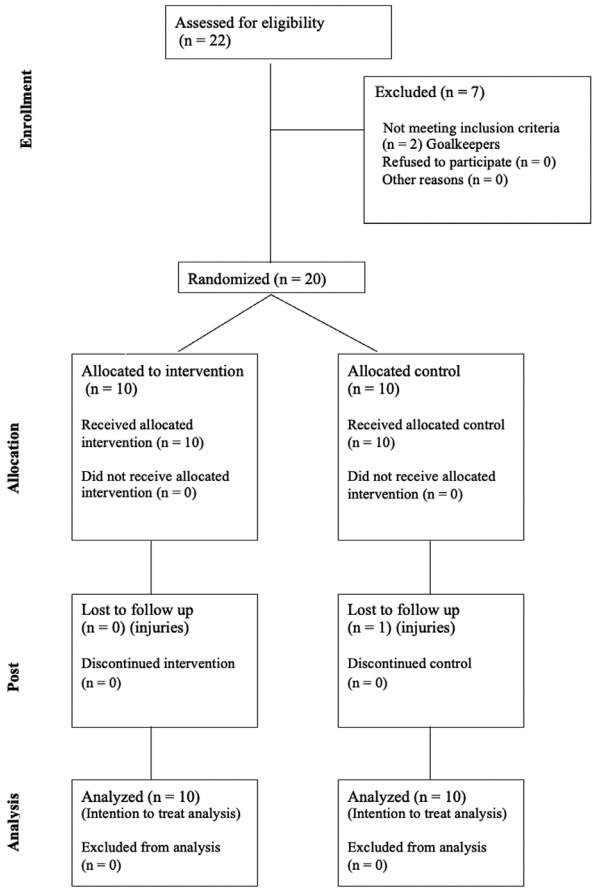


FIG. 1. CONSORT diagram showing the flow of participants through each stage of a randomized controlled trial.

30 m distance, which were used to evaluate the effect of the combined jump and sprint training on linear sprint ability [14]. Infrared timing gates (Microgate, Bolzano, Italy) were placed at the start and end of each of the mentioned distances. The players performed each test three times with 2 min of recovery between the sprints and the best result in each assessment was considered for the data final analysis. The reliability of these tests was previously reported [24] and confirmed in this study; intraclass coefficient correlation (ICC) = 0.88 (*good*) and 0.92 (*excellent*), respectively.

The variation of COD ability after the training protocol was assessed by a 505-COD test. The reliability of this protocol was previously reported [28] and confirmed in this study (ICC = 0.91, *excellent*). On the starting command, the players sprinted for the distance of 15 m. Timing gates were positioned at 10 m and the players passed through it. Players turned on their dominant limb and sprinted back through the timing gates.

A standing long jump test (LJ) was used to evaluate the players' power capacity of the leg muscles following the 6 weeks of intervention. LJ was used to evaluate improvement of horizontal non-rebounding ability, which has been previously described as a reliable assessment [14, 21] – ICC in this study was 0.95, *excellent*. Players performed three trials of a maximal bilateral jump with free arms. The jump distance was measured using a measuring tape from the starting line to the point at which the heel contacted the ground on landing.

Researchers asked the players to avoid intake of alcohol and caffeine 24 hours before the tests, as well as to maintain their normal nutritional routine during the protocol period. To avoid any circadian effect on physical data, both assessments and training protocol were performed at the same time of the day (from 15.00 to 17.00).

Training program

The combined jump and sprint training utilized in the current protocol is supported by previous evidence [8, 22]. Previous research reported that short-term training protocols are generally not appropriate to obtain significant variations [15], while longer duration protocols (e.g., 6 weeks or longer) are generally suitable to obtain some significant and meaningful fitness variations in soccer players [8, 29]. Moreover, two sessions a week are generally needed to obtain such variation in season, while previous studies reported that a single session a week is generally a training frequency too low to offer such variations [24]. The team enrolled in this study performed 3 sessions a week, and one match; players of the two groups performed the same training except for the combined jump and sprint training performed by the TG.

Training was designed with the sport scientists of the soccer club involved in this study, which considered the period of the season and the aims of the club. Two training session a week were considered adequate for the period of the season (in-season) in line with previous literature [8, 14]. Training intervention was divided into two parts, where the first three weeks utilized a specific jumps and sprinting volume, which was increased from the fourth week of 10%. TG undertook the program reported in table 1. Tapering procedure was not planned in the last week of the protocol, however at least 72 h of recovery separated the last training session from the testing

TABLE 1. Training programme.

Weeks	Training Programme
1 – 3 weeks	- 10 cm hurdle jumps (4 jumps) + 5 m sprint (× 5 sets) - Split squat jump + 10 cm hurdle jumps (5 jumps) + 5 m sprint (× 4 sets) - Linear sprint 30 m (3 repetitions) (× 7 sets) The recovery between sets was 20–30 seconds, recovery between exercises was 2 minutes Total jumps: 64 jumps per session Total sprint distance: 675 m per session
4 – 6 weeks	- 10 cm hurdle jumps (5 jumps) + 5 m sprint (× 5 sets) - Split squat jump + 10 cm hurdle jumps (6 jumps) + 5 m sprint (× 4 sets) - Linear sprint 33 m (3 repetitions) (× 7 sets) The recovery between sets was 20–30 seconds, recovery between exercises was 2 minutes Total jumps: 70 jumps per session Total sprint distance: 738 m per session (10% increment compared to the first training block)

session. A standard warm-up routine was performed before each training session (10 to 12 min), which included low-intensity running, dynamic stretching (static stretching was avoided) and sport-specific movements that allowed for the preparation of the players to perform jump and spring sessions. The intensity required during jumps and sprints was maximal – S&C coaches of the team incited the players during the conditioning sessions. Each group (TG and CG) was always coached by a minimum of one qualified S&C coach during the protocol (minimum players/coach ratio was 10/1).

The CG did a recovery session composed of low intensity technical with the coach. CG did not perform any additional jump or sprint training to compensate for what was performed by the TG. Both TG

TABLE 2. Summary of baseline and post-training data before and after 6 weeks of TG (n = 10) and CG (n = 10). Data are presented in mean ± SDs.

Variable	Baseline Mean ± SDs	Follow-up Mean ± SDs	Delta difference (95% CI)	P-level	Effect Size	Qualitative assessment
			TG			
Sprint 10 m (s)	1.82 ± 0.06	1.74 ± 0.10	-0.08 (-0.18, 0.02)	0.100	-0.58	*Small*
Sprint 30 m (s)	4.28 ± 0.24	3.99 ± 0.10	-0.29 (-0.45, -0.12)	0.004	-1.12	*Large*
505-COD (s)	5.33 ± 0.18	5.19 ± 0.10	-0.13 (-0.25, -0.02)	0.024	-0.85	*Moderate*
Long Jump (cm)	222 ± 17	227 ± 19	4.6 (0.8, 8.4)	0.022	0.87	*Moderate*
			CG			
Sprint 10 m (s)	1.92 ± 0.13	1.94 ± 0.16	0.02 (-0.09, 0.15)	0.658	0.14	*Trivial*
Sprint 30 m (s)	4.24 ± 0.29	4.42 ± 0.24	0.17 (-0.04, 0.40)	0.109	0.52	*Small*
505-COD (s)	5.52 ± 0.19	5.28 ± 0.20	0.03 (-0.05, 0.11)	0.453	0.25	*Small*
Long Jump (cm)	214 ± 15	212 ± 16	-1.9 (-5.2, 1.8)	0.299	0.35	*Small*

TG = Training group; CG = Control group; 505-COD = 505 change of direction test; SD = Standard deviations; CI = Confidence intervals; m = meters; s = seconds.

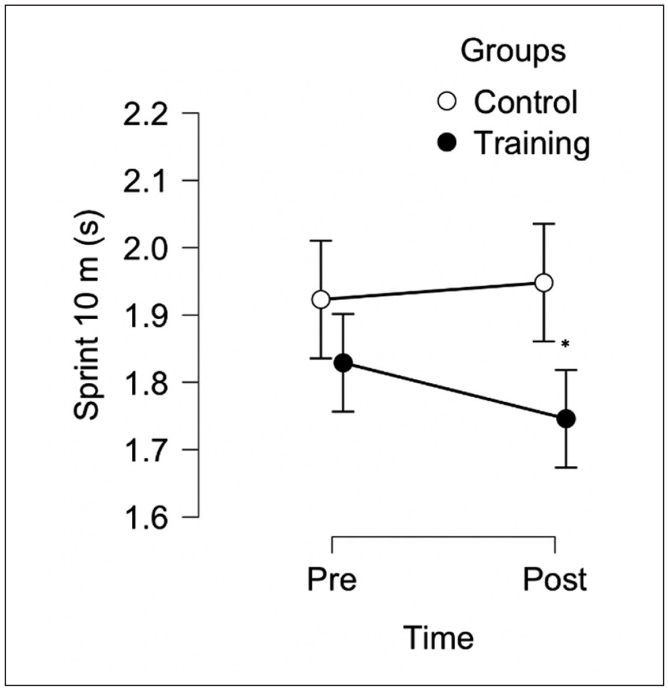


FIG. 2. Between-group analysis after 6 weeks of Training Group (n = 10) and Control Group (n = 10). * Represents a significant difference (p < 0.05) between groups following analysis of convariance (ANCOVA) using baseline values as covariate.

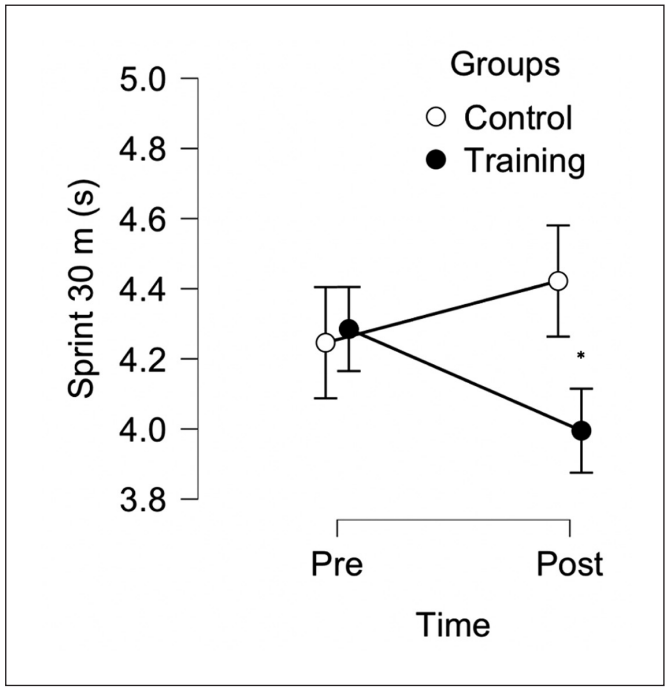


FIG. 3. Between-group analysis after 6 weeks of Training Group (n = 10) and Control Group (n = 10). * Represents a significant difference (p < 0.05) between groups following analysis of convariance (ANCOVA) using baseline values as covariate.

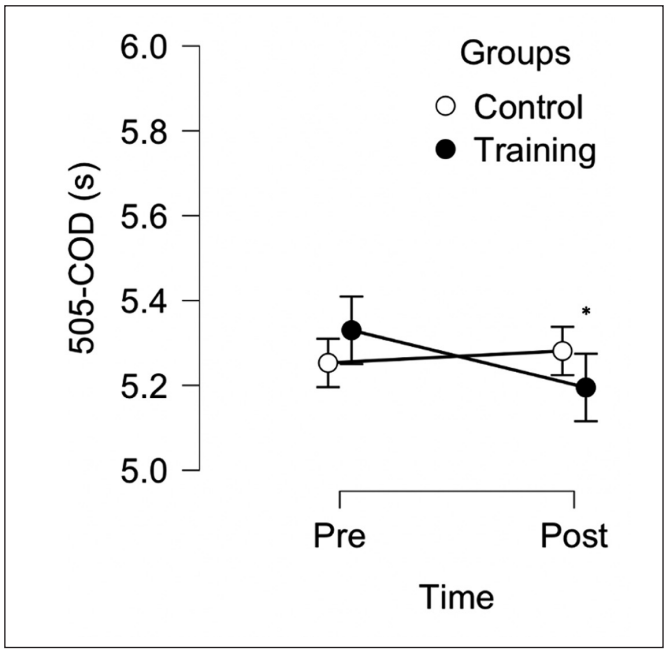


FIG. 4. Between-group analysis after 6 weeks of Training Group (n = 10) and Control Group (n = 10). * Represents a significant difference ($p < 0.05$) between groups following analysis of convariance (ANCOVA) using baseline values as covariate.

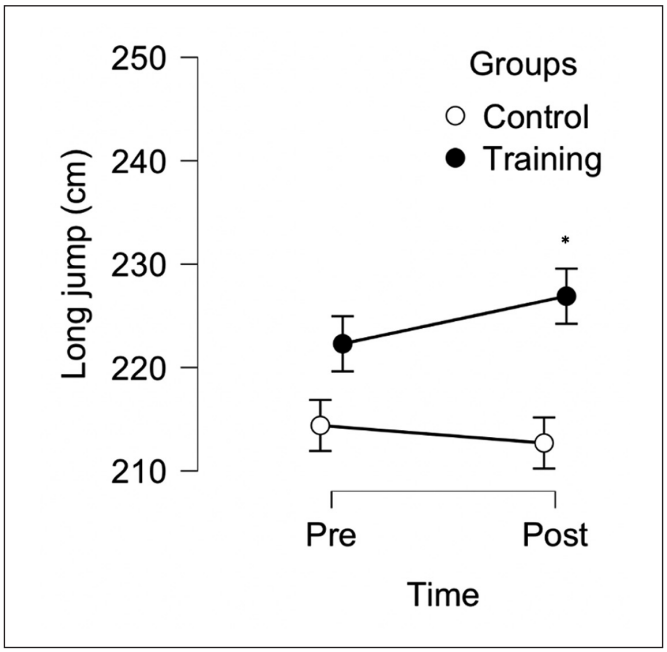


FIG. 5. Between-group analysis after 6 weeks of Training Group (n = 10) and Control Group (n = 10). * Represents a significant difference ($p < 0.05$) between groups following analysis of convariance (ANCOVA) using baseline values as covariate.

and CG did the same soccer training during the research protocol of 6 weeks.

Statistical analysis

Data were presented as mean ± standard deviation (SD). Before the beginning of the study, researchers performed a test-retest reliability assessment (ICC, two-way mixed model) of each test between familiarization session and testing session (1 week distance) and interpreted as follows: > 0.9 = *excellent*; > 0.8 = *good*; > 0.7 = *acceptable*; > 0.6 = *questionable*; > 0.5 = *poor*; < 0.5 = *unacceptable* [30]. Intention to treat analysis was adopted (every participant was considered for the final analysis) [26, 27]. Shapiro-Wilk test was used for checking the normality (assumption) and Levene's test for equality of variance (heteroscedasticity). Two-way analysis of variance (ANOVA) was employed to detect possible within-in and time*groups interactions [31]. Between-group differences were analyzed using the analysis of covariance (ANCOVA) using baseline values as covariate. Robust estimates of 95% confidence intervals (CI) were calculated using bootstrapping technique (randomly 1000 bootstrap samples). Mean difference estimate is based on the median of the bootstrapping distribution. Statistical significance was set at $p < 0.05$. Partial eta squared (η^2) was calculated after ANOVA and ANCOVA and interpreted as follow, *trivial* $\eta^2 < 0.01$, *small* $\eta^2 > 0.01$, *moderate* $\eta^2 > 0.06$, and *large* $\eta^2 > 0.14$. Within effect was assessed using Cohen's *d* and interpreted as *trivial* < 0.2, *small* = 0.2–0.6, *moderate* = 0.6–1.2, *large* = 1.2–2.0, *very large* > 2.0 [31]. Statistical analyses were performed by JASP software version 0.10.2 (Amsterdam, Netherland) for Macintosh.

RESULTS

An attendance of 95% for both groups (TG and CG) was reported at the end of this study. Within-group variations after 6 weeks of training for both TG and CG are reported in Table 2.

After 6 weeks of training, between-group analysis following ANCOVA using baseline values as covariate reported statistical difference in favor of the TG in sprint 10 m ($F = 7.258$, $p = 0.015$, $\eta^2 = 0.295$, *large*), sprint 30 m ($F = 27.719$, $p < 0.001$, $\eta^2 = 0.599$, *large*), in 505-COD ($F = 5.942$, $p = 0.026$, $\eta^2 = 0.154$, *large*), and long jump ($F = 6.004$, $p = 0.025$, $\eta^2 = 0.027$, *small*). Sprint 10 m reported a mean difference of -0.18 s, 95% CI (-0.36, -0.03), sprint 30 m reported a mean difference of -0.42 s, 95% CI (-0.61, -0.29), COD-505 reported a mean difference of -0.12 s, 95% CI (-0.25, -0.03), and LJ reported a mean difference of 5.9 cm, 95% CI (1.09, 10.4).

A time*group interaction was reported for 505-COD ($F = 7.1$, $p = 0.016$, $\eta^2 = 0.057$, *small*) and long jump ($F = 7.690$, $p = 0.013$, $\eta^2 = 0.008$, *trivial*).

DISCUSSION

The aim of this study was to evaluate the effect of 6 weeks, two sessions per week, of a TG (combined protocol, jump and sprint training) compared to CG on sprint 10 m, sprint 30 m, 505-COD

and LJ performance in male soccer players. After the training period, TG reported some within group meaningful improvements for sprint 30 m, 505-COD and LJ, but not for sprint 10 m (see Table 1). Following between-group analysis, TG reported significant differences compared to the CG in all variables (Figure 2, Figure 4, Figure 4, Figure 5). These data indicate that combined sprint and jump training, when performed twice a week, in addition to the regular team training, can improve specific physical performance in male soccer players. Given that this training protocol leads to greater physical adaptations than regular soccer training, these findings support their combined use within soccer players training programs.

The importance of improving sprinting, COD, and jump performance within professional soccer players to compete at high level is well known [3, 5, 6, 32]. However, it is not clear what is the most suitable approach to obtain the desired adaptations, in particular when training is performed in season with a limited time to dedicate to physical training [14, 33]. The protocol proposed in the current study used a training frequency of 2 sessions a week as it seems to be sufficient to induce physical adaptations in soccer players in-season in a relatively short period (i.e., 6–8 weeks) [14, 18, 22, 34], but not too demanding to interfere with the other training and coaching aspects such as technical and tactical training. In this study, we found meaningful between group differences in favor of the TG in sprint 10 m, sprint 30 m, COD and LJ performance, which considering the short-term protocol administered (6 weeks), may be primarily associated with neural adaptations (e.g., motor unit recruitment strategy and Hoffman reflex) [19, 35]. Neural adaptations are associated with improvement in maximal voluntary contraction, intermuscular coordination, stretch reflex excitability, and changes in leg muscle activation strategies [19]. Moreover, the combination of jumps included in this protocol, which have an emphasis on quick but high-intensity eccentric contractions (landing phase during the jump) and accelerations (which have a high neuromuscular load) may explain some of the adaptations found after only 6 weeks of training [36]. It is well known that the eccentric contraction can produce higher force levels (above isometric force capacities) than the concentric contraction [37], which could explain part of the improvements obtained in this study. Moreover, the advantages offered by the jump exercises are not only related to the eccentric demands, but the combination of eccentric and concentric phases, involving the SSC (muscle action when the muscles lengthening is immediately followed by muscles shortening), which allows elastic energy storage and consequently enhanced force and power production in the following concentric action [19, 38].

The development of short-distance (i.e., 5–20 m) sprint performance is a vital component of athletic performance within soccer [8, 9]. In the current study, there were some significant performance enhancements within the sprint 30 m (*large*) performance over the training period (Figure 3) as well as in in sprint 10 m (Figure 2) with a significant (p = 0015, *large*) between-group difference (however, we found only *small* but non-significant difference in the with-in analysis). Therefore, the results of this study are not surprising, given the recent meta-analysis by Nicholson et al. [8], who identified that combining training methods (e.g., sprinting and strength/jump related exercises) is effective for developing short-sprint performance producing significant moderate-large standardized mean difference at 0–10 m (0.60 [95% CI 0.44, 0.75]) and 0–20 m (0.56 [95% CI 0.39, 0.74]). The explanation of these improvements could be associated with benefits offered by the combining sprint and jump training, as used in this study, which has been previously reported as capable of inducing improvements in acceleration performance [18, 34]. Reasons for this are unclear but it is possible that some neural adaptations from a combined training program are likely to improve short-sprint performance [8, 14, 21, 22].

In a systematic review [25], 24 studies suggested that plyometric training improves COD ability with a mean effect size range from 0.26 to 2.8. As aforementioned, following our combined protocol, we observed a significantly *moderate* improvements in 505-COD and LJ performance, which may be explained due to improved neural adaptations reported above (between group analysis reported in Figure 4 and Figure 5) [21] – although it is difficult to ascertain the exact physiological mechanisms since such data were not recorded in this study. However, in previous research that administered directional and jump training in youth soccer players, 505-COD did not improve [14]. Reasons for this are unclear however some methodological differences (in training design) could possibly explain such differences in findings between studies. Some previous studies used a lower training frequency and volume [14, 24] compared to the current study as well as training took place in a different moment of the season when players could have had different fitness levels. Finally, initial players' training status and the contextual effect of team training with the administrated training protocols can play a key role in sport-specific physical adaptations [14, 24].

The positive results reported in this study are very important for practitioners because they show that a low volume of sprint and jump training, with a training frequency of twice a week (see Table 1), can be very beneficial for the improvement of sprint, jump and COD performance. Although this study found significant between-group differences in all the parameters analyzed, a higher volume protocol could have offered large benefits since adaptations (usually) follow a dose-response principle [19, 39]. Another important finding of this study is related to the positive sport specific improvements obtained during an in-season period since most intervention studies are performed in pre-season when more time is available for physical training. Throughout the annual soccer season, it is generally reported that there is a fitness improvement in preseason, with a maintenance of fitness in-season [40]. Subsequently, larger benefits of physical adaptation are expected for training programs administered in the preseason compared with in-season, when it is more difficult to elicit physical adaptations [19, 39]. Another strength of this study is the protocol used such as an RCT, which offers the highest scientific rigor.

Limitations and future directions

Despite the novelty and practical application of the current study, this study is not without limitations. First, a larger sample size would allow further analysis of the effect of TG protocols on physical fitness, however this study is a reflection of the sample size available within this semi-professional soccer team. Second, this sample is only reflective of one male semi-professional team and, hence, may not be applicable to other specific populations such as professional male or female players. Third, this study is unable to ascertain if improvements in performances are mainly due to the sprint training, plyometric training, or the combination of the two training, however, this protocol was designed *a priori* to answer the needs of the club involved that was interested to understand if a combination of jump and sprint training was superior compared to soccer training alone – which was demonstrated. Future research should look to isolate specific training modalities within the same group of players to gain a greater understanding into the mechanisms of adaptation.

CONCLUSIONS

This study indicates that combined sprint and jump training, when performed twice a week, for a duration of 6 weeks, in addition to the regular team training, can improve specific physical performance in male soccer players compared to a control condition (regular team training) and supports previous research findings. This study offers a unique practical application for programmes to be implemented in season such as combined sprint and jump activities are an effective training stimulus to improve sprint (e.g., 30 m), COD and jump performance in semi-professional soccer players. These training stimuli identify that it is possible to improve soccer players fitness levels in season in a short period of time (6 weeks). Fitness coaches and sports scientists can integrate their training proposals with the protocol described in this study (see Table 1). Specifically, a combination of 64–70 jumps and 675–738 m of sprinting training per session can yield such benefits. Finally, a volume increment of 10% after 3 weeks of training can be a suitable training dose progression.

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Disclosure of interest

The authors report no conflict of interest.

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The type and extent of travel for professional footballers undertaking national team duties for a national football federation

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ABSTRACT: Elite football (soccer) involves club, continental and international fixtures, requiring players to undertake extensive travel [1]. For a national football federation, this includes the transport of players between club and camp/tournament commitments, which is often a point of contention between respective organisations [2]. Partly this contention results from the effects of travel, whereby jet lag and travel fatigue can negatively affect physical performance [3–5] and athlete wellbeing [6, 7]. Given the scarcity of data on elite players following travel, an initial step for any national football federation is to understand the volume and nature of travel undertaken by national team players. Such insight may better identify the schedule, timelines and needs of athletes' post travel. Better awareness of these travel needs can help maximise availability for training and minimise the impact of travel related stresses on performance or wellbeing. However, the regularity and volume of travel to national football team commitments has not previously been described. Further, travel demands are likely to vary significantly based on the location of the athlete and the national team camp. For countries outside of Europe, such as Australia, the travel demands and ensuing effects on player preparation can be substantial for both arrival into national team and on return to clubs [7]. Hence, detailed information regarding the type, frequency, and extent of travel for national team duties is important to aid in planning optimal travel schedules and interventions to assist players for international or club duty.

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INTRODUCTION

In the absence of player data in the research literature, specific detail related to national team travel demands is needed, as the influence of jet lag and travel fatigue will differ based on a number of different factors related to the journey. Time zone shifts of > 3 h are likely to induce symptoms of jet lag, though athletic performance reductions exist with greater time zone differences [8, 9]. For example, reductions in intermittent and maximal sprint performance [4] and jump performance [3, 4] are observed after time zone shifts of > 8 h. Similarly, long-haul travel of > 22 h can reduce sleep duration [5, 6, 10, 11], which may explain elevated fatigue, [6, 10] and reduced intermittent sprint performance [6] and lower body power [5] following arrival. In contrast, northbound travel of 10 h where athletes did not travel overnight had negligible effects on sleep and wellness [12]. The lack of effect from this flight may be attributed to the northward direction of travel and thus lack of significant time zone change, while it is also possible that the timing of the flight relative to the sleep period may be more critical than the duration of travel. Thus, flights of roughly > 10 h with time zone changes of > 3 h should be of concern given the likelihood of inducing jet lag symptoms or interrupting normal sleep cycles. Understanding the frequency and extent of potentially problematic travel may assist national football federations in planning training schedules and recovery interventions following arrival.

Currently, only two studies report travel in national football teams, with trips of 15 h across 4 time zones [13] and 19 h across 11 time zones [7]. Separately, the travel schedules of Australian club sides competing in Asian continental competitions report travel durations of 10 h [12] and 25.6 h [11]. However, these reports do not describe the full range of travel demands likely to be experienced or allow planning for the diversity of demands for national team players. Furthermore, it is possible that the travel demands for players contracted to clubs outside of their home continent are greater than players within the national domestic competition. For a national football federation based outside of Europe, such as Australia, a large number of national team players are contracted to European and Asian clubs. A greater understanding of the travel demands of national team players based on club location can inform tailored travel schedules and interventions based on specific needs. Accordingly, the aim

of this study is to describe the nature and extent of travel performed by Australian national team football players for international duties over a two-year period. In addition, this study compared the travel demands for national duties between players based in Australian (domestic), Asian and European club locations.

MATERIALS AND METHODS

Participants

Participants were 58 male senior Australian national football (soccer) team representatives who had undertaken travel to train or compete for the national team between March 2018 and November 2019. Through contractual agreements, participants provided consent to Football Australia for the use of their anonymous data for research purposes, and human ethics approval was provided by the institutional Human Ethics Committee (ETH20–5080).

Data Collection

Details of all travel schedules undertaken as a part of Australian national team duties between March 2018 and November 2019 were provided by Football Australia. This included the details of 569 different trips (including multiple flights per trip). Of note, during this period the Australian team competed in the 2018 FIFA World Cup Finals in Russia, the 2019 AFC Asian Cup Finals in the United Arab Emirates, and the Round 2 qualifying process for the 2022 World Cup. Participant data was anonymised prior to being provided with player names replaced by numerical codes.

All flights were provided based on booked travel schedules, which were then independently verified to obtain the actual arrival and departure times through an online flight database (Flightera.net). For each listed trip, the following data was extracted, i) total flight time ii) total travel time iii) time zone change iv) number of overnights per trip v) departure time vi) arrival time vii) number of trips per player and viii) generic direction i.e. East/West. In defining these variables, arrival and departure time relate to the specific time the aircraft took off and landed, as reported via the online flight database. Total flight time was measured as the duration of all flights included in the journey from departure to arrival location. The total travel time was the difference between departure time and arrival time, and included both flight time and stop-over time, however, did not include any additional travel requirements outside air-travel. The time zone change was calculated based on the difference between the arrival and departure time zone on the day in which the player arrived and coded for direction as East, West, or No change. A trip was considered to have occurred overnight if the arrival time was later than midnight of the day of departure. The geographical continent in which a player competed at club level at the time of travel was provided by Football Australia and was used for comparisons between the travel demands of players in Australia, Europe and Asia. All flight measures for each player were collated in a Microsoft Excel spreadsheet and time-based measures were converted into a decimal of hours (i.e. 12 h 30 min was equal to 12.5 h). Time-based variables are reported in 3 h groupings to better report the range and frequency of travel demands. For comparisons between club locations, all flights were labelled as being either outbound (travelling to national team duty, n = 244) or return (returning to club from national team, n = 244). Transition trips between national team commitments or to a location other than the players club were excluded from location-based comparisons (n = 71).

Statistical Analysis

Descriptive data for mean, standard deviation, median, minimum, and maximum values for all flight variables are reported. Shapiro-Wilk normality tests demonstrated that the data was not normally distributed, and comparisons between club location groups for all travel variables were assessed using non-parametric Kruskal-Wallis tests from the "stats" package in R [14]with significance set at $p < 0.05$. Where a significant difference was observed between the groups, pairwise comparisons were made using Dunn Tests [15] with Holm corrected p values. All statistical tests were performed in the R statistical software [14].

RESULTS

A majority of trips involved time zone differences of ≤ 3 h (66%), though 34% of flights involved differences of > 3 h and 17% of flights involved large time differences of ≥ 8 h (Figure 1). The direction of time shifts included 50% westward travel, 43% eastward and 7% without any change in time zone. Travel times of ≥ 10 h occurred in 51% of trips, while 8% involved ≥ 24 h travel time. For flight durations, 41% of trips involved ≥ 10 h flight time, while 7% involved ≥ 20 h flight time. Most flights (64%) did not include overnight travel, while 33% involved one night and 3% involved two nights. The most common arrival time was in the evening between 18:00 and 24:00 (39%), with early morning arrivals between 24:00 and 09:00 occurring for 23% of flights and 39% of flights arrived during the day (09:00 to 18:00). Players most often departed during the day between 09:00 and 18:00 (59%), while 21% of trips departed in the evening (18:00–24:00) and 20% of trips departed in the early morning (24:00–09:00).

A significant effect of player location on time zone change was observed for both outbound ($H = 10.18$, $p = 0.006$; Table 1) and return ($H = 7.505$, $p = 0.023$; Table 2) travel. Asian-based players crossed significantly fewer time zones than Australian- ($p = 0.042$) and European-based players during outbound travel ($p = 0.004$), and Australian-based ($p = 0.018$) players during return travel.

Significant differences for total travel time existed for both outbound (Table 1) and return (Table 2) travel (Outbound: $H = 6.159$, $p = 0.046$; Return: $H = 16.754$, $p < 0.001$) and for total flight time (Outbound: $H = 7.580$, $p = 0.023$ Return: $H = 16.221$, $p < 0.001$). Travel time was significantly greater in Australian- compared to European-based players for return travel ($p = 0.001$) and neared significance for greater outbound travel duration ($p = 0.073$). Australian-based players had significantly greater return travel

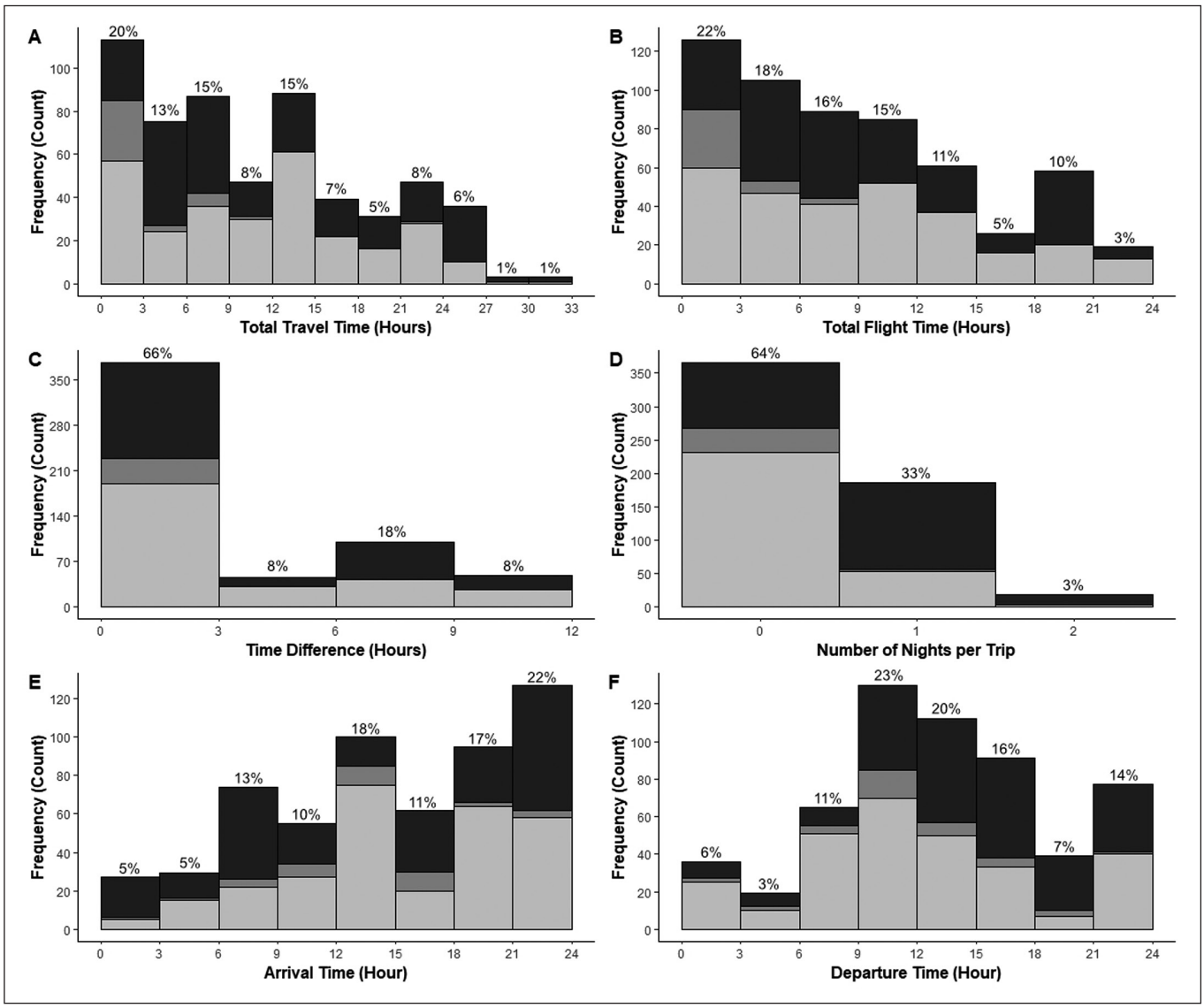


FIG. 1. Distribution of A) Total Travel Time B) Total Flight Time C) Time Difference D) Flights per Trip E) Arrival Time F) Departure Time for national team footballers during a twoyear period (n=569) for Eastward (Dark), Westward (Light) time zone shifts, and No time change (Grey). Percentages above bars represent the proportion of each bar relative to all trips.

duration ($p = 0.001$) and neared significance for greater outbound travel duration ($p = 0.064$). Total flight time for both outbound and return groups was significantly greater for Australian-based players (European Outbound: $p = 0.030$ Return: $p = 0.003$; (Asian Outbound: $p = 0.043$ Return: $p = 0.001$).

The number of overnight trips per player was significantly different between groups for both outbound ($H = 6.066$, $p = 0.048$) and return ($H = 11.850$, $p = 0.003$). With Bonferroni correction, no pairwise comparisons reached significance for outbound travel, while Australian-based players travelled overnight more frequently than both European- ($p = 0.002$) and Asian- ($p = 0.046$) based players during return travel. Significant differences existed in arrival time for both outbound ($H = 6.597$, $p = 0.037$) and return travel ($H = 6.567$, $p = 0.038$); however, with Bonferroni correction, no pairwise comparisons for outbound travel reached significance ($p > 0.05$). For return travel, Australian-based players arrived significantly earlier in the day than European-based players ($p = 0.035$). Significant differences existed in departure time for return ($H = 9.556$, $p = 0.008$), but not outbound travel ($H = 2.050$, $p = 0.359$). Post-hoc analysis showed significantly earlier departure times for European compared to Asian-based players ($p = 0.049$) for return trips.

No significant differences existed for the total number of trips per player for outbound ($H = 3.967$, $p = 0.138$) or return ($H = 3.694$, $p = 0.158$) travel. Significant differences existed in the number of trips in both eastward (Outbound: $H = 31.282$, $p < 0.001$ Return: $H = 20.497$, $p < 0.001$) and westward (Outbound: $H = 28.667$, $p < 0.001$ Return: $H = 31.468$, $p < 0.001$) directions. European-based players completed significantly more outbound eastward trips than both Australian ($p < 0.001$) and Asian-based players ($p = 0.016$) and significantly less westward outbound trips than

TABLE 1. Travel demands of Australian professional footballers based on club geographical location travelling to a national team commitment over a two-year period (n = 244)

Measure	Player Location	Mean (± SD)	Median	Min.	Max.
Trips per Player (N)	All Players	4.1 ± 2.4	3.5	1.0	10.0
	Australia	3.2 ± 1.9	3.0	1.0	7.0
	Europe	4.6 ± 2.6	4.5	1.0	10.0
	Asia	3.2 ± 1.6	3.0	1.0	7.0
Flight Duration (Hours)	All Players	9.2 ± 6.4	6.7	0.8	23.0
	Australia	12.1 ± 6.5*#	12.8	0.9	20.8
	Europe	8.9 ± 6.4	6.4	0.8	23.0
	Asia	7.9 ± 5.4	7.5	1.2	17.8
Travel Duration (Hours)	All Players	11.1 ± 8.1	7.7	0.8	31.0
	Australia	14.3 ± 8.0	14.1	0.9	27.6
	Europe	10.7 ± 8.2	6.9	0.8	31.0
	Asia	9.5 ± 6.4	10.0	1.2	21.5
Time Difference (Hours)	All Players	3.8 ± 3.3	2.0	0.0	10.0
	Australia	4.3 ± 3.5#	5.0	0.0	10.0
	Europe	3.9 ± 3.3#	2.0	0.0	10.0
	Asia	2.6 ± 3.0	1.0	0.0	9.0
Eastward Trips per Player (N)	All Players	2.8 ± 2.5	2.0	0.0	8.0
	Australia	0.2 ± 0.4*	0.0	0.0	1.0
	Europe	4.1 ± 2.3#	4.0	0.0	8.0
	Asia	1.3 ± 0.9	1.0	0.0	3.0
Westward Trips per Player (N)	All Players	1.0 ± 1.5	0.0	0.0	7.0
	Australia	2.8 ± 1.7*	3.0	1.0	7.0
	Europe	0.3 ± 0.7	0.0	0.0	2.0
	Asia	1.2 ± 1.3	1.0	0.0	3.0
Overnight Trips per Player (N)	All Players	2.3 ± 1.8	2.0	0.0	7.0
	Australia	1.5 ± 1.4	1.0	0.0	5.0
	Europe	2.7 ± 2.0	2.5	0.0	7.0
	Asia	1.3 ± 1.2	1.0	0.0	3.0
Arrival Time (HH:mm)	All Players	13:54 ± 07:18	14:59	00:00	23:54
	Australia	12:42 ± 05:42	11:48	00:18	22:18
	Europe	14:24 ± 07:48	16:54	00:00	23:54
	Asia	11:48 ± 05:36	11:12	00:54	21:18
Departure Time (HH:mm)	All Players	14:36 ± 05:36	14:42	00:12	24:00
	Australia	13:06 ± 07:42	10:42	00:12	23:42
	Europe	15:00 ± 04:42	15:00	02:06	23:00
	Asia	13:48 ± 06:42	11:54	00:36	24:00

* Significantly different to Europe ($p < 0.05$); # Significantly different to Asia ($p < 0.05$)

TABLE 2. Travel demands of Australian professional footballers based on club geographical location returning to club teams following a national team commitment over a two-year period (n = 244)

Measure	Player Location	Mean (± SD)	Median	Min.	Max.
Trips per Player (N)	All Players	4.1 ± 2.4	4.0	1.0	10.0
	Australia	3.3 ± 1.9	4.0	1.0	8.0
	Europe	4.7 ± 2.7	4.0	1.0	10.0
	Asia	3.1 ± 1.4	3.0	1.0	6.0
Flight Duration (Hours)	All Players	9.6 ± 5.8	8.5	0.6	21.8
	Australia	12.2 ± 5.3*#	12.9	1.2	19.3
	Europe	9.3 ± 5.8	7.7	0.6	21.8
	Asia	7.2 ± 5.3	4.6	0.9	18.3
Travel Duration (Hours)	All Players	12.2 ± 7.3	11.1	0.6	30.7
	Australia	15.9 ± 7.0*#	16.4	1.2	29.2
	Europe	11.7 ± 7.1	10.3	0.6	30.7
	Asia	9.3 ± 7.0	8.0	0.9	23.9
Time Difference (Hours)	All Players	3.7 ± 3.3	2.0	0.0	11.0
	Australia	4.8 ± 3.5#	6.5	0.0	10.0
	Europe	3.6 ± 3.3	2.0	0.0	11.0
	Asia	2.8 ± 3.2	1.0	0.0	9.0
Eastward Trips per Player (N)	All Players	1.2 ± 1.4	1.0	0.0	6.0
	Australia	2.8 ± 1.6*	3.0	1.0	6.0
	Europe	0.6 ± 0.9	0.0	0.0	3.0
	Asia	1.3 ± 0.9	1.0	0.0	3.0
Westward Trips per Player (N)	All Players	2.5 ± 2.4	1.5	0.0	8.0
	Australia	0.2 ± 0.4*	0.0	0.0	1.0
	Europe	3.8 ± 2.2#	4.0	0.0	8.0
	Asia	0.9 ± 0.6	1.0	0.0	2.0
Overnight Trips per Player (N)	All Players	1.3 ± 1.4	1.0	0.0	5.0
	Australia	2.8 ± 1.8*#	3.0	0.0	5.0
	Europe	0.9 ± 1.0	1.0	0.0	3.0
	Asia	1.0 ± 1.2	1.0	0.0	3.0
Arrival Time (HH:mm)	All Players	15:00 ± 05.48	17:00	0.1	23.9
	Australia	13:06 ± 06.24*	18:00	04:54	22:36
	Europe	15:36 ± 05.30	11:00	01:00	23:54
	Asia	14:48 ± 05:54	17:12	00:06	23:24
Departure Time (HH:mm)	All Players	11:48 ± 06:00	10:54	00:30	23:42
	Australia	13:12 ± 06:00	10:06	01:36	23:18
	Europe	11:06 ± 06:00#	14:36	00:30	23:12
	Asia	13:48 ± 05:00	13:48	03:24	23:42

* Significantly different to Europe ($p < 0.05$). # Significantly different to Asia ($p < 0.05$)

Australian- ($p < 0.001$) and Asian-based ($p = 0.074$) players. For return trips, European-based players completed significantly more westward trips than both Australian ($p < 0.001$) and Asian-based ($p = 0.009$) players, and significantly fewer eastward trips than Australian-based players ($p < 0.001$).

DISCUSSION

This study describes the type and extent of travel demands for Australian national team duties and compares travel demands based on a player's club location. A large number of trips by national team players are unlikely to affect performance and wellbeing (66% ≤ 3 h time difference, 64% not overnight, 49% < 10 h travel time). Despite this, a number of flights exceed 3 h of time difference (34%), occur overnight (36%) or are prolonged in duration (51%, > 10 h) and therefore potentially pose concerns for performance or recovery. Being aware of the frequency of extensive travel demands may in turn allow national team staff to better prepare for the arrival of players and guide preventative measures before and after travel. Furthermore, Australian-based players generally had greater travel demands than Asian or European-based players. Therefore, travel strategies should consider location-specific demands of players; with those travelling into the national team from Europe or returning to Australian-based clubs needing greater attention for circadian adaption and promotion of sleep assistance strategies.

This study shows a number of trips resulting in time zone differences of > 3 h (34%), which have been previously observed to induce jet lag symptoms in athletes [13, 16–18], though symptoms are expected to be more detrimental with greater time zone differences [19–21]. Although no performance measures were recorded in this study, 17% of trips, exceeded 8 h of time zone difference, with such time zone changes previously being shown to cause reductions in intermittent and maximal sprint as well as jump performance [3, 4]. This study highlights that many national team trips for this federation have the potential to induce detrimental jet lag symptoms and thus practitioners should consider interventions that can hasten the rate at which an athlete adapts to time zone changes. Further, 36% of trips required overnight air travel, with this potentially putting athletes at risk of impaired sleep [6, 10, 11]. Impairments in sleep may then have further implications for wellbeing and performance [5, 6, 10, 22], highlighting the need for appropriate strategies to monitor and promote sleep during travel [10, 11, 13]. Related to the overnight nature of travel, 33% of flights arrived in the first half of the day (24:00–12:00), and thus are likely to involve longer durations between full sleep periods which may have additional consequences for sleep and adaptation [23]. For such trips, daytime naps may be useful where athletes were unable to obtain sufficient sleep during travel [24]. Currently, no studies have reported jet lag, travel fatigue or other perceptual responses of national team footballers across varying travel demands. Although no specific jet lag or travel fatigue measures were available, based on the observations of previous research and the extent of travel observed in this study, it is likely that a considerable volume of national team travel may induce circadian misalignment, jet lag or sleep disruption. Hence, given the short-turnaround between club and national team fixtures, strategies to alleviate these consequences are recommended i.e. sleep hygiene, naps and awareness of travel schedules. Such strategies may be important in maximising the availability of players to train and prepare for both national team and club competition [24].

Understanding locational differences in travel demands of players travelling into national team commitments will enable staff to better cater to player-specific needs. Despite similarities in time zone difference for European- and Australian-based players, travelling from Europe required more eastward trips. Although not measured here, eastward trips are reported to induce more prolonged symptoms of jet lag [4, 20, 25] and may warrant earlier arrivals for European players or greater focus on interventions to hasten circadian adaptation. Asian-based players experienced significantly smaller time zone changes and thus the risk of jet lag when travelling into camp is less than that for European- or Australian-based players. Interestingly, players who were based at clubs in Australia had the greatest travel durations. Such a finding likely reflects the unique situation of the Australian national team in which the country is geographically based in Oceania but competes under the Asian Confederation and thus often compete in Asia. While time zone changes may still be a concern for Australian-based players, the greater concern may result from travel fatigue due to longer travel durations and potential implications of long-duration flights [9, 19, 21]. However, as long-haul daytime travel ≤ 10 h has not been observed to affect performance and wellbeing [12], similar travel fatigue symptoms theoretically may persist in all groups given overnight travel requirements were similar [5, 6, 10]. The similarities in overnight travel amongst all players suggests interventions to reduce travel induced sleep loss should be of focus for national team practitioners for player arrival into camp. Accordingly, a need for attention on circadian re-entrainment exists for European-based players, while sleep-promoting interventions during and after travel are required for all players arriving for national team duties.

Given the prevalence of fixture congestion in elite football [1], returning players to clubs from national teams requires effective communication between national and club team staff to enhance player recovery and selection availability. During return travel, Australian-based players had the worst travel schedules, with more eastward trips, longer travel durations and more trips requiring overnight travel. These travel schedules may place the athletes at greater likelihood of jet lag due to the longer lasting effects following eastward travel [4, 26], while longer travel durations and overnight flights have previously been observed to reduce sleep and increase fatigue [5, 11]. Therefore, additional focus on hastening time zone adaptations in players returning to Australian clubs is suggested, while attempts to reduce sleep deficits from overnight travel are also recommended. Earlier arrivals have previously been observed to contribute to

greater symptoms of jet lag due to longer durations between full sleep periods [23]; and should also be considered in Australian-based players who on average arrived significantly earlier than European-based players. While greater attention is required for Australian-based players, the average time zone differences of 3.5 ± 3.2 h may still be enough to induce jet lag in European-based players [8, 9, 19]. Given these players largely travelled westward on return to clubs, it is speculative whether these symptoms may potentially alleviate quicker than eastward travelling players [4, 20, 26].

Despite the novelty of these results, several limitations should be considered when interpreting these findings. Importantly, as this study did not obtain any measures of wellness, performance or sleep from players, any suggested effects of travel are based on previous research. Additionally, the travel demands represent a case study of one national team undertaking tournaments at that point of the time. Furthermore, while a broad date range was used there is likely a bias in the findings based on the location of tournaments. Different travel demands are therefore likely to be observed between other national teams and time frames. Lastly, while a majority of international travel is performed via aircraft, this study does not consider additional modes of transport i.e. road or railway travel and its potential effects on players, nor does it account for travel to and from the airport [8].

CONCLUSIONS

Overall, this study provides a detailed case-study of the type and extent of travel involved in a national football team, while demonstrating that these demands are likely to differ based on a player's club location. Travel for national team duties are diverse, and there remains many schedules that require planning to maximise performance and wellbeing. A single squad-wise approach to travel scheduling may not be appropriate as the nature of travel differs significantly between player's club locations. For the Australian national team, travel into camp is likely most demanding for European-based players, while Australian-based players may be more at risk of negative travel consequences following return travel. As such, it is important to consider the specific demands of players on an individual or at least regional basis.

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The selection advantages associated with advanced biological maturation vary according to playing position in national-level youth soccer

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ABSTRACT: This study investigated the extent to which biological maturation selection biases existed according to playing position in national-level youth soccer. A total of 159 players from the U13 to U16 age groups in the Football Association of Ireland's national talent pathway and international representative squads had their relative biological maturity status assessed using the Khamis-Roche method for the percentage of predicted adult height at the time of observation. Players were categorised as goalkeeper (GK), central defender (CD), full-back (FB), centre defensive midfielder (CDM), centre midfielder (CM), centre attacking midfielder (CAM), wide midfielder (WM) or centre forward (CF). A series of one-sampled means t-tests were used to examine the degree to which biological maturation selection biases existed across playing positions. A non-parametric Kruskal-Wallis test was used to evaluate inter-positional differences. A small to very large selection bias in favour of early maturing players existed for GK ($D = 0.7$), CD ($D = 1.65$), FB ($D = 0.49$), CM ($D = 0.62$), WM ($D = 0.78$), and CF ($D = 0.76$) ($p < 0.05$). Maturational selection biases did not exist for CDM or CAM. Moreover, CD were significantly more advanced in maturation compared to FB, CDM and CAM ($p < 0.05$). This study supports the contention that maturation selection biases exist in youth soccer, but the magnitude of this bias is highly dependent upon playing position. The very strong maturity selection biases at the national level evidenced in this investigation highlight the need for Football Associations to explore strategies, such as futures programmes, to help to retain talented, yet late maturing athletes.

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INTRODUCTION

Biological maturation is the process of progression toward the mature adult state and can be defined in terms of status, timing and tempo [1, 2]. Maturation status describes the stage of maturation an individual has attained at the time of observation (i.e., prepubertal, pubertal, postpubertal); whereas timing refers to the chronological age at which specific maturation events (e.g., peak height velocity, menarche) occur [2]. Tempo refers to the rate at which maturation progresses [1]. Biological maturation is governed predominantly by a combination of genetic and, to a lesser extent, environmental and behavioural factors (i.e., chronic malnutrition, disease, climate) [3]. Human tissues, organs and organ systems mature; however, this occurs independent of chronological age [3]. Thus, youth of the same chronological age can vary substantially in their status, timing and tempo of maturation [4]. For instance, from late childhood, same age peers have been shown to vary by as much as five-to-six years in skeletal age, an established index of maturation status in youth [5, 6]. The individual differences in biological growth and maturation are central to the identification and development of talented youth soccer (football) players [7].

Early maturing males are generally taller and have greater muscle mass, fat mass and muscular strength compared to their on-time and later maturing counterparts [8]. As a direct consequence, early maturing youth outperform later maturing youth in tests of muscular strength, power and speed [9, 10, 11]. Advanced skeletal maturity is also associated with higher absolute VO_2 peak values in adolescent footballers [12]. In a youth football context, these physiological and functional advantages transfer directly into match-play, with players advanced in maturation performing more high-intensity actions, covering more high-speed distances, and achieving faster peak speeds than later maturing players [13, 14]. These strength and performance advantages increase the likelihood of the early maturing boys being perceived as more talented at the point of selection and being recruited into the development system [7].

The selection bias toward players advanced in maturation emerges at the onset of puberty (circa 11–12 years) and increases in magnitude with chronological age and the level of competition [15, 16]. The disproportionate overrepresentation of early maturing boys within professional football academies is well documented [4, 15, 16, 17],

and early maturing boys have been shown to constitute as much as 74% of players within some academy cohorts [16]. As a direct consequence, late maturing boys are underrepresented within professional football academies, and in some instances, are deselected by age 14–15 years [15]. Indeed, early maturing boys are up to twenty times more likely to be retained within the academy system [16]. From a developmental perspective, many equally talented yet late maturing boys are subsequently denied exposure to the professional coaching, sports science and medical support, superior training equipment and facilities, and the high levels of competitive challenge that are experienced by those within the academy system [15, 16]. Once excluded, these late maturing players are less likely to be represented at the professional level [15].

Although the selection of youth players more advanced in maturation may elicit some immediate advantages (i.e., competitive success), it can be counterproductive in regard to long-term player development. The physical, physiological and functional advantages associated with advanced biological maturation are attenuated or even reversed by adulthood [4]. Consequently, by excluding later maturing players, football clubs and associations have excluded a large proportion of the available pool of talent to select from, in turn reducing the number of high potential players that can be produced for the senior level of the game. Of interest, several scholars have proposed that later maturing players may hold the greatest potential for senior success [4, 18]. The reasoning behind this proposition is attributed to the late maturing players being forced to overcome their biological limits through the development of other skills necessary for successful performance, including superior technical skills and tactical understanding, as well as the utilisation of more adaptive engagement in self-regulated learning, particularly self-evaluation and learning [4, 18]. The high-pressured academy environment may also encourage early maturing boys to utilise their athletic advantages in order to be successful at the expense of their technical-tactical and psychological development [4]. Moreover, early maturing players are likely underchallenged when competing against less mature players who are not as physically able, which may further hinder the development of the technical-tactical and psychological skills necessary to succeed at the highest levels [19, 20].

Despite our increasing understanding of the role of biological maturation on talent identification and development in youth football, there is a scarcity of research that has investigated how variations in maturation differ between players of different playing positions. It would seem logical to presume that the techno-tactical and physical requirements of specific playing positions influence how players at different stages of biological maturation are perceived by coaches. Malina et al. [21] investigated variations in skeletal maturation in national-level youth footballers by playing position and found that forwards were the most advanced, followed by defenders and then midfielders. However, the participant sample was small (n = 17) and aged only between 15–16 years, and players were broadly categorised as either defender, midfielder or forward (goalkeepers excluded). In contrast, using the same positional categorisations, other authors have found differences in skeletal maturation between regional-level youth players to be negligible [22]. Regardless, these positional categorisations fail to recognise the distinct physical, technical and tactical variations between players of the same broad playing position (e.g., full-backs vs. central defenders, central defensive midfielders vs. central attacking midfielders). More research is required to understand how variance in biological maturation differs between specific playing positions in youth footballers using larger participant samples, more specific positional categorisations, and a broader range of age groups. Investigating how maturation biases vary according to playing position would help to further support the talent identification and development process by allowing clubs and coaches to identify in which positions the physical and physiological advantages associated with advanced maturation are most influential. Moreover, findings would reveal whether coaches have a perception of the physical characteristics that they think players in specific positions should have at the point of selection, rather than looking at final attributes. These findings may help to support the provision of effective strategies to help to retain talented, yet later maturing players. With consideration to the previous discussion, the purpose of this investigation was to examine the variations in biological maturation between different playing positions in national-level youth footballers.

MATERIALS AND METHODS

Participants

159 players enrolled in the Football Association of Ireland's (FAI) national talent pathway at the time of investigation had their estimated relative biological maturation status assessed (FAI national talent development programmes begin at the U13 age group). The players assessed were either U13, U15 or U16 national-level players. Data was collected before training sessions over the first quarter of the year and each player was assessed once. 100% of players selected into a given national squad that were invited to participate in this research consented, making the sample representative of all players within the national pathway in the cohorts under investigation. The sample consisted predominantly of European Caucasians. Each parent/guardian and player received an information leaflet outlining the purpose of the research study and provided written informed consent before data collection. Ethical approval was granted by the first author's institutional Research Ethics Committee and conformed to the ethical standards of the Helsinki Declaration.

Biological maturity status

The maturity status of each player was estimated using the percentage of predicted adult height [23, 24]. Among children of the same chronological age, it is assumed that those closer to their predicted adult height are more advanced in maturation compared to those further removed from their predicted adult height. The Khamis-Roche method enables the prediction of a player's adult height using the regression formula based upon age and gender-specific regression

coefficients detailed by Khamis and Roche in their analysis of residents enrolled in the Fels longitudinal study [23, 24]. The Khamis-Roche protocol requires the current age, height and weight of the child, and biological mid-parent height (mean height of biological parents). Players had their body height measured to the closest 0.1 cm using a stadiometer (SECA, 217, Vogel and Halke, Hamburg, Germany) and their body mass measured to the closest 0.1 kg using digital scales (SECA, 877, Vogel and Halke, Hamburg, Germany). Parents' heights were self-reported and then adjusted for overestimation as outlined by Epstein et al. [25].

Mean adjusted paternal and maternal heights (178 cm and 165 cm, respectively) were in line with sex-specific means for Irish adults [26]. In instances where a biological parent was not in contact with a player and their parent/guardians, a national average for adult height was used for that biological parent (this accounted for approximately 8% of the sample). The median error bounds between actual and predicted adult height using the Khamis-Roche method is 2.2 cm in males aged between 4 to 17.5 years. For the age groups examined in this study, 12 to 16 years, the lowest 50% error was 1.3 cm for 16-year-olds, and the highest 50% error was 2.8 cm for 14-year-olds [23, 24]. Using the percentage of predicted adult height has demonstrated construct validity as an indicator of biological maturation status in samples of healthy American, Portuguese and German youth [17, 27, 28].

The height of each player was expressed as a percentage of predicted adult height which was used as an estimate of biological maturity status at the time of observation [29]. Estimated relative biological maturity status was then expressed as a Z-score using the child's percentage of adult height compared to age-specific means and standard deviations outlined by Bayer and Bailey in the Berkeley Growth Longitudinal Study [30]. Comparisons to reference values outlined by Bayer and Bailey have been utilised in recent football-specific studies on other European players [7, 15, 17, 19, 31]. These Z-scores were then used to classify the youth players as late, on-time or early maturing. A Z-score of -0.5 to + 0.5 was classified as on-time maturity status; a Z-score of > + 0.5 was classified as early maturity status; and a Z-score of < -0.5 was classified as late maturity status (as currently employed in the English Premier League Player Management Application; [15]). The ± 0.5 criteria were selected over the traditional ± 1 criteria to better differentiate between players that were more advanced or delayed. Using the latter criteria, players presenting maturity Z-scores of -.99 and + .99 would be both considered 'on-time', when in reality there is almost 2 standard deviations of variance in maturation between them. All growth and maturation assessments and calculations were made by the first author who was trained using standardised field practices.

Playing position

Players were categorised as either goalkeepers (n = 17), full-backs (n = 22), central defenders (n = 20), central defensive midfielders (n = 17), central midfielders (n = 30), central attacking midfielders (n = 12), wide midfielders (n = 23), and centre forwards (n = 18). Indeed, whilst recognising that youth players of such ages (12–16 years) are encouraged to be flexible and perform in several playing positions and tactical formations, for the purpose of this investigation, corroboration took place with each players' national head coaches in which the players' "best" position was chosen, which was subsequently assigned to the player for the analysis.

Data Analysis

Data were analysed using SPSS Version 27. Descriptive statistics were used to examine the variance in biological maturation status

TABLE 1. Descriptive statistics (Mean ± SD) for relative biological maturity status in the Irish football player pathway by playing position. Note the expected values for maturity Z-Scores for the general population are 0.0.

Playing position	n	Maturity Z-Score Mean ± SD	Cohens D (90% CI)	Magnitude of the selection bias
Goalkeeper	17	0.62 ± 0.90*	0.70 (0.24–1.13)	Moderate
Central defender	20	1.07 ± 0.65*	1.65 (1.06–2.20)	Very large
Full-Back	22	0.32 ± 0.66*†	0.49 (0.11–0.85)	Small
Central defensive midfielder	17	0.25 ± 0.70†	0.36 (-0.06–0.77)	No significant difference
Central midfielder	30	0.48 ± 0.77*	0.62 (0.29–0.94)	Moderate
Central attacking midfielder	12	0.07 ± 0.75†	0.09 (-0.34–0.56)	No significant difference
Wide midfielder	23	0.62 ± 0.80*	0.78 (0.38–1.16)	Moderate
Centre forward	18	0.69 ± 0.91*	0.76 (0.31–1.19)	Moderate
Total sample	159	0.54 ± 0.80*	0.67 (0.53–0.81)	Moderate

*Denotes a significant difference between the observed value and expected value. †Denotes a value significantly less than the value observed for centre defenders

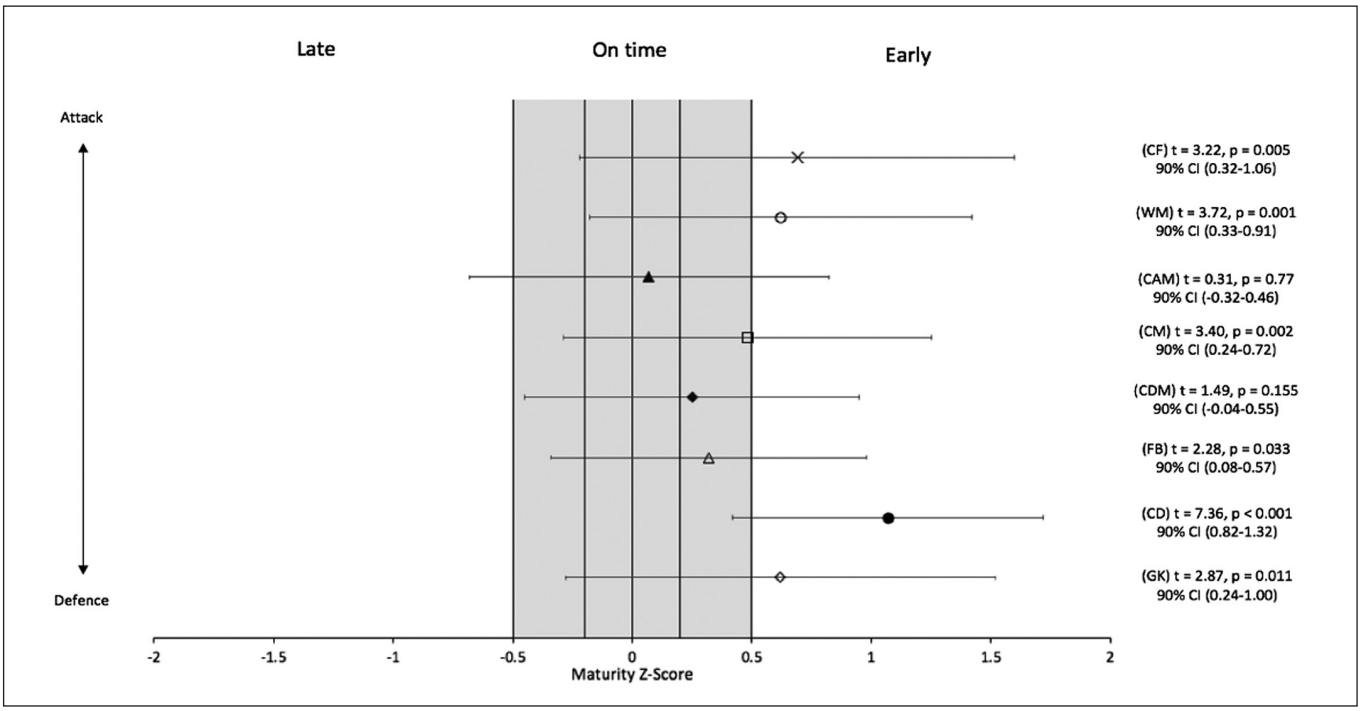


FIG. 1. Maturity selection biases by playing position from the series of one-sampled means t-tests. Data presented as Mean ± SD maturity Z-score for each position.
GK = Goalkeeper FB = Full-back CM = Central midfielder WM = Wide midfielder
CD = Central defender CDM = Central defensive midfielder CAM = Central attacking midfielder CF = Centre forward

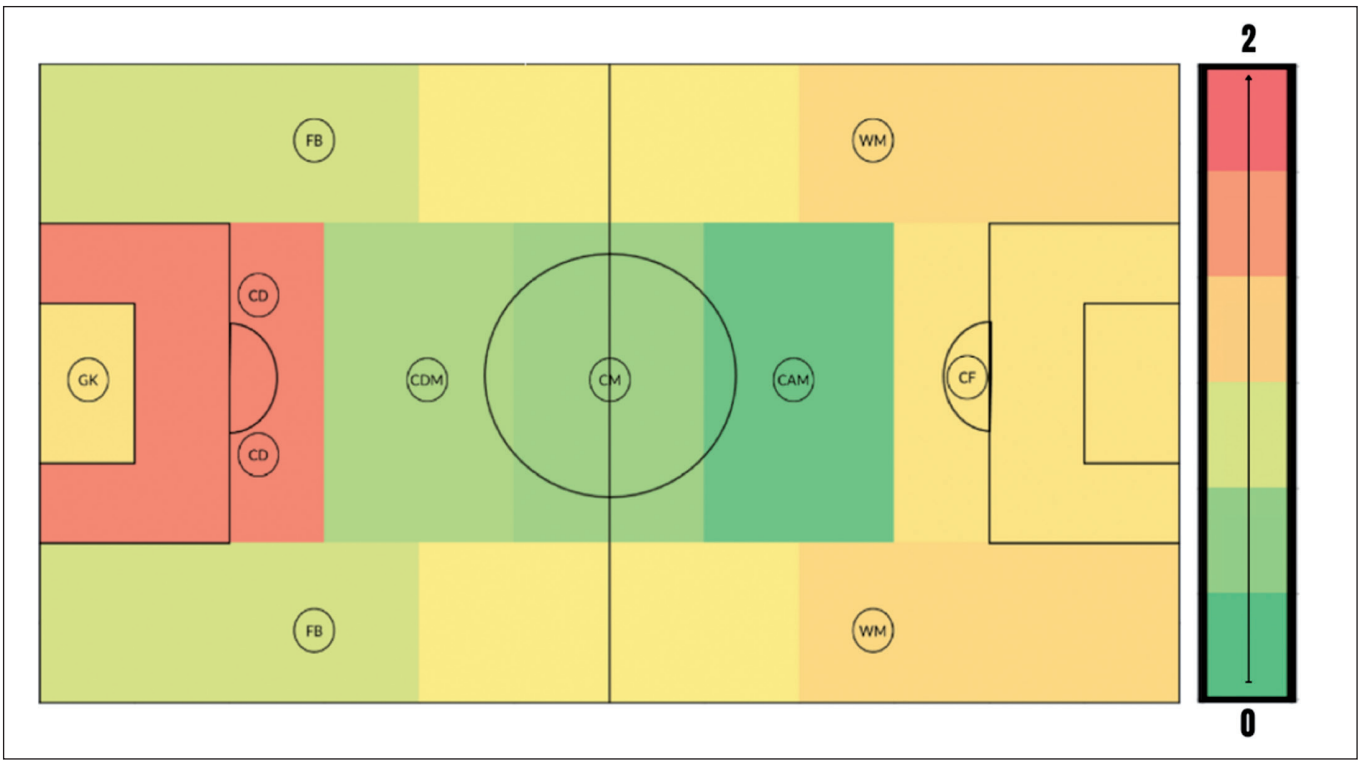


FIG. 2. Cohens D effect sizes for the mean values for relative maturation status (Z-Score) by playing position on the soccer field, attacking from left to right. Note the green value denotes a lower effect size and thus a lower selection bias in favour of early maturation, whereas red denotes a higher effect size and a larger selection bias. The scale denoting the effect size ranges (Cohens D) is displayed to the right.
GK = Goalkeeper FB = Full-back CM = Central midfielder WM = Wide midfielder
CD = Central defender CDM = Central defensive midfielder CAM = Central attacking midfielder CF = Centre forward

relative to chronological age (Z-Scores) across playing positions. Given the unequal sample sizes across different playing positions, a non-parametric Kruskal-Wallis test was used to evaluate group differences. Post-hoc comparisons were determined by the Bonferroni technique (0.05 was used for statistical significance). A series of one-sample means t-tests (one-tailed) were also used to examine the degree to which relative biological maturation selection biases existed across each playing position by comparing the observed mean values for relative biological maturation (Z-Score) against the values expected for the general population (0.0). Subsequent tests of equivalence were used to determine the magnitude of any biases and the degree to which any biases were or were not equivalent to the absence of bias. A 90% confidence interval that existed within the ± 0.5 Cohens D equivalence band was accepted as equivalent to the absence of bias. In contrast, confidence intervals that crossed the ± 0.5 Cohens D equivalence band were accepted as not equivalent to an absence of a bias. Effect sizes (Cohens D) were used to examine the magnitude of any significant differences (small = 0.2–0.49; moderate = 0.5–0.79; large = 0.8–1.19; very large = ≥ 1.2) [32].

RESULTS

The results of the one-sample mean t-tests to examine the presence of maturity selection biases by playing position are presented in Table 1. The mean value for relative maturation was significantly greater than the expected value for goalkeepers, central defenders, full-backs, centre midfielders, wide midfielders, and centre forwards ($p < 0.05$) (Figure 1). The magnitude of the statistically significant maturation biases ranged from small to very large (Cohens D = 0.49–1.65) (Figure 2). Each significant maturation bias was considered not equivalent to the absence of bias in the one-sampled mean t-tests. The result of the Kruskal Wallis analysis indicated that there was a significant difference in relative maturation status across playing positions ($H(7) = 19.31$, $p = 0.007$). Subsequent pairwise comparisons showed that central defenders were significantly more mature for their age than centre attacking midfielders ($p = 0.011$), defensive midfielders ($p = 0.027$) and full-backs ($p = 0.019$). There were no other significant differences between positions.

DISCUSSION

The purpose of this study was to investigate variations in biological maturation in national-level youth footballers of different playing positions. When taking the mean values for relative maturation status by position, a selection bias in favour of earlier maturation existed for goalkeepers, central defenders, full-backs, central midfielders, wide midfielders and centre forwards with effect sizes ranging from small to very large. In contrast, biological maturation selection biases were not observed for central defensive midfielders or central attacking midfielders. Controlling for differences in sample size, central defenders were significantly more mature than central attacking midfielders, central defensive midfielders and full-backs, with no other significant differences observed between positions.

Although there is a lack of existing studies to directly compare to the current investigation, Malina et al. [21] investigated variations in maturation status according to outfield playing position, noting forwards and defenders to be more mature than midfielders, with forwards being the most advanced. These findings were not replicated in the present study. Central defenders were the most biologically advanced, with a Z-Score notably higher than those observed for centre forwards (1.07 vs. 0.69). Central defenders were also significantly more advanced in maturation than two of the three midfield playing positions (central defensive and central attacking midfielders). Importantly, direct comparisons to the findings of Malina et al. [21] are done so with caution given the differences in sample sizes examined (17 vs. 159) and the number of different playing positions (3 vs. 8) analysed. It is equally important to note that the current sample represented a very select group of players that had been identified as the most able within a specific nation and, as such, greater selection pressures or a particular preference for style of play may have influenced the nature of the results. In line with the findings of this study, defenders have also been observed as the most mature players within a similar sized sample of French academy players, although differentiation between full-backs and central defenders was also not conducted [33].

At the youth level, players advanced in maturation perform more high-intensity actions (running ≥ 1 s at > 19 $km \cdot h^{-1}$), repeated high-intensity actions, and attain faster peak speeds during match-play [13]. In addition, early maturing boys are generally taller and have greater muscle mass and strength [8] which is beneficial during physical challenges. It is thus unsurprising that the maturation biases are more pronounced in the outfield positions in which many of these physical characteristics are most desirable. Central defenders were the most biologically advanced in this sample. Indeed, defenders were also amongst the most mature players in similar samples [21, 33]. This is likely due to the technical-tactical positional requirements in which greater size/stature and strength (e.g., to compete in aerial duals) is highly desirable in this position. During elite-level match-play, sprinting is the most frequent action in goal-scoring situations [34]. As advanced maturation is associated with increased levels of testosterone and maturation of the anaerobic system [3, 35], this may explain why the centre forwards and wide midfielders (the most offensive positions) selected are amongst the most mature players. Central defenders, centre forwards and wide midfielders had mean Z-Scores between 0.62–1.07, demonstrating a moderate to very large maturation bias (Cohens D = 0.76–1.65). As well as being taller and having greater muscle mass and strength, early maturing boys are generally heavier and have greater fat mass [8, 13]. As body size dimension is proposed as one of the most important prerequisites to becoming a professional goalkeeper, this may explain the extent of the maturation bias observed for goalkeepers [36]. The selection biases in favour of early maturing players within professional football academies are well documented [4, 15, 16, 17]. The magnitude of this selection bias emerges at

the onset of puberty and increases with chronological age and the level of competition [15, 16]. Results from this study demonstrate that the magnitude of these selection biases is also heavily influenced by playing position. It has previously been suggested that maturation biases may be the most prevalent in the central positions [15], but these results do not directly support this hypothesis. Interestingly, wide midfielders and full-backs were generally early maturing and more biologically advanced than both central attacking and defensive midfielders.

During senior-level match-play, central attacking midfielders have been shown to compete in the lowest number of aerial duals but spend the most time in possession of the ball and have the highest number of ball possessions with a role focussed on linking midfield and attack [37]. Likewise, central defensive midfielders have a role focussed on building passing sequences, with less emphasis on sprinting and high-speed running metrics compared to the other midfield/offensive positions [37, 38]. Given that the physical and physiological advantages associated with early maturation (e.g., increased lean muscle mass, power, strength, anaerobic metabolism) are not primary technical-tactical components of central attacking and defensive midfielders, this may explain why early maturation biases are not observed in these positions. However, it is important to note that the extent of the total, high-intensity and sprinting distances performed by players of each position during match-play is highly variable (e.g., influenced by formation, score-line, minute of match-play). Additionally, a small selection bias in favour of early maturing players was observed in full-backs, although full-backs were significantly less mature than central defenders. This may be attributed to the fact that full-backs operate in less congested areas of the pitch where such physical characteristics associated with advanced maturation may be less desirable. Typically, young players are identified and then selected based on subjective analysis by coaches on the factors thought to underpin senior performance; coaches may have a perception of the physical characteristics that they think players in specific positions should have. Although the physical, physiological and functional advantages associated with early biological maturation do not influence the (de)selection of central defensive midfielders or central attacking midfielders at the national level in this sample, this does not imply that late biological maturation does not influence the deselection of players in these positions in this sample.

Practical implications

In this sample of national-level youth footballers, selection biases in favour of early maturation were shown to exist in some, but not all, playing positions. Nevertheless, mean Z-scores for each position were positive values (≥ 0.07). These results suggest that late maturation does appear to be a negative selection factor in all positions, especially for central defenders and centre forwards. By preferentially selecting early maturing players for specific playing positions, a large proportion of the available pool of talent to select from is reduced, and in turn, so is the potential to maximise the quality and quantity of players produced for the senior level of the game [16]. Given that all players mature by adulthood, and therefore senior levels of performance, the effects of advanced maturation will no longer be present by this point. Yet, the later maturing boys deselected from the system are unlikely to return in the future despite possibly holding potential for senior success [4, 16, 18]. Late maturing youth who are techno-tactically and psychologically skilled need to be nurtured through the system until biological maturity is attained [33]. However, talent identification is a difficult and complex process for coaches. Late biologically maturing players may likely be ineffective performers in match-play during their adolescent and early teenage years in comparison to their early maturing peers, making it challenging for coaches to identify attributes in these players that suggest that they have the potential to develop into outstanding senior level performers. Contrastingly, even the best performing adolescent footballers often fail to attain elite-level senior status demonstrating that the road to senior success is a rocky one [39] and a road that many players may be excluded from travelling upon.

To maximise the opportunity for late maturing players to be retained within the national system, Belgium started a Futures Programme in 2008 [40]. This Futures team has consisted of players that have been identified as technically, tactically, and psychologically able, yet delayed in physical maturity. These teams compete against other nations and academy teams, enabling opportunity for late developers to be retained within the system and experience what it is like to compete and travel as part of a national team. Further research should examine the degree to which Future's teams are successful in retaining late maturing players and allowing them to succeed at the highest level. Indeed, the Belgian Futures programme has been in place for 14 years, and there are case examples of successful outcomes, although there is no published data to support its effectiveness in long-term player development, highlighting the bio-psychosocial complexity of talent development.

In immediate terms, several other strategies could be used to support the development of late maturing players, as well as players of on-time and early maturation statuses. One potential intervention is to reduce the pitch sizes during training/competition to emphasise the use of technical skills over physical/physiological attributes (and advantages) [41]. Similarly, matching players by maturity status during one-on-one training drills or matches (e.g., playing a right wide midfielder against a biologically matched left back) may help to support this process. In broader terms, the provision of generic coach education workshops and resources that educate clubs and their coaches in the area of growth and maturation may be a supplementary level of support that could be provided by Football Associations. Ongoing educational support for practitioners at the club and national level in the appropriate monitoring and training of the adolescent athlete would allow staff to support individual players based upon their physical needs.

Limitations

Whilst recognising that dividing players by eight playing positions rather than three reduces the sample sizes within each position, we believe our positional categorisations provide a more sensitive measure to examine maturation given the large variations in the technical-tactical (e.g., aerial duals, forward passes, crosses) and physical (e.g., high-speed running distance, sprint distance, number of accelerations and decelerations) demands between players in different positions (e.g., full back vs. central defender, attacking midfielders vs. defensive midfielder). Indeed, the overall sample size within this study is larger than similar studies conducted previously [21, 22, 33]. This investigation was conducted with national-level youth footballers and provides a contextualised assessment of maturation biases according to playing positions in a real-world setting. Second, parental heights for the prediction of adult height were self-reported and adjusted for overestimation using equations based upon participant samples from the United States [25]. The percentage of predicted adult height at the time of observation was used as the indicator of biological maturity status using the regression formula and coefficients outlined by Khamis and Roche, which was derived from samples of American youth of European ancestry [23, 24]. The Z-scores used to derive maturity status from the percentage of predicted adult height are calculated based on participants of European ancestry [30].

CONCLUSIONS

This study investigated the variations in biological maturation between different playing positions in national-level youth footballers. The findings indicated that central defenders were significantly more mature than full-backs and central defensive and attacking midfielders. Moreover, selection biases in favour of advanced maturation existed for goalkeepers, central defenders, full-backs, central midfielders, wide midfielders and centre forwards, although the magnitude of this bias ranged from small to very large. Selection biases did not exist for central defensive and attacking midfielders. This study supports the contention that maturation selection biases exist in youth football, but the magnitude of this bias is dependent upon playing position.

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Declaration of conflicting interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Multi-joint isometric measurement for the evidence-based assessment of upper limb strength impairment in wheelchair athletes with different health conditions: a preliminary study

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ABSTRACT: The present study presents a novel specific multi-joint isometric test to assess upper limb strength impairment for evidence-based classification in wheelchair sports. Sixteen wheelchair athletes participated in this study and were classified according to their type of physical impairment and health condition as follows: athletes with neurological impairment (ANI, n = 5) and athletes with impaired muscle power (IMP, n = 11). In addition, six non-disabled participants formed a control group (CG, n = 6). All the participants performed the isometric propulsion strength test (IPST), evaluating pushing and pulling actions, and two wheelchair performance tests. Excellent relative intra-session reliability scores were obtained for strength values for the ANI, IMP and CG groups ($0.90 < ICC < 0.99$) and absolute reproducibility showed acceptable scores of SEM (< 9.52%) for IPST pushing action. The ANI had significantly lower scores in strength and wheelchair performance than the IMP and the CG, while no differences were found between the IMP and the non-disabled participants. In addition, no correlations were found for wheelchair athletes between the isometric upper limb strength measure and wheelchair performance. Our findings suggest that the IPST is a valid test for strength measurement in upper limb impairment wheelchair athletes with different health conditions, which must be used in combination with a performance test to obtain a holistic assessment of this population.

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INTRODUCTION

Manual muscle testing has been widely used in classification in Paralympic sports to infer loss of strength by rating muscle resistance at different positions or ranges of movement [1]. However, this measurement is questioned due to the poor reliability as a result of the subjective assessment of muscle strength and the ordinal measures applied, which are also limited in defining their relationship with sporting performance [1–3]. For the purpose of inferring loss of muscle strength in Paralympic classification, isometric tests appear to have the most validity as they are (a) less training responsive; (b) instrumented, yielding a ratio-scale measure; (c) comprehensive, assessing all muscle actions of importance; and (d) parsimonious, assessing compound (or multi-joint) actions [2, 4]. In this regard, some authors have recently published key recommendations to develop isometric measures, suggesting that the most appropriate method to assess impaired strength in para-athletes should be multi-joint and isometric tests performed at specific joint angles that facilitate maximum force production in a standardized and sport-specific position [2]. Previous research suggested that isometric strength measures are valid to produce clusters of athletes with similar levels of activity limitation in wheelchair racing [5] and Para-swimming [6] and show high reliability across various upper body strength tests in the non-disabled population [6, 7], providing methodological guidance for the development of evidence-based classification systems. Maximal peak force has been suggested as the key outcome variable in isometric protocols for classification purposes to assess strength, being claimed to be less training responsive [2]. Despite these promising findings, these methods may not be valid for all disabled subjects, so future research is imperative to develop and evaluate them on wheelchair athletes with different health conditions.

Wheelchair athletes with health conditions such as spinal cord injury (SCI), amputations or cerebral palsy (CP) could present different manifestations of impaired strength and, consequently, their activity limitation is determined by the muscles affected and the extent to which voluntary force production is reduced [5, 6]. Whereas athletes with amputations or SCI tend to present a loss of voluntary motor control below the level of the lesion affecting the trunk and lower limb structures, neurological disorders have inconsistent manifestations, affecting upper limb, trunk and lower limb control movement [8].

Athletes with neurological impairments resulting in ataxia, hypertonia or athetosis (e.g., CP) tend to present highly affected neuromuscular functions, producing a loss of voluntary motor control that varies considerably depending on the severity and the location of the impairment [9–11]. Specifically, the presence of spasticity, weakness and abnormal dynamic activation patterns in those para-athletes produces a global motor dysfunction, and it limits their capability to produce force during movement and motor performance [12], which affects the range of motion [13], the ability to rapidly generate force, and the ability to generate maximum force [14]. Considering the aforementioned literature, it seems pertinent to consider that athletes with CP will present less upper limb strength than healthy subjects, which could cause decreases in wheelchair performance (e.g., change of direction ability), although this relationship is still unknown.

In wheelchair court sports, the key determinants of mobility performance are the ability of the athlete to accelerate, sprint, brake and turn with the wheelchair [15, 16], so pushing and pulling actions are the main relevant movements. To ensure that an isometric test is valid, sport-specific and related to performance, the participants' position during the test should be related as much as possible to the propulsion actions [2]. Isometric strength tests using multiple joints have been shown to have a stronger relationship with athletic performance [17–19], especially when the most specific positions are used and the muscles contributing to the force production are representative of the activity of interest. Upper limb maximal strength has been correlated with wheelchair propulsion acceleration and top speed in wheelchair rugby [20] and wheelchair racing [5] athletes, respectively. During wheelchair propulsion, wheelchair athletes are required to follow the path of the push rim, being part of a shoulder to hand closed chain [21, 22]. Shoulder flexion power has been reported as an essential contributor to manual wheelchair propulsion and starting push phase kinematics has been described with a flexion and adduction shoulder movement from an extended and abducted initial position [22–24]. Thus, the most parsimonious and sport-specific approach would be a single test, with each athlete positioned in his/her own wheelchair pushing maximally on the push rim, involving key pushing muscle groups [5].

The present study presents a novel specific isometric test to assess upper limb strength impairment for evidence-based classification in wheelchair sports. The aims of this study were (i) to determine the relative and absolute within-day reliability of a sport-specific isometric strength test to assess upper limb strength impairment for wheelchair athletes, (ii) to assess the capacity of a specific multijoint isometric test to determine upper limb strength impairment in wheelchair athletes with different health conditions and non-disabled participants, and (iii) to establish the strength of association between upper limb isometric strength and wheelchair performance.

MATERIALS AND METHODS

Experimental design

A cross-sectional design was used to assess the reliability of the isometric propulsion strength test (IPST) and to identify impaired upper limb muscle strength and its relationship with wheelchair propulsion performance. In a prior session the chief researcher visited the three participant clubs and explained the procedures and aim of the investigation to participants and coaches. Testing was conducted over a single session and was supervised by the research team consisting of experts in evidence-based classification sport science. Participants performed the IPST and two wheelchair performance tests – the wheelchair change of direction ability test (WCODA) and the linear wheelchair sprint test (LWST) – in a randomized order. A rest interval of 5 min was allowed between each test in order to reduce the fatigue effects. Prior to the assessment session, wheelchair athletes participated in two familiarization sessions, in which they performed all the tests, with corrections, after the pertinent explications. The experimental protocol was completed on a synthetic indoor court, and the wheelchair athletes used their specific sports equipment (e.g., gloves, strapping). Two wheelchairs (Quickie All Court, Sunrise Medical, Torrance, California) were used by the control group for testing, with the same strapping system as their counterparts. Before each testing session a standardized warm-up consisting of 5 min of self-paced, low-intensity wheelchair propulsion, dynamic stretching and six 5 m sprints was performed.

Participants

Sixteen wheelchair athletes with different physical impairments and six non-disabled participants were recruited from three regional clubs of wheelchair basketball, wheelchair slalom and paratriathlon and were divided into two sub-groups according to the origin of their eligible impairment. Five athletes with spastic and mixed forms of CP (age = 32 ± 10 years; sitting height = 81 ± 6 cm; body mass: 70 ± 14 kg; body mass index = 32 ± 9 kg/m^2, training experience = 5.5 ± 3 years) composed the sub-group of athletes with neurological impairment (ANI), which presented as global impairment, including upper limbs, lower limbs and trunk. Participants with medical conditions such amputation (n = 3), incomplete lumbar SCI (n = 4) and spina bifida (n = 4) comprised the impaired muscle power sub-group (IMP) (age = 36 ± 11 years; sitting height = 88 ± 10 cm; body mass = 74 ± 19 kg; body mass index = 28 ± 4 kg/m^2, training experience = 4.5 ± 3.2 years), with impairment below the injured area (upper limbs not affected). Non-disabled participants comprised the control group (CG) (age = 30 ± 4 years; sitting height = 84 ± 5 cm; body mass = 68 ± 7 kg; body mass index = 23 ± 2 kg/m^2). Wheelchair athletes' coaches and adapted physical education teachers formed the CG to ensure regular handling and manoeuvrability of the wheelchair. All participants signed an informed consent form after being informed about the aims and procedures of the experiment and participated voluntarily. The study was conducted according to the Declaration of Helsinki, and the protocol was fully approved by the ethics committee of the authors' university.

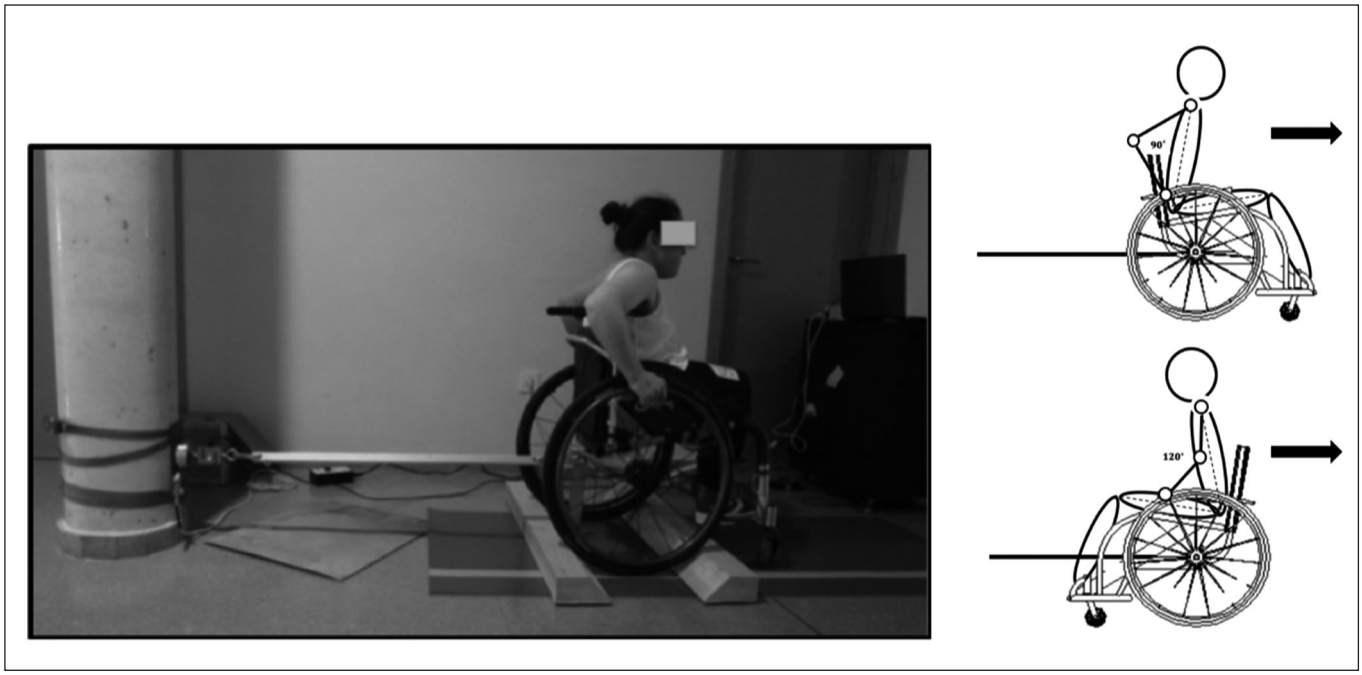


FIG. 1. Schematic representation of the isometric propulsion strength test configuration for push and pull actions.

Procedures

Isometric propulsion strength test (*IPST):* Participants were required to perform push and pull propulsion actions. A strain gauge load cell (Globus Iso Control, Codogné, Italy) was used to register isometric wheelchair propulsion forces. The load cell was instrumented on the athletes' wheelchairs, attached and centred on webbing above the wheels' axes, and fixed to a rigid structure aligned horizontally through a rigid bar ($94 \times 2.5 \times 2.5$ cm). The wheelchair was blocked up and a non-slip surface was used to prevent the wheels from turning. Elbow flexion angle was standardized at 90º for the push action and 120º for the pull action for all the participants [25, 26] (Figure 1). Trunk flexion was standardized within 70–80º to the horizontal for push and pull actions and corrected before each repetition. A goniometer (Lafayette model 01135) was used to check the standard elbow and trunk positions and a real-time video feedback system was used to ensure the correct position during executions [5].

Once positioned, participants performed six maximum, voluntary contractions (firstly three push actions and then three pull actions) of 5 s duration each, separated by 2 min for resting. Wheelchair positions were turned 180º during the rest period to perform push and pull actions. Prior to the initiation of the test series researchers ensured that participants understood the test procedure and participants performed two submaximal practice trials. All participants were monitored by the same tester and instructed to gradually build towards maximal force over the first 2 s and to maintain that force for the remaining 3 s, based on previous recommendations [5]. The instantaneous force was displayed in real time to ensure that the trials were valid and visual feedback of the force-time curve was also provided to participants. The horizontal force applied on the wheelchair was registered with the load cell and digitalized by a Data Acquisition Toolbox (DAQ, National Instruments, USB-1208FS) into a 5 V signal. The signal was sampled at 500 Hz by the software Tracer Daq (Measurement Computing Corporation, Norton, MA, USA) to generate a visual feedback display during the test. Force data analysis was conducted with LabVIEW (v.2010, National Instruments, Austin, USA) and low-pass filtered at 50 Hz and maximal resultant peak force (F_{peak}) was analysed. The best of the trials in each action was used for the statistical analysis considering the maximal force executed [5, 6].

Wheelchair change of direction ability (WCODA) test: The participants propelled themselves forward 8 m in a straight line. At 4 m, participants crossed back between two wood cylinders (40 cm height, 10 cm diameter, 1.75 kg weight), turning 180º, which required a pulling action. This test was adapted from Altmann et al. [27] to assess acceleration ability in a linear sprint incorporating a change of direction. These equipment and distances are specific to the wheelchair slalom para-sport. Participants completed three trials with 2 min of recovery between trials. Time measurement was registered by timing gates (Globus, Codogné, Italy) placed 1 m above the ground over the start and finish lines. This height was established as the mean shoulder height from the ground of the participants seated in their own wheelchairs. The best score was used for further statistical analysis (Figure 2A).

Linear wheelchair sprint test (LWST): The participants performed three maximal wheelchair sprint tests of 4 m distance, with a rest period of 2 min between trials [27]. Timing gates (Globus, Codogné, Italy) were positioned at the start and finish lines 1 m above the ground. Participants were instructed to "cross the 4 m line at

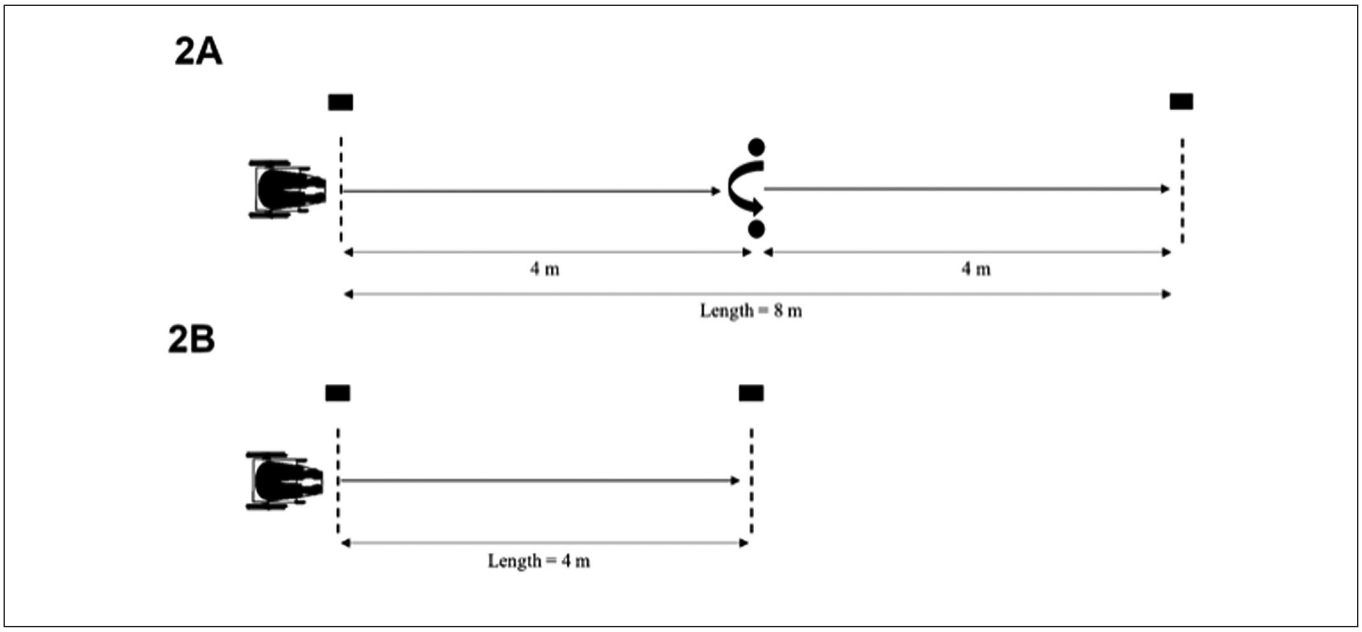


FIG. 2. Schematic representation of the wheelchair change of direction ability test (2A) and the linear wheelchair sprint test (2B).

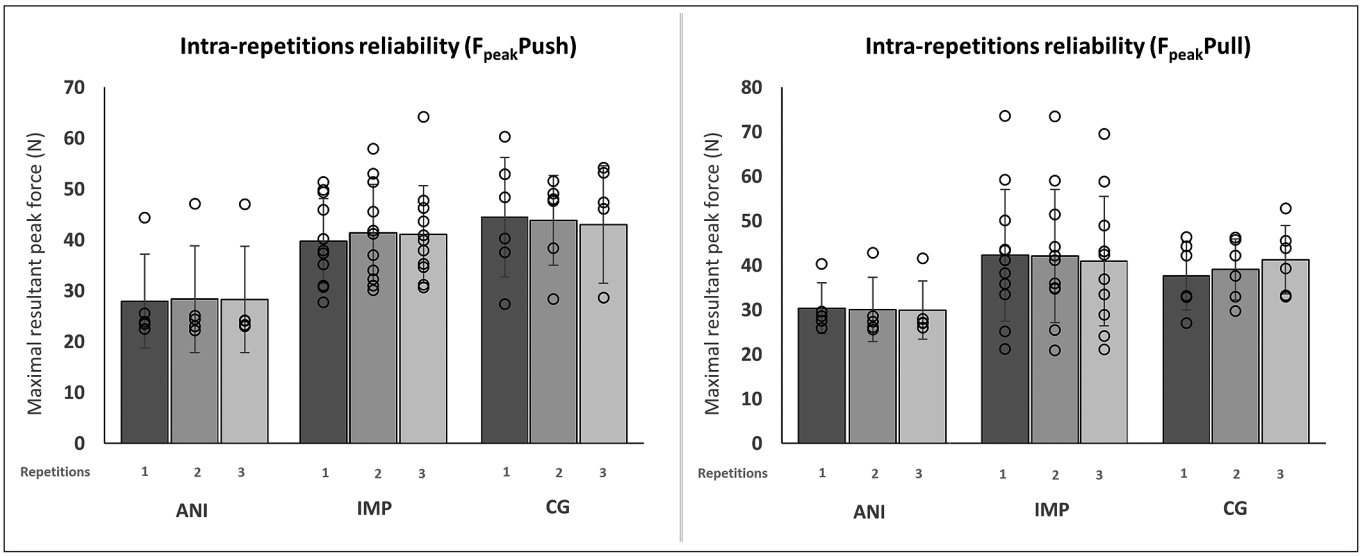


FIG. 3. Intra-repetition reliability related to force values (push and pull) for each group. ANI = athletes with neurological impairment; IMP = athletes with impaired muscle power; CG = control group.

maximal speed." The best score was used for further statistical analysis (Figure 2B).

Statistical analyses

Data are presented as mean ± standard deviations (SD). The normal distribution of the results of the variables applied was tested using the Kolmogorov-Smirnov test, and statistical parametric techniques were carried out. Relative and absolute reliability among trials in each test was assessed using intra-class correlations (ICCs) and standard error of measurement (SEM) respectively [28]. Intra-session reliability was calculated as the immediate test-retest reliability related to the random variability of the measurement per se that could be subject to the inaccuracy of the measurement or athlete's performance variations. ICC values were calculated and categorized as excellent (0.90–1.00), high (0.70–0.89), moderate (0.50–0.69), or low (< 0.50) [29]. The SEM was calculated using the following formula: SEM = SD and expressed as a percentage of the mean scores (SEM%) considering values lower than 10% as acceptable [30].

TABLE 1. Differences in the isometric propulsion strength and wheelchair performance mean values among groups.

	Mean ± SD [confidence intervals (95%)]			Mean difference (%); ES, interpretation		
	ANI (n = 5)	IMP (n = 11)	CG (n = 6)	ANI-IMP	ANI-CG	IMP-CG
F_{peak}Push (N)	28.6 ± 10.4 [19.3–37.9]	43.6 ± 10.1 [37.6–49.6]	46.9 ± 11.5 [37.7–56.1]	52.4; -1.7, large *	64.3; -1.7, large*	7.8; -0.3, small
F_{peak}Pull (N)	32.9 ± 11.2 [22.9–42.9]	44.7 ± 16.5 [35.0–54.4]	41.7 ± 7.8 [35.5–47.9]	35.9; -0.8, moderate	26.8; -0.9, large	6.8; 0.2, small
WCODA (s)	10.5 ± 3.4 [7.5–13.5]	6.5 ± 1.5 [5.6–7.4]	7.9 ± 0.9 [7.2–8.6]	37.4; 1.8, large**	24.4; 1.1, large	20.7; -1.0, large
LWST (s)	3.9 ± 1.5 [3.0 to 4.8]	2.4 ± 0.3 [2.2–2.6]	2.6 ± 0.2 [2.4–2.8]	40.9; 1.9, large**	35.7; 1.4, large*	8.9; -0.7, moderate

Abbreviations: SD = standard deviation; ES = Effect size; ANI = athletes with neurological impairment; IMP = athletes with impaired muscle power; CG = control group; F_{peak}Push = maximal horizontal peak force in push action; F_{peak}Pull = maximal horizontal peak force in pull action; WCODA = wheelchair change of direction ability test; LWST = linear wheelchair sprint test. * Significant level set at $p < 0.05$; ** Significant level set at $p < 0.01$.

TABLE 2. Relationships (r) with a 90% confidence interval (CI) between the players' isometric propulsion strength test and wheelchair performance test in each age group.

		F_{peak}Push	F_{peak}Pull	WCODA
ANI		–		
IMP	**F_{peak}Push**	–		
CG		–		
ANI		0.98 ± 0.32 NP**	–	
IMP	**F_{peak}Pull**	0.13 ± 1.17 ?	–	
CG		0.94 ± 0.48 NP **	–	
ANI		-0.42 ± 1.69 ?	-0.43 ± 1.68 ?	–
IMP	**WCODA**	0.25 ± 1.11 ?	-0.07 ± 1.19 ?	–
CG		0.64 ± 1.30 ?	0.65 ± 1.30 ?	–
ANI		-0.4 ± 1.65 ?	-0.47 ± 1.65 ?	0.99 ± 0.14 NP**
IMP	**LWST**	0.40 ± 1.06 ?	0.16 ± 1.18 ?	0.84 ± 0.47 VL**
CG		0.89 ± 0.7 VL*	0.58 ± 1.06 ?	0.87 ± 0.78 VL*

Abbreviations: ANI = athletes with neurological impairment; IMP = athletes with impaired muscle power; CG = control group; F_{peak}Push: maximal horizontal peak force in push action; F_{peak}Pull: maximal horizontal peak force in pull action; WCODA: wheelchair change of direction ability test; LWST: linear wheelchair sprint test. Correlation magnitude: ?, unclear; S, small; M: moderate; L, large; VL, very large; NP, near perfect. * Significant level set at $p < 0.05$; ** Significant level set at $p < 0.01$.

A one-way analysis of variance (ANOVA) with a least significant difference post hoc comparison (Bonferroni correction) was used to examine isometric strength push and pull actions and wheelchair performance mean differences among groups (i.e., ANI, IMP and CG). Practical significance was assessed by calculating Cohen's effect size (ES) [31]. ES of above 0.8, between 0.8 and 0.5, between 0.5 and 0.2, and lower than 0.2 were considered as large, moderate, small, and trivial, respectively. Paired comparisons among groups for each variable were expressed using mean differences, calculated as: mean difference (%) ((mean 1 – mean 2)/mean 2) × 100. Pearson's product-moment correlation coefficient (r) with a 90% confidence interval (CI) was used to examine the relationship between isometric strength test and wheelchair performance for each group. The following scale of magnitudes was used to interpret the correlation coefficients: < 0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; and > 0.9, nearly perfect [30]. If the 90% confidence limits (CLs) overlapped small positive and negative values, the magnitude was deemed unclear; otherwise, the magnitude

was deemed to be the observed magnitude [32]. Data analysis was carried out using IBM SPSS Statistics for Windows, version 25.0 (IBM Corp., Armonk, NY, USA). Statistical significance was set at $p < 0.05$.

RESULTS

Within-session reliability for each player was evaluated among the three trials performed. Excellent relative intra-session reliability scores were found for F_{peak} values for the ANI, IMP and CG groups ($0.90 < ICC < 0.99$) and absolute reproducibility showed acceptable scores of SEM (< 9.52%) for the IPST pushing action. On the other hand, IPST pull action showed higher values of SEM for the ANI (SEM = 13.50%) and IMP (SEM = 11.62%) while CG absolute reliability was SEM = 5.56%. The intra-session reliability of the two performance tests shows excellent-high reliability ($0.80 < ICC < 0.99$) for all participants' scores and good SEM values (< 5.88%). Intra-repetition reliability related to force values (push and pull) for each group is presented in Figure 3.

Results observed for the isometric propulsion strength and wheelchair performance in each group are presented in Table 1. The ANI obtained the worst values for the F_{peak}Push ($p < 0.05$; ES = -1.47/-1.67) and LWST ($p < 0.01$; ES = 1.40–1.91) in comparison with IMP and CG groups. Additionally, ANI showed a worse performance for WCODA ($p < 0.01$; ES = 1.79) compared with IMP. No significant differences ($p < 0.05$) were found between IMP and CG.

The relationships among IPST and the wheelchair performance tests for the ANI, the IMP, and the CG are presented in Table 2. For the ANI and the IMP, these relationships were unclear when compared to the isometric propulsion strength and wheelchair performance tests. However, in the CG participants who obtained higher values of isometric strength in the push condition showed better performance in the LWST ($r = 0.89$; ± 0.7, very large, $p < 0.05$). Moreover, the two IPSTs correlated for the ANI and the CG ($r = 0.94–0.98$; ± 0.32–0.48, near perfect, $p < 0.05$), whereas the two performance tests correlated ($r = 0.84–0.99$; ± 0.14–0.78, near perfect-very large, $p < 0.05–0.01$) for all the groups.

DISCUSSION

The aim of this study was to propose a specific test to evaluate upper limb isometric strength in a multi-joint propulsion position to identify upper limb strength impairment in wheelchair athletes, while also establishing the strength of the association between these measures and wheelchair propulsion performance. This is the first study that correlates the performance regarding upper limb isometric strength in a multi-joint propulsion position with functional tests (i.e., WCODA and LWST) in wheelchair athletes. The main results of this study report good relative and absolute intra-session reliability of the proposed measures, being able to discriminate between wheelchair athletes with and without altered upper limb muscle force production. In addition, higher values of isometric strength in the push condition were related to better performance in the LWST for the non-disabled participants.

Although previous studies have shown excellent reproductivity of the isometric upper limb test, assessing F_{peak} in wheelchair athletes [33] and the non-disabled population [7], the feasibility and reliability of those measurements have not been studied for specific wheelchair multi-joint pushing and pulling positions. The analysis of the reproducibility of F_{peak} in the IPST showed excellent relative values ($ICC > 0.90$) for wheelchair athletes with different health conditions (ANI and IMP) and non-disabled participants (CG). Additionally, acceptable scores of absolute reliability (SEM) were obtained for the pushing action, in spite of the higher SEM values for the pulling action for the ANI (SEM = 13.50%) and IMP (SEM = 11.62%), when compared to the pushing condition. Although these results reflect the intra-session consistency of the measure for all participants and could be considered to assess upper limb strength impairment in wheelchair athletes with different physical impairments, future studies are necessary to verify the test-retest reliability.

Previous researchers agree that test batteries developed for the purposes of evidence-based classification should favour multi-joint actions wherever possible and a sport-specific approach to assess upper limb isometric strength in wheelchair athletes [5, 33]. Our results showed that ANI produced less isometric force (F_{peak}) during all test conditions compared to the IMP and CG participants, being significant when comparing results from the push test, and suggesting more upper limb strength impairment in those athletes with impairments of neurological nature. These results are in line with previous investigations of propulsion mechanics, which reported that individuals with upper-limb impairment (i.e., CP and multiple sclerosis) showed a lower power output along with a lower resultant force, propulsive moment (M_z), and overall resultant moment on the hand rim during propulsion than users without upper limb impairment (i.e., SB, amputations, thoracic and lumbar SCI) [13, 34]. Conversely, the results obtained by Hogarth et al. [6] show similar upper limb strength values between para swimmers with hypertonia (e.g., CP) and impaired muscle power (e.g., incomplete and complete SCI, SB and polio). These differences could be explained by the range of medical health conditions of the impaired muscle power group including athletes presenting a different distribution of strength impairment across their body structures.

The spastic form of CP and other related neurological conditions present neuromuscular disorders that affect upper and lower extremities involving global body muscle weakness, muscle shortening, and diminished selective motor control [35]. In addition, neural (e.g., motor unit recruitment) and muscular factors (e.g., morphology of muscle fibres) reduce voluntary muscle activation, and consequently a lower muscle force is produced [35, 36]. Thus, athletes with physical impairment such as hypertonia could present an inconsistent strength impairment distribution along all of the muscle structures required for optimal wheelchair propulsion, these being the shoulder flexors/adductors, the elbow extensors and wrist pronators [22]. Additionally,

they could present motor coordination impairment and diminished range of motion that could affect the resultant force applied on the hand rim. It is pertinent to highlight that no differences were found between the IMP and the CG for the IPST, probably due to the injury level and health condition of wheelchair athletes from the IMP group, mainly involving athletes presenting trunk and lower limb strength impairment. These results are in line with those observed by Kotajarvi, Basford, & An [37], who did not find significant differences in maximum isometric shoulder strength when comparing participants with paraplegia with the able-bodied controls.

A key step towards evidence-based classification systems in parasport is developing valid tests of impairment and establishing their relationship with sports performance [38]. The results obtained in the current study show unclear correlations between IPST and the two performance tests for both sub-groups with physical impairments, which do not support previous findings. Regarding this, Connick et al. [5] reported that a multi-joint (combining arm push with trunk flexion) strength measure significantly correlated with a 15 m wheelchair propulsion sprint test. These results could be due to the fact that these authors conducted the correlation test using the overall sample. On the other hand, Mason et al. [33] reported that six upper body isometric strength tests correlated with a 2 m and 10 m sprint, although the sample (i.e., athletes without trunk function) and the used test (i.e., single-joint actions) were different from those in our study. Additionally, our results show a significant correlation between isometric strength in the push condition and wheelchair sprint in 4 m for the CG participants. An explanation for the above observation is that the type of physical impairment and health condition influences the association between the strength test and wheelchair performance. These results could be explained by the fact that the strength test might be associated with the level of spasticity that affects athletes with CP and may be collinear with other physical impairments such as motor coordination [39], whereas in athletes with SCI or SB trunk function impairment should be considered [40].

The main limitation of this study was the sample size in regard to the number of players of each group. A larger sample should be analysed, including more wheelchair athletes with a broader range of underlying health conditions leading to upper limb strength impairment. Also, physical activity between tests was not recorded, which could have influenced the obtained results. Likewise, for further investigation, it would be useful to assess the test-retest reliability of the multi-joint upper limb strength measure. To ensure greater reproducibility of the data, focusing a familiarization period could be employed for impaired participants for the IPST to ensure that variability is not a result of the nature of the impairment. Finally, while the isometric test measures have been correlated with wheelchair propulsion performance for the non-disabled participants, only total time was assessed. Other performance variables, such as maximal velocity or acceleration in the first propulsion, could be appropriate to analyse in studying wheelchair sports.

CONCLUSIONS

In summary, the multi-joint isometric upper limb strength test presented in this study (IPST) show acceptable intra-session reliability and was found to differ between wheelchair athletes with upper limb impairment caused by neurological conditions and wheelchair athletes without upper limb impairment and non-disabled participants. This suggests that the IPST could be considered to provide a useful benchmark to evaluate upper limb impairment in wheelchair athletes with different health conditions, especially in those athletes who present inconsistent strength impairment distribution. The absence of correlations between strength measures and wheelchair sprint in wheelchair athletes questions the utility of the strength measures for the performance evaluation with this population. Finally, the results obtained could contribute to evidence-based methods of classification for wheelchair athletes with upper limb strength impairments, although further studies on this topic are necessary.

Conflict of interests

The authors declared no conflict of interests regarding the publication of this manuscript. There are no funding sources and are no conflicts of interest surrounding this scientific investigation.

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Typical weekly physical periodization in French academy soccer teams: a survey

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ABSTRACT: In elite-level youth soccer players, weekly training periodization is of paramount importance to plan for short- and long-term physical development. The present study investigated current practices for physical periodization strategies in elite male French academies. An online survey was completed by elite French academies strength and conditioning coaches to determine the typical weekly periodization with particular reference to daily training in relation to match day (MD) in youth soccer players. The survey attempted to characterize the importance of physical development compared to match result, and practices used (expected difficulty and content) for each training session according to duration, exercises, and objective. The frequency rates of the responses were compared using two-tailed Chi-square tests with the significance level set at $p < 0.05$. Forty-five questionnaires were analyzed. Respondents indicated that their training sessions focused mainly on physical development (95.6%) rather than match result. Active recovery (34.2%) and aerobic conditioning exercises (40.8%) were primarily conducted on MD+1 and MD+2 using passing circuits and aerobic technical drills. Physical development was mostly pursued during sessions on MD-4 (38.8%) and MD-3 (37.3%). The number of large-sided games was highest on MD-3 (58.1%). On MD-2 and MD-1, a decrease in the training load was highlighted, with speed (40.4%) and tapering sessions (52.4%) mostly implemented. Intensive use of small-sided games (92.3%) and reactivity exercises was observed at MD-1 (100.0%). Our results revealed discrepancies between the physical objectives set for each day and the content implemented, which could potentially be more physically demanding than expected.

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INTRODUCTION

Effective training periodization within the academy systems is key for developing elite soccer players and ensuring that they are prepared for future demands at professional standards. In elite academy settings, young players usually train three to seven times a week, with the greatest workload being the competitive match at the end of the week [1, 2]. Weekly periodization, here referred to as a 'microcycle', is of paramount importance for short and long-term player development and performance [3]. Unfortunately, the multifactorial approach to training in soccer academies can render difficult the implementation of any periodization strategy. Indeed, academy staff must ensure players' educational, physical, technical, and tactical development while ensuring they perform maximally during the weekly competitive games. Furthermore, balancing these double aims must be considered alongside management of other associated factors such as fatigue, recovery [4, 5], and injury prevention [6].

Currently, research describing the in-season weekly training periodization of young soccer teams is fairly limited [2, 5, 7, 8]. Studies have shown that external loads were progressively increased up to three days before match day (MD-3), and decreased the day preceding the match (MD-1) [5, 7]. In U17 players belonging to a Portuguese academy, the lowest external load was observed at MD-1 [5]. Sprinting frequency was notably 7.4% and 19.0% less than post-match or mid-week, respectively. In the same study, in U19 players, the difference was even greater with the number of sprints almost 90% lower than in post-match or mid-week sessions. In contrast, unclear differences have generally been observed in measures of training loads between post-match and mid-week sessions [5]. For example, in an English Premier League academy [2], the greatest training load was obtained at MD+2. A reasonable explanation for this result is that the players participated in double training sessions

inevitably increasing their daily training load, while it is almost never the case for professional teams [9].

While the above studies in academy settings highlight day-to-day differences in training load over a typical weekly periodization period, to the best of our knowledge, only one study has described the typical training content on a day-to-day basis [8]. Briefly, an academy team was firstly shown to rest on MD+1. It then performed development/maintenance training of aerobic capacity on MD+2, development/maintenance of aerobic power and/or maximal power on MD-4, position-specific training on MD-3, team tactical organization on MD-2, and development/maintenance of reactivity and acceleration on MD-1. Such a periodization strategy would suggest that practitioners emphasize players' development over match result.

More generally, research is needed to confirm this in all elite French academies rather than in a single team and identify the workload strategies. This different approach to data collection could allow the whole practice to be compared with the practices of academies in other countries.

Similarly, although previous studies have arguably provided useful insights into weekly periodization amongst academy teams, studies have mostly been conducted in single club settings. Furthermore, key information on physical training content (speed, strength or aerobic) is lacking during the microcycle. Similarly, information specifically relating to the exercises used to enhance these physical qualities is unavailable. Accordingly, the present study aimed, through an online survey, to determine the typical microcycle periodization (expected difficulty and content) prior to a competitive weekend game in multiple French elite male soccer training academies. Particular focus was given to determining the content of each daily training session. We also hypothesized that the academies would be primarily concerned with the technical and physical development of their players rather than match result.

MATERIALS AND METHODS

Subjects

Strength and conditioning (S&C) coaches from 36 elite French academies were invited via email to complete the online survey concerning their U17 and U19 teams. Unanswered questions were excluded from the analyses. Data were collected from the beginning of October to the end of November 2020. All responses were confidential and anonymized. All respondents were notified of the research protocol, benefits and risks before providing consent in accordance with the declaration of Helsinki. Approval of the study was obtained from the local ethics committee. Respondents were clearly informed that their consent was obtained by responding to the first question of the survey.

Procedures

The survey was developed in French and administered via an online survey software (Google Form). The number of questions depended on the number of sessions performed by the team. As such, practitioners had to respond to a number of questions ranging from 17 (only mandatory questions and no training session at all), to 179 (mandatory questions and 3 sessions per day for 6 days). The survey included multiple-choice, close-ended and open-ended questions (depending on the answers submitted, respondents had to respond to additional questions to provide further information when necessary) (Table S1). The survey first described key information about the study, its purpose as well as information related to the research team associated with an e-mail contact. Respondents were then asked to describe the competitive week. For inclusion, the selected week should have been preceded and followed by a competitive match (7-day interval between each competitive match).

Questions covered four main themes: 1) participant information; 2) their subjective rating on the overall importance of physical development compared to the results of competitive matches (1 to 10 scale: 1 = maximum importance of the match result); 3) description of each training session from MD+1 (first day after match day) to the following MD (match day) with particular reference to the physical conditioning work performed (duration, physical quality focus, integrated or dissociated exercises, exercises, expected difficulty), and 4) periodization improvements that could be operated to increase players' physical development. The design of the survey was based on extensive discussions, suggestions and feedback between the research team and practitioners. The content of the final version of the questionnaire was validated by calculating the content validity index (CVI). Eight experts (including coaches and scientists) were requested to rate the relevance of the different items questioned. The content of the present survey was validated with an average scale-CVI greater than 0.89 [10]. The survey was subsequently pilot-tested in five French soccer academy teams to review content clarity prior to the sending of official invitations. This process removed two questions, merged four questions into two, and several rewordings were made for clarity [11].

Statistical analyses

Data were first reviewed and any incomplete responses subsequently excluded from the analyses. The distribution of the response frequencies was analyzed. Descriptive statistics are reported in the form of counts out of the total number of answers for the question. The frequency distribution between days was compared using two-tailed Chi-square tests with the significance level set at $p < 0.05$. In the event of a significant Chi-square, pairwise comparisons were achieved using a Z-test. Repeated measures ANOVA, with Bonferroni's post hoc test were performed to determine differences between days for physical importance and expected difficulty of the sessions. Statistics were performed using JASP (Ver 0.13, JASP Team (2020), University of Amsterdam) and SPSS (Ver 27, IBM-SPSS Inc., Armonk, NY, USA). Open-ended responses were arranged and read several times to ensure an understanding of their meaning. The list of themes of the open responses was discussed by all researchers until consensus was reached regarding data interpretation and theme credibility [12].

RESULTS

Response rate

A total of 50 responses were obtained out of a possible 72 which represent a 69.4% survey return rate. Of these, 45 were included in the analyses (Table S2) while 5 surveys were excluded owing to incomplete responses. These numbers correspond to a 90.0% completion rate and 10.0% omission. These numbers are in line with survey papers in the soccer literature [13, 14].

Training session information

Respondents rated the overall perceived importance of physical development relative to the match result as 7.3 ± 1.6 out of 10 (1 = maximum importance of the match result). The large majority of respondents (95.6%) prioritized players' physical development over competitive match results. The physical importance ($p < 0.001$) and training expected difficulty ($p < 0.001$) varied between-days. Both variables increased progressively until MD-3 before a reduction was observed on MD-2 and MD-1. No difference occurred between MD-4 and MD-3 (Figure 1).

The number of training sessions was different between days ($p < 0.001$) (Table 1). Most teams did not train at MD+1. A single training session was conducted daily at MD+1, MD+2, MD-2, MD-1. Two training sessions per day were generally conducted on MD-4 and MD-3. Training duration also differed between days ($p = 0.041$) (Table 1). Training lasted predominantly between 30 and 60 min on MD+1 and MD-1. On the remaining days, most training sessions lasted between 60 and 90 min.

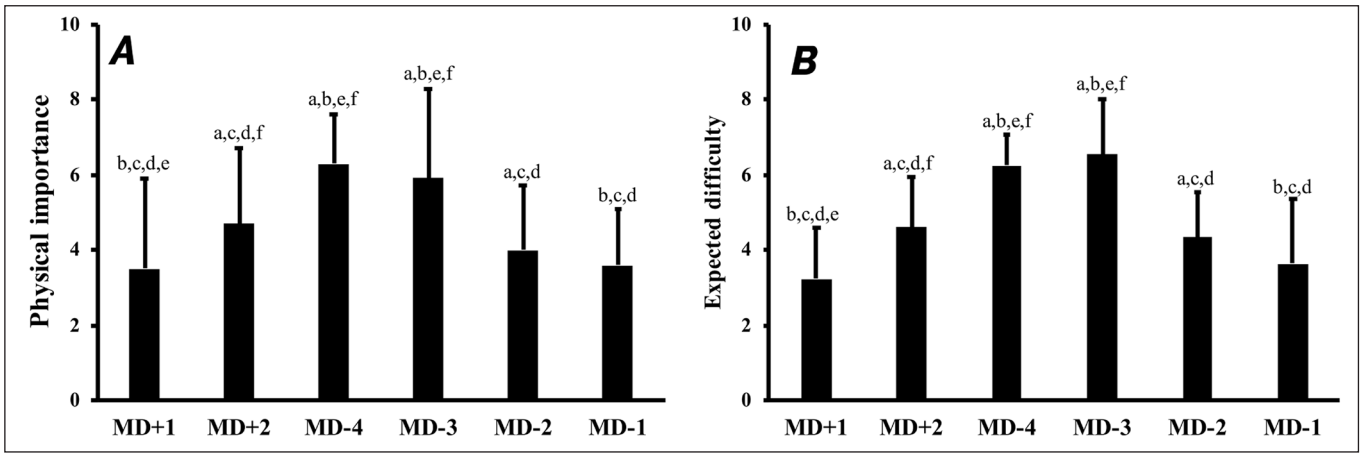


FIG. 1. (A) Physical importance, and (B) Expected difficulty, for each day (/10). Significant differences between days according to repeated measures ANOVA are shown for $p < 0.05$ from a: MD+1; b: MD+2; c: MD-4; d: MD-3; e: MD-2; f: MD-1. MD: match day.

TABLE 1. Information on training sessions.

	MD+1	MD+2	MD-4	MD-3	MD-2	MD-1
Number of training sessions a day (number of responses / total number of responses)						
0 training session***	27/45^{b,c,d,e,f}	0/45^{a,e,f}	0/45^{a,e,f}	0/45^{a,e,f}	5/45^{a,b,c,d}	4/45^{a,b,c,d}
1 training session***	18/45^{b,c,d,e,f}	32/45^{a,f}	23/45^{a,e,f}	31/45^{a,f}	37/45^{a,c}	41/45^{a,b,c,d,e}
2 training sessions***	0/45^{b,c,d,e}	13/45^{a,e,f}	22/45^{a,e,f}	14/45^{a,e,f}	3/45^{a,b,c,d,f}	0/45^{b,c,d,e}
Duration of the session (number of responses / total number of session)						
Up to 30 min*	0/18	0/58	1/67	3/59	0/43	0/41
More than 30 min and up to 60 min***	17/18^{b,c,d,e}	23/58^{a,c,d,e,f}	14/67^{a,b,e,f}	13/59^{a,b,e,f}	18/43^{a,b,c,d,f}	31/41^{b,c,d,e}
More than 60 min and up to 90 min***	1/18^{b,c,d,e}	29/58^{a,f}	33/67^{a,f}	33/59^{a,f}	24/43^{a,f}	10/41^{b,c,d,e}
More than 90 min***	0/18^{c}	6/58^{c,f}	19/67^{a,b,e,f}	10/59^{e,f}	1/43^{c,d}	0/41^{b,c,d}

Values are presented as the number of responses and percentage of the total number of answers (n) for number of training sessions and duration. Significant frequency distribution between days with respect to Chi-square for * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Significant differences between days according to Z-score for $p < 0.05$ are shown from a: MD+1; b: MD+2; c: MD-4; d: MD-3; e: MD-2; f: MD-1. MD: Match day.

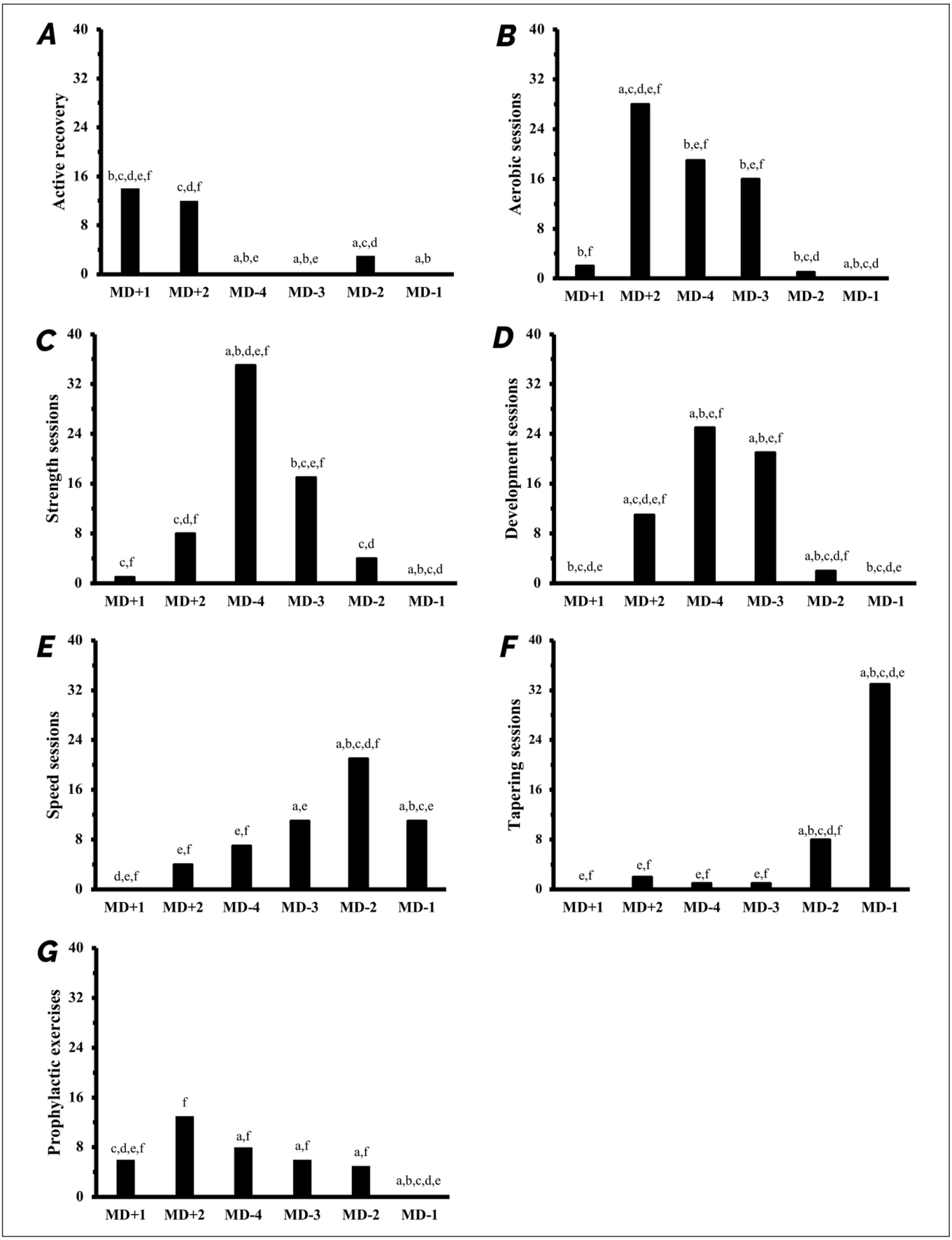


FIG. 2. Number of training sessions through the week for (A) active recovery sessions, (B) aerobic training sessions, (C) strength training sessions, (D) development training sessions, (E) speed training sessions, (F) tapering sessions, (G) prophylactic exercises. Results represent number of responses for each day. Significant differences between days according to Z-scores are shown for $p < 0.05$ from a: MD+1; b: MD+2; c: MD-4; d: MD-3; e: MD-2; f: MD-1. MD: match day.

Differences were observed between days for physical quality focus ($p = 0.002$) (Figure 2). MD+1 and MD+2 were mainly characterized by active recovery (Figure 2A). Aerobic sessions were usually performed from MD+2 to MD-3 (Figure 2B) while strength sessions were predominantly conducted during MD-4 and MD-3 (Figure 2C). The frequency of speed training sessions gradually increased until MD-2 and was prominent on MD-2 and MD-1 (Figure 2E). Tapering sessions were implemented on MD-2 and MD-1 (Figure 2F). While prophylactic exercises were mostly performed on MD+2, these were performed evenly throughout the week except for MD-1 (Figure 2G).

Both integrated and dissociated training types were used for physical conditioning training. Integrated physical content included different exercises with varying frequencies during the week ($p = 0.028$) (Table 2). Passing circuits, alongside aerobic technical drills, were mostly practiced during MD+2, while large-sided games were mainly used on MD-3. However, no differences were observed during the week for small-sided games ($p = 0.180$), medium-sided games ($p = 0.085$), rondo ($p = 0.508$), technical drills ($p = 0.735$), or football tennis ($p = 0.059$). Similarly, the frequency of dissociated physical contents varied during the week ($p = 0.020$) (Table 2). Continuous aerobic exercises were exclusively performed on

TABLE 2. Physical quality focus of the training sessions.

	MD+1	MD+2	MD-4	MD-3	MD-2	MD-1
Integrated exercise(s) $ (number of responses / total number of integrated session)						
Small-sided games	2/4	14/34	20/29	12/31	4/23	12/13
Medium-sided games	2/4	16/34	9/29	13/31	9/23	2/13
Large-sided games***	2/4[f]	4/34[d]	5/29[d]	18/31[b,c,e,f]	7/23[d,f]	0/13[a,d,e]
Rondo	0/4	6/34	4/29	8/31	5/23	4/13
Technical drills	2/4	11/34	8/29	9/31	6/23	5/13
Passing circuit*	2/4	18/34[c,d]	6/29[b,f]	6/31[b,f]	8/23	7/13[c,d]
Football tennis	2/4	4/34	0/29	1/31	2/23	0/13
Aerobic technical drills*	0/4	5/34[c]	0/2[b]	1/31	1/23	0/13
Dissociated exercise(s) $ (number of responses / total number of dissociated session)						
Upper-body strength session**	5/12[e,f]	5/2[f]	11/32[f]	6/25[e,f]	1/14[a,d]	0/27[a,b,c,d]
Lower-body strength session***	0/12[b,c,d]	6/21[a,f]	15/32[a,e,f]	10/25[a,e,f]	1/14[c,d]	0/27[b,c,d]
Speed*	0/12[d,e,f]	3/21[e]	4/32[e]	7/25[a,e]	10/14[a,b,c,d,f]	5/27[a,e]
Reactivity***	0/12[e,f]	0/21[e,f]	0/32[e,f]	0/25[e,f]	4/14[a,b,c,d,f]	27/27[a,b,c,d,e]
Continuous aerobic exercises***	8/12[b,c,d,e,f]	6/21[a,c,d,e,f]	0/32[a,b]	0/25[a,b]	0/14[a,b]	0/27[a,b]
Intermittent aerobic exercises*	3/12[e,f]	6/21[e,f]	10/32[e,f]	10/25[e,f]	0/14[a,b,c,d]	0/27[a,b,c,d]
Repeated-sprint aerobic exercises***	1/12[d]	2/21[d]	8/32[e,f]	12/25[a,b,e,f]	0/14[c,d]	0/27[c,d]
Plyometric*	0/12[c,e]	3/21[c]	14/32[a,b,f]	5/25	4/14[a]	2/27[c]
Coordination	5/12	7/21	7/32	3/25	5/14	7/27
Duration of the dissociated contents (number of responses / total number of dissociated session)						
Up to 20 min***	4/12[e,f]	8/21[e,f]	17/32[e,f]	12/25[e,f]	12/14[a,b,c,d,f]	27/27[a,b,c,d,e]
More than 20 and up to 40 min***	7/12[c,e,f]	7/21[e,f]	8/32[a,e,f]	10/25[e,f]	0/14[a,b,c,d]	0/27[a,b,c,d]
More than 40 and up to 60 min	1/12	5/21	6/32	3/25	2/14	0/27
More than 60 min	0/12	1/21	1/32	0/25	0/14	0/27
Dissociated exercises (number of responses / total number of dissociated session)						
Field-based session***	9/12[f]	12/21[f]	21/32[f]	17/25[f]	12/14[f]	27/27[a,b,c,d,e]
Gym-based session***	3/12[f]	9/21[f]	11/32f	8/25[f]	2/14[f]	0/27[a,b,c,d,e]

Values are presented as the number of responses and as the percentage of the total number of answers (n) for the question for each day as reported below the question. $ Questions with the possibility to give multiple responses. Significant frequency distribution between days with respect to Chi-square for * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Significant differences between days according to Z-score for $p < 0.05$ are shown from a: MD+1; b: MD+2; c: MD-4; d: MD-3; e: MD-2; f: MD-1. MD: Match day.

MD+1 and MD+2. Upper-body strength sessions were mainly used from MD+1 to MD-3. On MD-4 and MD-3, practitioners primarily implemented lower-body strength sessions, intermittent aerobic, repeated-sprint aerobic, and plyometric exercises. Speed and reactivity exercises were mostly used on MD-2 and MD-1. The use of coordination exercises did not show any significant differences between days ($p = 0.149$).

The duration of the dissociated contents differed through the week ($p < 0.001$) (Table 2). Sessions lasting more than 20 min and up to 40 min were used more frequently from MD+1 to MD-3. Sessions lasting up to 20 min were mostly used from MD-4 to MD-1. However, no differences were obtained for the few sessions lasting longer than 40 min.

DISCUSSION

In this survey, the results partly confirmed our hypothesis that in theory academies prioritized physical development over match results. However, in reality training sessions specifically dedicated to physical development were only observed on two days (MD-4 and MD-3). Results demonstrated that teams mainly performed recovery-oriented sessions on MD+1 and MD+2 and tapering sessions on MD-2 and MD-1. The novelty of this study is that it is the first study to describe the periodization of weekly training for all elite academies in a country. It therefore appears that training periodization was only partly congruent with the expected training objective.

On MD+1, responses from the present survey showed that recovery was the primary physical aim, with the implementation of different recovery strategies (active or passive). Research examining physical, physiological and perceptual markers has shown that recovery following a soccer match is incomplete on MD+1 [15]. As such, active recovery should be [16] and was implemented by academy practitioners [17, 18] during MD+1, no doubt in an attempt to aid the recovery process. Indeed, the intensity of the MD+1 session was the lowest of the week. Results showed that training duration was increased by the coaching staff on MD+2. Additionally, a large number of sessions lasting at least 60 min, and double sessions were reported on this day. In line with our results, a previous study also reported greater training loads on MD+2 [19]. In contrast, findings are not consistent as other studies reported lower training volumes in both professional [17] and youth teams [18], while some reported the greatest weekly training load on MD+2 [2]. These discrepancies across results could be related to contextual variables such as the number of training sessions on MD+2 (e.g., 2 training sessions [2] vs. 1 training session [17]) or training content (implementation of strength training [2]).

The training content on MD+2 demonstrated a preference for small- and medium-sided games rather than large-sided games. This choice could be explained by practitioners accounting for the highest values of creatine kinase that typically occur on MD+2 resulting from the previous match, which are associated with muscle damage [20] and delayed onset muscle soreness [21]. Indeed, small- and medium-sided games have been shown to be a more suitable option to ensure lower overall physical (external load) demands in comparison to large-sided games [22]. However, depending on the format and particularly the number of players involved, in relation to the area per player available [23], external loading in small- and medium-sided games could potentially be more intensive than peak periods observed in official match-play format particularly in relation to the frequencies of accelerations and decelerations and player load [24]. Rules can also impact the physiological demands of small-sided games [25]. Accordingly, the number of players (i.e., area per player) and rules should be adjusted to ensure that the physiological impact of these training sessions is not too intensive. Future research should examine whether this is the case or not across academies.

Here, the greatest training load was reported on MD-4 and MD-3. The external loads experienced by players on these days (farthest away from match-day) usually aim to replicate competitive demands [17, 26]. As such, practitioners reported the greatest expected difficulty, and number of physical development sessions during these two days. Increases in dissociated training contents were observed during these two days with the greatest number of lower-body strength sessions, intermittent aerobic, repeated sprint, and plyometric exercises. Hence, it would seem that the dissociated training contents were perceived as more efficient than integrated contents to develop players' physical qualities.

Practitioners often reported using small-sided games on MD-4. Small-sided games have been shown to induce greater neuromuscular constraints (i.e., accelerations and decelerations) than other forms of integrated training [27, 28]. During this day, the amount of strength training reported by practitioners was greater compared to the other days, but was still very low. Indeed, our results highlighted that very few lower-body strength and plyometric sessions (33.3% and 31.1% of the practitioners, respectively) were programmed. Dissociated strength and plyometrics training contents should be emphasized further to favor neuromuscular development. It is well known that these dissociated exercises impose high neuromuscular stress that obviously favor strength development [29, 30].

During MD-4 and MD-3, coaches reported using aerobic development sessions. For this, both dissociated (intermittent and repeated-sprint aerobic exercises) and integrated training contents were used to develop aerobic quality. Such exercises appear in accordance with findings in the literature. A previous study for example, demonstrated that integrated contents can result in comparable aerobic improvements to dissociated contents [31].

Speed development training was only occasionally reported. To train this component, practitioners prioritized integrated contents with large-sided games. This choice can be legitimized by the greater high intensity demands imposed by large-sided games as compared to other integrated training forms [28]. However, as for strength development, implementing dissociated speed situations could optimize training efficiency through better control of sprinting exercises (e.g., a set number of sprints) [32].

A decrease in the training load (expected difficulty and physical importance) was observed two days prior to the match (MD-2 and MD-1). This is highlighted by the almost complete absence of voluminous and double sessions per day. On MD-2 and MD-1, speed and tapering were the primary focuses. This tapering method is commonly observed in soccer during the final two days leading up to competition [2, 5, 33, 34]. On MD-2, practitioners reported an increased use of medium- and large-sided games and dissociated speed sessions. The implementation of large-sided games and dissociated speed training are a mismatch with the expected training objectives. Indeed, these sessions might favor physical development over tapering as a large amount of high speed running can lead to neuromuscular impairments still observable 48 h post training intervention [35]. Reduced distances [33] should be favored to limit unexpected impairments potentially detrimental for the subsequent match.

On MD-1, most coaches used similar content. Small-sided games and reactivity drills were extensively performed. Previous studies also report the use of reactivity drills close to the competition [8, 19]. Small-sided games do not involve significant demands for high-speed running [28]. We could hypothesize that high-speed running is reduced to limit excessive demands and reduce delayed onset of fatigue. However, small-sided games do result in a large number of accelerations and decelerations [28, 36] potentially resulting in neuromuscular impairments [22]. The present results are not consistent with previous findings for MD-1 since most studies reported light training loads [4, 17, 37], and low-load exercises [17]. The contents implemented during MD-2 and MD-1 do not appear to support the tapering strategy aimed for by practitioners.

Limitations

Limitations in the present study include potential bias related to the coaches' willingness to share information. Furthermore, this study only solely reflects the convenience of the teams' consideration and therefore their strength and conditioning coaches, which is a inherent bias of research of this nature. This survey aimed to describe the weekly collective periodization strategy and as a result, individualized sessions were not considered. It would have been of interest to precisely determine training workload through the week using external and internal measures such as GPS and HR. Moreover, although a substantial number of teams (n = 45) completed the present survey, additional responses would potentially have increased knowledge of academies' weekly periodization strategies. Additional respondents, and from different countries, would have increased the opportunities to identify different strategies for optimal conditioning for match-play.

Practical applications

The present survey revealed that coaches placed more emphasis on physical development than match result. Yet, this result is contraindicatory since only two training sessions per week were dedicated to physical development. MD+1 and MD+2 were mainly dedicated to recovery, and MD-2 and MD-1 to tapering. This type of periodization is comparable to professional teams that mainly focus on competition rather than development. To favor player development, we propose to implement more dissociated contents. Dissociated strength sessions should be performed more than once a week to generate larger improvements [38, 39]. We also propose to change MD-1 training contents with more tactical contents to support the tapering strategy and potentially ensure a better level of readiness on MD.

CONCLUSIONS

This study showed that although emphasis was placed upon physical development by practitioners, in reality this was only really performed over two days (MD-4 and MD-3). Our results revealed discrepancies between the physical objectives set for each day and the content actually implemented, which potentially could be more physically demanding than expected. Further studies should clarify the fatigue caused by each training session to ensure that training periodization matches practitioners' expectations.

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Authors' contribution

TD, CP and NB participated in the study design. TD performed the data analysis, interpretation, and results and produced the first draft of the present manuscript. All authors contributed to data collection in the manuscript revisions. All authors approved the final version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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SUPPLEMENTARY TABLES

TABLE S1. Questionnaire used during the present study.

Questions	Responses	Other information
Q1 – By clicking 'Yes', you give your informed consent to your voluntary participation.	Yes, No	
Q2 – How important is the players' physical development in comparison to matches' results?	Linear scale from 1 (not important at all) to 10 (very important)	
Q3 – Do you realise a training session on this day?	Yes, No	Duplicate question if additional training/ day – Close-ended question
Q4 – What is the duration of the session?	Up to 30 min, More than 30 min and up to 60 min, More than 60 min and up to 90 min, More than 90 min	Duplicate question if additional training/ day – Close-ended question
Q5 – How much physical work is done during the training session?	Linear scale from 1 (no physical work at all) to 10 (only physical work)	Duplicate question if additional training/ day – Close-ended question
Q6 – What is(are) the physical aim(s) of the training session?	No physical aim, Active recovery, Tapering, Maintenance, Development, Speed, Aerobic, Strength, Prophylactic work	Duplicate question if additional training/ day – Close-ended question * Multiple responses
Q7 – How is practiced the main physical work?	Integrated, Dissociated on the field, Dissociated outside of the field, No physical work	Duplicate question if additional training/ day – Close-ended question
Q8 – Which exercise(s) is(are) used during this session?	Small sided games, Medium sided games, Large sided games, Rondo, Technical drills, Passing circuit, Football tennis, Aerobic technical drills, Others	If Q7 is 'Integrated' Duplicate question if additional training/ day – Close-ended question * Multiple responses
Q9 – Which exercise(s) is(are) used during this session?	Upper body strength session, Lower body strength session, Speed, Reactivity, Continuous aerobic work, Intermittent aerobic work, Repeated sprint aerobic work, Plyometric work, Coordination, Others	If Q7 is 'Dissociated on the field' or 'Dissociated outside of the field' Duplicate question if additional training/ day – Close-ended question * Multiple responses
Q10 – What is the duration of this work?	Up to 20 min, More than 20 min and up to 40 min, More than 40 min and up to 60 min, More than 60 min	If Q7 is 'Integrated' Duplicate question if additional training/ day – Close-ended question
Q11 – What is the expected difficulty of this session?	Linear scale from 1 (very very easy) to 10 (maximal)	Duplicate question if additional training/ day – Close-ended question
Q12 – Do you practice another training session on this day?	Yes, No	Duplicate question if additional training/ day – Close-ended question
Q13 – In your opinion, what changes could you operate in your weekly periodization, in order to optimize the players' physical development, and without negatively impacting match performance?		Open-ended question
Q14 – What is the level of your team?	Academy, Professional, Amateur	Close-ended question
Q15 – What is the gender of the players?	Female, Male	Close-ended question
Q16 – Which category do you coach?	Adults, U18/U19, U16/U17, Others	Close-ended question
Q17 – What is your role inside the team?	Coach, Strength and conditioning coach, Others	Close-ended question
Q18 – What is your education?	Bachelor, Master's degree, Federal education, University diploma, Others	Close-ended question
Q17 – How long have you been coaching?	Up to 1 year, More than 1 year and up to 3 years, More than 3 years and up to 5 years, More than 5 years and up to 10 years, More than 10 years	Close-ended question

TABLE S2. Respondents' information.

Gender	
Male	45 (100%)
Female	0 (0%)
Role	
Coach	1 (2.2%)
Strength and conditioning coach	44 (97.8%)
Other	0 (0%)
Education $	
Bachelor	8 (10.1%)
Master degree	31 (39.2%)
Federal education	18 (22.8%)
Other diploma from University	20 (25.3%)
Other	2 (2.5%)
Experience	
Up to 1 year	0 (0%)
More than 1 year and up to 3 years	8 (17.8%)
More than 3 years and up to 5 years	12 (26.7%)
More than 5 years and up to 10 years	17 (37.7%)
More than 10 years	8 (17.8%)

Values are presented as the number of responses and as the percentage of the total number of answers for the question. Questions with the possibility to give multiple responses ($).

TABLE S3. Periodization improvements.

In your opinion, what changes could you operate in your weekly periodization, in order to optimize the players' physical development, and without negatively impacting match performance? $	
Number of answers for the question	**45**
Change the session schedule	3 (6.7%)
Add lower body strength sessions	4 (8.9%)
Improve training load monitoring	2 (4.4%)
Add more sessions / increase training volume	11 (24.4%)
Decrease the number of sessions	1 (2.2%)
Change the physical aim of the days	4 (8.9%)
Add dissociated work	1 (2.2%)
Improve individualisation	3 (6.7%)
Add a training the morning preceding the match	2 (4.4%)
Improve tapering close to the match	2 (4.4%)
No possibility	1 (2.2%)
No response	11 (24.4%)

Values are presented as the number of responses and as the percentage of the total number of answers (n) for the question as reported below the question. Answers were grouped according to their similar nature.

TABLE S4. Typical microcycle.

Day	Description
MD+1	Recovery or One 30–60 min training session – Active recovery – Continuous aerobic work – Upper body strength session
MD+2	One 60–90 min aerobic development session – Passing circuit – Small- medium-sided games
MD-4	One/two 60–90 min strength development sessions – Small- sided games – Upper/lower body strength sessions – Plyometric exercises
MD-3	One 60–90 min aerobic/strength development session – Large-sided games – Repeated sprint aerobic exercises
MD-2	One 60–90 min speed session – Small- and medium-sided games – dissociated speed – reactivity
MD-1	One 30–60 min tapering session – small-sided games – reactivity

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Taurine supplementation enhances anaerobic power in elite speed skaters: A double-blind, randomized, placebo-controlled, crossover study

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ABSTRACT: Taurine (2-aminoethanesulfonic acid) is a semi-essential sulphur-containing amino acid abundant in skeletal muscle. Taurine supplementation is popular among athletes and has been purported to enhance exercise performance. This study aimed to investigate the ergogenic effects of taurine supplementation on anaerobic (Wingate; WanT) performance, blood lactate, ratings of perceived exertion (RPE), and countermovement vertical jump (CMJ) in elite athletes. For this study, randomized, double-blind, placebo-controlled crossover designs were used. Thirty young male speed skaters were randomly assigned to either taurine (TAU; single dose of 6 g) or placebo (PLAC; single dose of 6 g) 60 minutes before testing. Following a 72-hour washout, period participants completed the opposite condition. TAU improved peak ($\Delta\% = 13.41$, $p < 0.001$, $d = 1.71$), mean ($\Delta\% = 3.95$, $p = 0.002$, $d = 1.04$), and minimum power output ($\Delta\% = 7.89$, $p = 0.034$, $d = 0.48$) compared to placebo. Further, RPE ($\Delta\% = -10.98$, $p = 0.002$, $d = 0.46$) was significantly lower following the WanT in the TAU condition compared to placebo. There were no differences between conditions for the countermovement vertical jump. In conclusion, acute TAU supplementation augments anaerobic performance in elite speed skaters.

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Anaerobic Power
CMJ
Fatigue
Taurine
Wingate

INTRODUCTION

Taurine (TAU) is an essential amino acid derived from cysteine metabolism, and this sulphur-containing component is abundant in skeletal muscle [1]. Despite mixed or limited evidence supporting its efficacy, TAU is a popular purported ergogenic aid in athletes [2]. Mechanistically, taurine, generated from cysteine metabolism, plays a vital role in various physiological and metabolic actions [3, 4], including antioxidant pathways, lipid or glucose oxidation, anti-inflammatory modulation, and energy metabolism provision [1]. As such, TAU has been purported to improve exercise performance. Taurine ingestion causes taurine plasma concentrations to rise within 10 minutes and peaks within 60 minutes (0.03 to 0.06 mmoL). Taurine plasma concentrations typically return to baseline after 6.5 hours following ingestion [5].

When performing the high-intensity anaerobic exercise, blood lactate (BLa) and hydrogen ions (H^+) concentrations increase, declining the muscle cell pH [6] and lowering its ability to produce adenosine triphosphate (ATP) required for sustained muscle contractions [7]. A 30-seconds (s) Wingate test (WanT), has been widely used due to its ability to assess non-oxidative energy metabolism [8]. Accumulation of H^+ during WanT suppresses resynthesis of phosphocreatine (PCr) and phosphofructokinase enzyme activity (which is the rate-limiting enzyme involved in anaerobic glycolysis) and both contributing to muscular fatigue [9]. Specifically, fatigue is defined as a decline in the ability to create power [10]. Furthermore, the countermovement jump (CMJ) test is a practical method for evaluating neuromuscular fatigue (NMF) [11], adaptations associated with training [12], and recovery status [13] making it a handy tool for measuring muscle fatigue/recovery in athletes [14]. Along with jump height, force and power production during the CMJ are directly related to the total jump time. This lower body extremity muscle power output [15]. A decrease in CMJ performance after exercise is considered a helpful tool for monitoring the neuromuscular state [16].

When the experimental [17–19] and meta-analysis [20] studies on taurine are examined, it is seen that there is no consensus on its

positive effects in terms of performance. In addition, it is thought that the elite population of our choice and the effect it will have on performance may be the focus of attention of those who do sports at the elite level. In this study, thirty young male speed skaters were subjected to the WanT test after TAU supplementation, and primarily their anaerobic performance was evaluated. There was a reason why especially speed skaters were chosen in the study. Speed skating is divided into two primary categories: short-track and long-track racing [21]. A sports discipline with a higher physiological demand is practiced on a short-track. The biomechanically advantageous crouching position, which is necessary for speed skating performance, must be adopted by skaters [22]. An inclined posture, due to the nature of this sport, results in physiological drawbacks, such as deoxygenation of active muscles [23]. A decrease in tissue pO2 can be detected by changes in muscle oxygenation, which may then be related to performance and fatigue [24]. In these circumstances, glycolysis will serve as the primary energy source for the muscle fibers, potentially aggravating fatigue [23]. It has been stated that taurine has lactate-lowering activity due to its buffering effect [25, 26]. This is probably owing to a potential interaction between taurine and calcium's function as a buffer in the mitochondria. Taurine can help keep mitochondrial activity intact during exercise and improve the buffering capacities of the cells [27].

In addition, success in short-track skating depends not only on the skater's excellent riding technique but also, and perhaps more importantly, on the high speed that is created thanks to the power of the lower limbs, which converts into work including anaerobic alterations [28]. Taurine helps release Ca^{2+} from the sarcoplasmic reticulum, enhancing the sensitivity of force-generating myofilaments in skeletal muscle [4], resulting in an increase in muscular force [3] and better performance results.

Another point that should be mentioned in terms of anaerobic performance is the antioxidant activity of taurine. Studies have indicated taurine's capacity to serve as an antioxidant, which may create an enhanced cellular environment to handle exercise- induced oxidative stress [29, 30]. Since the speed skater is a high-intensity branch, free radicals are formed. Free radical generation might harm cellular components, following high-intensity exercise [31]. Due to the presence of sulfonic acid, Taurine, which induces the conversion of extremely cytotoxic chemicals like chloride and hypochlorous acid into stable chloramine, and it has been referred to as a powerful antioxidant [32]. The body cannot produce enough taurine under conditions of high intensity exercise, highlighting the need of taurine-based dietary supplements [33]. Hence, using antioxidant supplements, like taurine, after exercise aims to reduce oxidative stress and possibly improve performance [34].

At the same time, TAU is classified as non-essential amino acid and it has an effect on brain metabolism (via regulating neural transmission) [35]. TAU plays the role of an extra synaptic GABAA receptor agonist, which can boost network activity at many brain locations, including the thalamus [36]. Although taurine differs from other amino acid-based supplements in this respect, when we look closely at the literature, there are scarcely any studies examining the effect of taurine on neuromuscular fatigue [33]. Regrettably, research on the effect of fast or practice alternative supplements on sportive performance and brain metabolism is very limited because studies have mostly focused on examining the long-term supplement use effects. Therefore, this study focused on the hypothesis that acute intake of TAU would improve athletic performance without affecting neuromuscular fatigue.

Furthermore, it is unclear whether TAU may be considered ergogenic for elite athletes participating in anaerobic sports (e.g., speed skating) and whether TAU alters post-exercise NMF. Hence, the objectives of this study were: (a) to evaluate the ergogenic effect of TAU on WanT performance in elite athletes and (b) to determine its effects on post-exercise BLa and possible decrease in CMJ. We hypothesize that TAU will improve anaerobic performance (WanT) and BLa concentration without altering exercise NMF.

MATERIALS AND METHODS

Participants

Thirty male short-track speed skaters (age: 23.9 ± 2.8 years, body mass: 76.18 ± 2.8 kg, height: 177.54 ± 7.6 cm, BMI: 23.9 ± 3.7 kg/m^2; training experience:11.4 ± 3.4 years) were a part of Turkey's Olympic Preparation Centre team volunteered (Table 1). The weekly training program consisted of strength training 2.0 ± 0.1 sessions $\cdot$ wk^{-1} and endurance training 3.0 ± 0.1 sessions $\cdot$ wk^{-1} and was completed by all the participants. Since the sports dietitian controlled the food consumption of all participants, 24-hour dietary recalls were taken in this study. The carbohydrates (g $\cdot$ kg^{-1}), protein (g $\cdot$ kg^{-1}), fat (g $\cdot$ kg^{-1}), and total energy (kcal) values of each food in these records were obtained from the TURKOMP database (http://www.turkomp.gov.tr/database) (TURKOMP is a food composition database that includes nutritional components and energy values of the wide variety of foods produced and consumed in Turkey) [37]. The daily macronutrient intakes were calculated in excel sheets for all participants. The average values of macronutrients (carbohydrates (g $\cdot$ kg^{-1}), protein (g $\cdot$ kg^{-1}), fat (g $\cdot$ kg^{-1}), and total energy (kcal)) calculated in Excel are summarized.

To take part in the study, researchers verbally verified that all of the volunteers met the inclusion/exclusion criteria a) participants were not taking any dietary supplements within the past three months before the start of the study, b) participants did not smoke, c) participants were healthy with no diagnoses of cardiovascular, respiratory, or metabolic diseases which may impair muscle biology, d) had no orthopedic injury that would impact cycling performance and e) had to have previous experience of performing high-intensity exercise. Before signing an informed consent form, all participants were briefed about the procedures and risks. All the experimental testing sessions were carried out at Atatürk University Athlete Performance Measurement Evaluation and Rehabilitation Center. This study was supported by the Research Fund of Ataturk University. Project Number: 10115.

TABLE 1. Participant Characteristics

Variables	Male athletes (n = 30)	
	mean ± SD	[95% CI]
Age (years)	23.90 ± 2.80	[22.00, 24.00]
Training experience (years)	11.40 ± 3.40	[9.78, 12.99]
Body mass (kg)	76.18 ± 2.80	[75.00, 77.00]
Height (m)	1.77 ± 7.60	[1.74, 1.79]
BMI (kg/m^2)	23.90 ± 3.70	[21.68, 24.32]
ST frequency (sessions per week)	2.00 ± 0.10	[1.96, 2.04]
ET frequency (sessions per week)	3.00 ± 0.10	[2.96, 3.04]
Total energy intake (kcal)	2900 ± 243	[2813, 2986]
Carbohydrate intake (g·kg^{-1})	4.50 ± 0.10	[3.96, 4.04]
Protein intake (g·kg^{-1})	2.20 ± 0.10	[2.16, 2.24]
Fat intake (g·kg^{-1})	1.00 ± 0.50	[0.82, 1.18]

Abbreviations: The mean and standard deviation [95% CI] are used to represent the data. ST: strength training, ET: endurance training, kcal: kilocalories; g/kg^{-1}: grams per kilogram of body mass.

Study Design

A randomized, double-blind, placebo-controlled, crossover study was used. All testing sessions were completed within a 72-hour time frame to minimize training effects and were finished at the same time of day (within ~0.5 hours) to reduce any biological variability due to circadian rhythm [38]. Each visit was separated by no more than 72 h for each participant, which was deemed sufficient to wash out taurine based on a half-life of between 70 and 100 minutes [18]. Participants were randomized to receive either placebo (PLAC) or TAU supplementation on the first experimental session and the opposite condition on the second experimental session using a computerized randomization software (GraphPad, San Diego, USA; available at: https://www.graphpad.com/quickcalcs/randomize1.cfm).

Following acute supplementation, participants complete a series of physical performance tests including a Wingate anaerobic test (WanT) and a counter movement jump test (CMJ) to assess neuromuscular fatigue. The CMJ was performed immediately before and after the WanT and 3 min post WanT. Further, blood lactate (BLa) was assessed at baseline (rest) and post-WanT (immediately and 3.5 min after completion). An overview of the experimental protocols is shown (Figure 1).

Supplementations and Dietary Control

Participants were instructed to visit the laboratory ~90 minutes before the start of WanT and to ingest the supplement 60 minutes before the performance tests. Participants ingested either TAU (single dose of 6 g) or an isovolumetric isocaloric PLAC (single dose of 6 g of starch supplement). The supplements were provided in liquid form, mixed with 500 mL of water. TAU and PLAC supplementation was given 60 minutes before measurements because TAU plasma concentrations peak at 1 hour [39]. Seventy-two hours before the start of each experimental condition, participants were instructed to follow nutritional guidelines, which dietitians monitored to ensure similar nutrient intake before both conditions. Furthermore, participants were instructed to avoid caffeine within seventy-two hours of the experimental sessions.

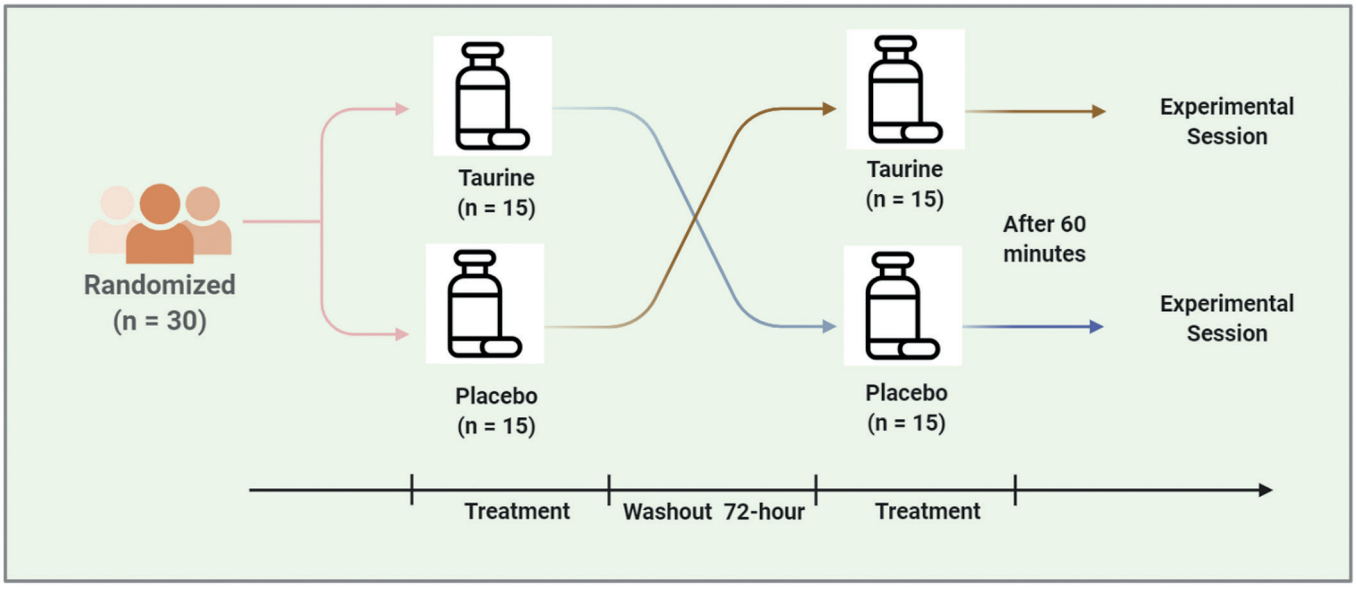


FIG. 1. Summary of the experimental session.

Rating of Perceived Exertion (RPE)

The Borg Scale (6–20) is a valuable indicator of personal effort and is commonly used in exercise science, also known as RPE [40]. Rating of perceived exertion was recorded immediately after each WanT.

Blood Lactate

Blood lactate was measured at three-time points: at rest (baseline), immediately after completion of the WanT (L-post), and 3.5 minutes during recovery (L-post-3.5). Blood samples (5 μl) were taken from the tip of the index finger of the left hand using the Lactate Scout 4 (Leipzig, Germany) analyzer and following manufacturing instructions.

Neuromuscular Fatigue

CMJ performance was measured before and after the WanT using a pre-determined protocol that has been previously described [41]. CMJ was assessed at three different time points: baseline, immediately after the WanT (CMJ post), and 3 minutes after WanT (CMJ post-3). At each time point, participants performed two CMJ separated by a 45-s rest period using a force platform (Microgate Opto Jump, Mahopac-USA): before WanT (CMJ-pre). The mean values of peak power (PP), jump total time (TT), mean power (MP), and from the two CMJ measurements were recorded. Peak power measurement is calculated automatically from the program according to the formula below [42].

$$\text{Peak Power (Watts)} = [60.7 \times \text{Jump Height (cm)}] + [45.3 \times \text{Body Mass (kg)}] - 2055$$

Wingate Anaerobic Test (WanT)

WanT was conducted according to previously published protocols. The WanT was completed on a Monark cycle ergometer (Monark Classic Ergomedic 894E, Vansbro, Sweden). The participants' feet were fixed onto the pedals and seat height was adjusted to ensure near full extension at the bottom of each pedal revolution. The seat height and position were recorded and replicated for each condition. The load on the front basket was set at 7.5% of the participant's body mass (kg). The participants were asked to go as fast as possible before engaging the resistance. The participants then maintained an "all-out" effort for 30-s [8, 9]. Each participant was encouraged with standardized verbal encouragement throughout the WanT. During the test, power output (W) was recorded every second. Peak power output, time to reach peak power, minimum power output and average power output were extracted for data analysis. The lowest power recorded in the final 10-s of the test was defined as the minimum power. Average power was calculated separately for five-second splits, 6 times for a total of 5-s, WanT ($W_split_{0–5}$, $W_split_{5–10}$, $W_split_{10–15}$, $W_split_{15–20}$, $W_split_{20–25}$, and $W_split_{25–30}$).

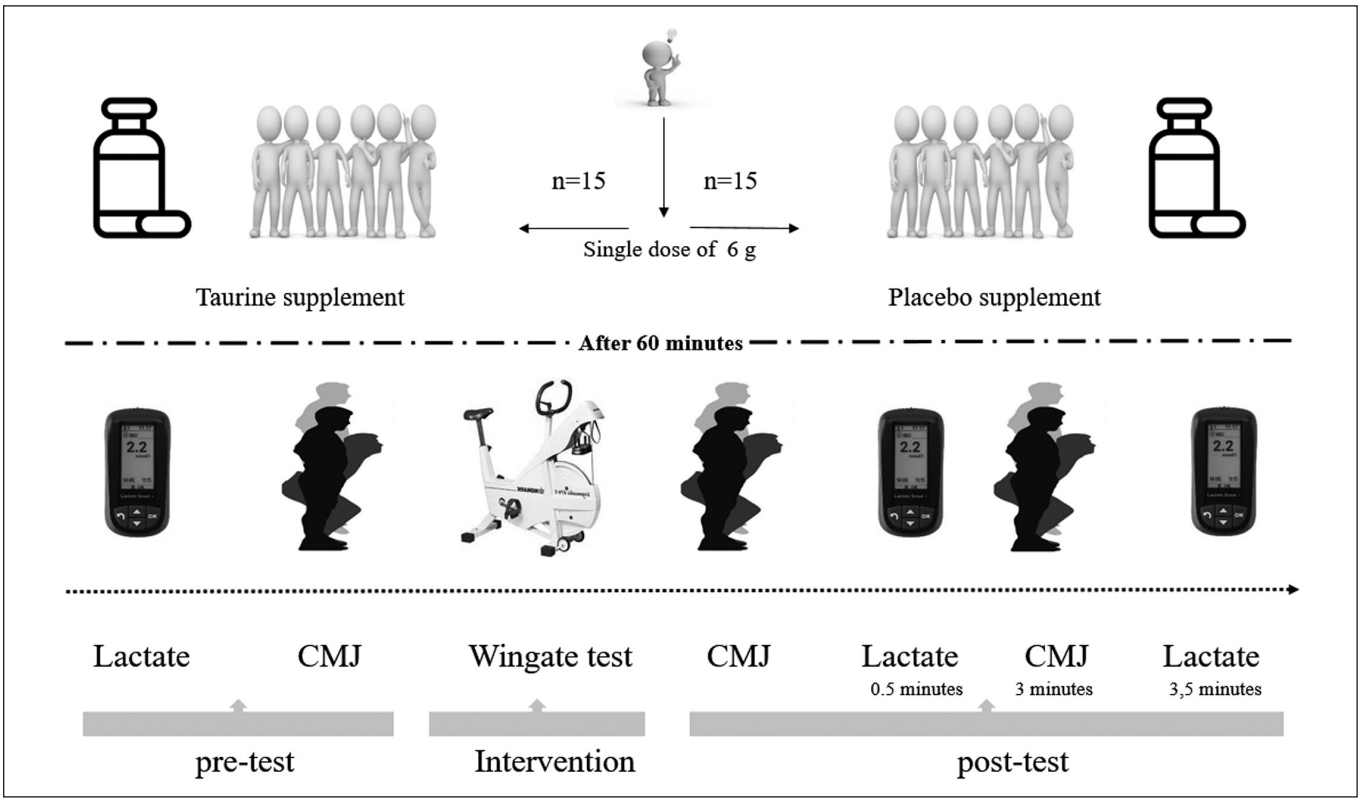


FIG. 2. Visualization flow of the experimental procedure.

Familiarization

All participants participating in the research were determined within the scope of the project. Participants were already familiar with the Want test protocol as they were elite athletes. However, in order to avoid any problems, all participants were informed about the practice/trial process and the exercise to be applied. Then, one week before the exercise protocol, all participants were brought together and the Want test protocol was applied. Thus, it has gone through the habituation/trial process. A predetermined visualized experiment flow chart was created for this study within the scope of the project. All experimental procedures (other details of the implementation/testing phase) are summarized (Figure 2).

Statistical analysis

The data are shown as [95% CI], mean and standard deviation (SD). The significance level for all analyses was accepted as $p < 0.05$. The Shapiro-Wilk test was preferred because the sample sizes ($n < 50$) were low [43]. The WanT was analyzed using a dependent t-test following confirmation of normality via the Shapiro-Wilk test and if data were non-normally distributed, the Wilcoxon test was applied. For BLa and NMF, a supplementation by time analysis of variance for repeated measurements (ANOVA-RM) was used, whereas for split-specific mean power, a supplementation by split ANOVA-RM was used. Compliance with the sphericity assumption was checked with Mauchly's test. In the conditions where the sphericity assumption was not met ($p < 0.05$), Epsilon (ε) values were examined for the degrees of freedom, Greenhouse-Geisser correction was applied for $\varepsilon < 0.75$, and Huyn-Feldt correction was applied for $\varepsilon > 0.75$. The effect size was calculated with the partial eta squared coefficient (η_p^2) and classified as 0.099 = small, 0.0588 = moderate, 0.1379 = large effect [44]. The effect size of Cohen's d was calculated, with values > 0.8, 0.5–0.8, 0.2–0.5, and < 0.2 being considered high, moderate, small, and trivial, respectively for pairwise comparisons [45]. SPSS software (IBM Corp. Released 2016. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp) was used for all statistical analyses.

TABLE 2. Effects of TAU supplementation on WanT power output

	PLAC		TAU					
	mean ± SD	**[95% CI]**	**mean ± SD**	**[95% CI]**	**D%**	**t**	***p***	**d**
P_{peak} (W)	894.03 ± 105.47	[856.43, 931.57]	1014.7 ± 183.02	[948.51, 1079.4]	13.41	4.524	**< 0.001**	1.71
P_{peak} (W/kg)	10.84 ± 0.89	[10.32, 11.36]	12.80 ± 1.87	[11.72, 13.89]	18.08	3.534	**0.003**	1.36
P_{mean} (W)	657.09 ± 119.25	[614.42, 699.58]	683.90 ± 105.20	[645.43, 720.57]	3.95	3.787	**0.002**	1.04
P_{min} (W)	423.87 ± 93.83	[389.72, 456.28]	457.32 ± 104.85	[419.78, 494.22]	7.89	2.235	**0.034**	0.48
T_P_{peak} (s)	8.85 ± 0.77	[8.41, 9.30]	6.82 ± 1.03	[6.22, 7.41]	-22.93	5.920	**< 0.001**	2.23
RPE (score)	17.11 ± 3.77	[15.93, 18.07]	15.23 ± 4.32	[13.45, 16.55]	-10.98	3.985	**0.002**	0.46

Abbreviations: WanT: Wingate anaerobic test, TAU: taurine, PLAC: placebo, D%: percentage difference from PLAC, P_{peak}: peak power, P_{mean}: mean power; P_{min}: minimum power, 95% CI: 95% confidence interval, T_P_{peak}: time to reach, *d*: Cohen's *d* effect size, RPE: Rating of Perceived Exertion, mean ± SD: mean ± standard deviation.

TABLE 3. During WanT, mean power output was measured in 5-s splits.

	PLAC		TAU		Statistical significance		
	mean ± SD	**[95% CI]**	**mean ± SD**	**[95% CI]**	**supplement**	**time**	**supplement × time**
$split_{0–5}$	700.38 ± 106.68	[662.07, 737.93]	766.59 ± 109.28	[726.99, 805.01]			
$split_{5–10}$ †	761.28 ± 119.45	[718.42, 803.60]	886.67 ± 125.00	[841.27, 930.73]			
$split_{10–15}$ †ǯ	725.16 ± 109.45	[685.99, 764.20]	822.88 ± 115.21	[780.85, 863.15]			
$split_{15–20}$ ǯ	709.16 ± 148.98	[656.04, 761.96]	760.71 ± 109.25	[720.99, 799.01]	**< 0.001**	**0.003**	0.407
$split_{20–25}$ ǯΣ	681.97 ± 118.31	[638.77, 723.23]	707.85 ± 118.77	[664.77, 749.23]			
$split_{25–30}$ †ǯΣΦ	655.78 ± 119.86	[614.42, 697.58]	680.71 ± 105.63	[642.43, 717.57]			

Abbreviations: WanT: Wingate anaerobic test, 95% CI: 95% confidence interval, TAU: taurine, PLAC: placebo, †: significantly different ($p < 0.001$) from $split_{0–5}$, ǯ: significantly different ($p < 0.001$) from $split_{5–10,}$ Σ: significantly different ($p < 0.001$) from $split_{15–20}$, Φ: significantly different ($p < 0.001$) from $split_{20–25}$, mean ± SD: mean ± standard deviation.

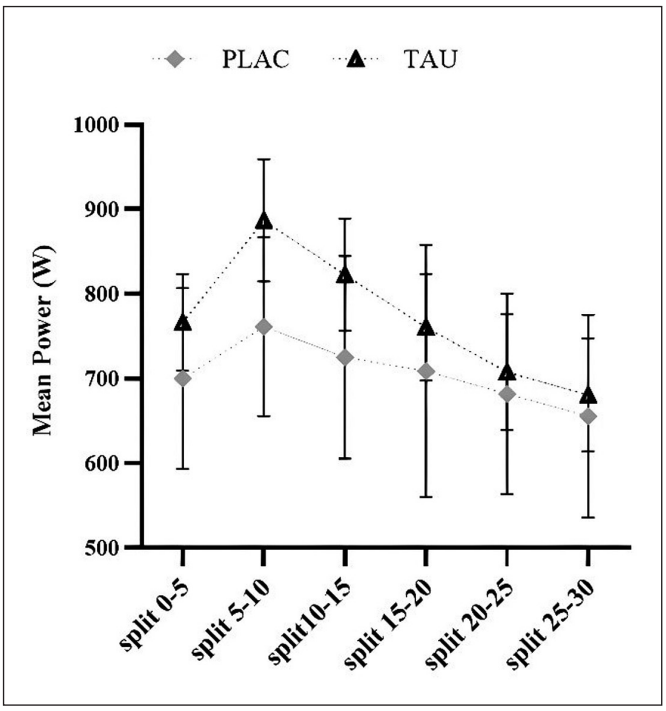


FIG. 3. 5-s split graphical representation of average power output during Wingate anaerobic test.

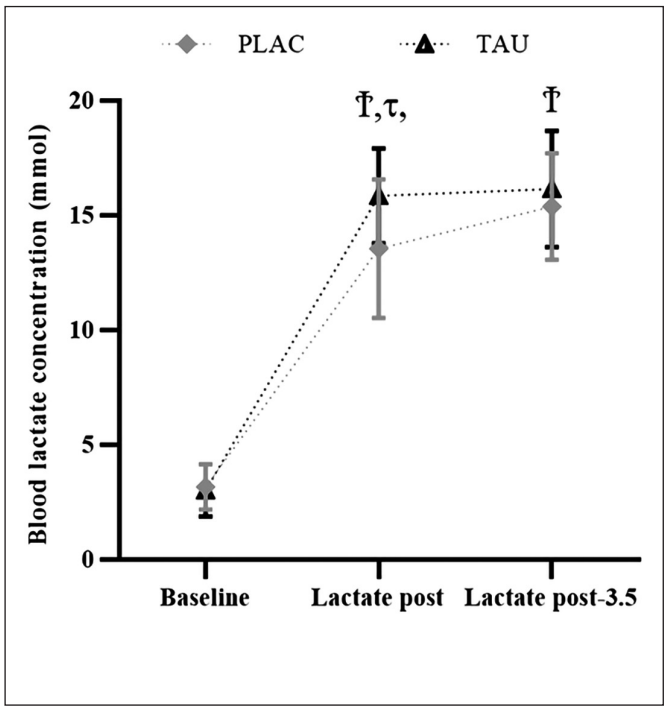


FIG. 4. This figure shows the mean ± [95% CI] for blood lactate concentration registered at Lactate pre, Lactate post, and Lactate post-3.5 τ: significant differences between TAU and PLAC ($p < 0.05$), †: significant differences from Lactate pre ($p < 0.05$).

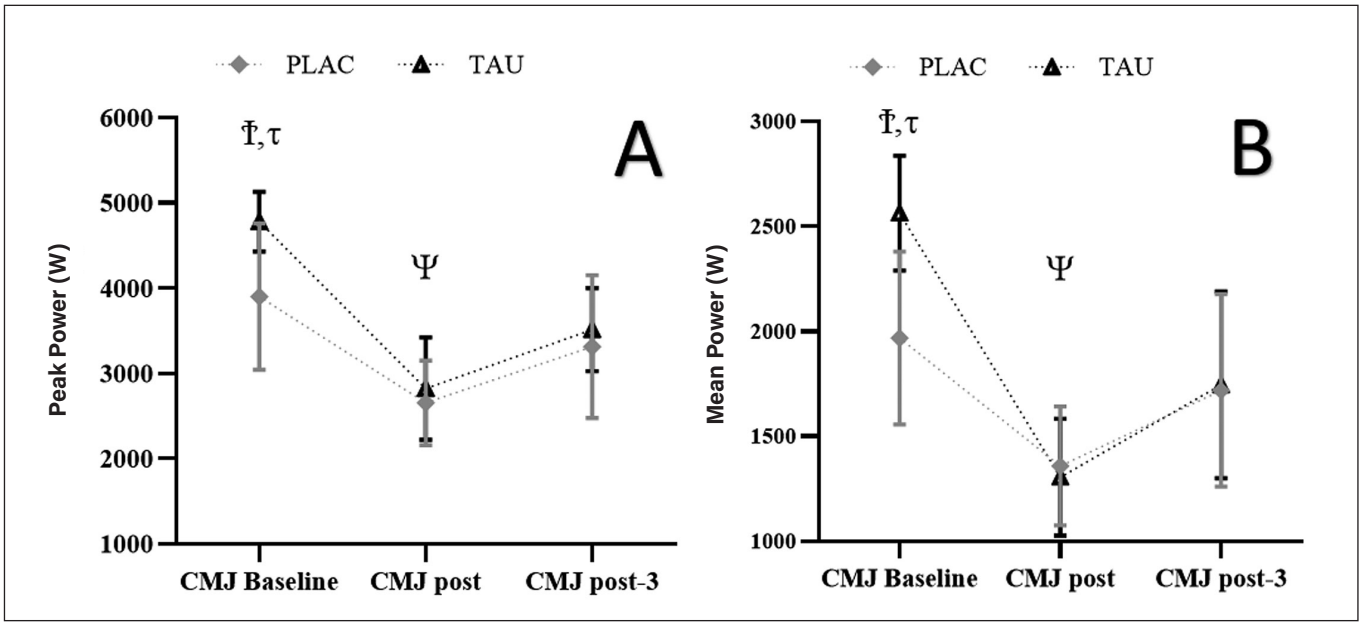


FIG. 5. This figure shows the mean ± [95% CI] for PP (A) and MP (B) registered at CMJ pre, CMJ post, and CMJ post-3. **τ**: significant difference ($p < 0.01$) between TAU and PLAC, **Ψ**: significant difference ($p < 0.001$) compared to post-3 for TAU and PLAC, **†**: significant difference ($p < 0.001$) compared to post and post-3 for TAU and PLAC.

RESULTS

Wingate test performance

Enhanced P_{peak} (W) (D% = 13.41; t = 4.524; $p < 0.001$; d = 1.71), P_{peak} (W/kg) (D% = 18.08; t = 3.534; $p < 0.003$; d = 1.36), P_{mean} (D% = 3.95; t = 3.787; $p < 0.002$; d = 1.04), P_{min} (D% = 7.89; t = 2.235; $p < 0.034$; d = 0.48) and along with decreased T_P_{peak} (D% = -22.93; t = 5.920; $p < 0.001$; d = 2.23), and RPE (D% = -10.98; t = 3.985; $p < 0.002$; d = 0 .46) were indicated in the WanT for the TAU condition, compared to PLAC (Table 2). Consequently, there was a higher mean power output for TAU, compared to PLAC (683.90 ± 105.20 vs. 657.09 ± 119.25 W).

The findings of comparing mean power statistics across splits are detailed (Table 3 and Figure 3). An effect of supplementation ($F_{1,13} = 30.65$; $p < 0.001$; $\eta_p^2 = 0.78$) and Time ($F_{3.632, 47.21} = 4.839$; $p < 0.003$; $\eta_p^2 = 0.85$), with no Supplementation × Time interaction ($F_{3.478, 45.21} = 1.005$; $p = 0.407$; $\eta_p^2 = 0.24$), as during WanT protocol, it was discovered for mean power measured in 6 splits of 5-s each.

Blood lactate concentration

This study analysis unveiled an effect of Time ($F_{2,78} = 301.4$; $p < 0.001$; $\eta_p^2 = 0.365$), Supplementation ($F_{1,78} = 4.274$; $p < 0.001$; $\eta_p^2 = 0.95$), and a Supplementation × Time interaction ($F_{2,78} = 2.362$; $p < 0.024$; $\eta_p^2 = 0.29$). BLa was ascertained to be raised ($p < 0.001$) at L-post and L-post-3.5, under both the TAU and PLAC conditions. BLa was also higher in the TAU condition at L-post ($\Delta\% = 16.99$; $p < 0.026$) and L-post-3.5 ($\Delta\% = 4.96$; $p < 0.041$), compared to PLAC (Figure 4).

Neuromuscular fatigue

A time effect was found for CMJ TT ($F_{1,96} = 2.920$; $p < 0.034$; $\eta_p^2 = 0.78$), with greater CMJ post measurement noted compared to CMJ post-3 (0.95 ± 0.21 vs. 0.69 ± 0.14; $p < 0.044$). The supplementation effect ($F_{1,06} = 0.184$; $p = 0.652$; $\eta_p^2 = 0.09$) and Supplementation × Time interaction ($F_{1,96} = 0.179$; $p = 0.703$; $\eta_p^2 = 0.04$) was both found to be non-significant.

For PP, there was a Supplementation by Time interaction ($F_{1,96} = 3.120$; $p < 0.028$; $\eta_p^2 = 0.34$) as well as a Time effect ($F_{1.489, 9.547} = 116.754$; $p < 0.001$; $\eta_p^2 = 0.92$) but no Supplementation effect ($F_{1,06} = 2,985$; $p = 0.063$; $\eta_p^2 = 0.13$). For all circumstances, greater measurements ($p < 0.001$) were found at CMJ pre, compared to CMJ post and CMJ post-3, while smaller values ($p = 0.001$) were found at CMJ post, compared to CMJ post-3. Furthermore, TAU had a greater PP at CMJ pre compared to PLAC (3.900 ± 860 vs. 4780 ± 548 W; $p < 0.022$; Figure 5A.

For MP, there was a Supplementation by Time interaction ($F_{1,96} = 3.745$; $p < 0.035$; $\eta_p^2 = 0.26$) and a Time effect $F_{1.863, 24.421} = 132.754$; $p < 0.001$; $\eta_p^2 = 0.78$) but no Supplementation effect ($F_{1,06} = 3.234$; $p = 0.074$; $\eta_p^2 = 0.16$). For all circumstances, greater values ($p < 0.001$) were found at CMJpre, compared to CMJ post and CMJ post-3, while smaller values ($p < 0.001$) were found at CMJ post, compared to CMJ post-3. Furthermore, TAU had a higher MP at CMJ pre compared to PLAC (1968 ± 411 vs. 2563 ± 247 W; $p < 0.001$; Figure 5B.

DISCUSSION

The significant results from the study support our hypothesis that acute TAU supplementation enhances anaerobic power outputs without altering neuromuscular fatigue. According to our findings, TAU supplementation improves athletic performance and ameliorates athletes' functional response to training, but it does not influence fatigue concentration.

Compared to other studies, it appears that athletes ingesting TAU can enhance WanT performance leading to higher BLa compared to placebo. For example, the results of the study conducted by Y Matsuzaki, et al. [46] support our findings. Although speculation, the higher BLa concentration following anaerobic exercise with TAU compared to PLAC may be associated with factors related to the inhibitory mechanisms of adenosine receptors causing an increase in the mean power, as well as the assumption that there may be an increase in lactate production with the increase in the need for ATP by the phosphagen and glycolytic systems. When comparing BLa concentrations, the high BLa following TAU in L-post and L-post-3.5 is evidence of increased anaerobic glycolysis [47]. Further, the PP and MP values, which we determined as anaerobic power outputs, between TAU and PLAC conditions, were not significantly different between CMJpost and CMJpost-3 time points, and it was found to be at a lower level than CMJpre in both conditions. Again, this data is supported by previous literature [48, 49]. However, it is unclear which mechanisms are involved in TAU supplementation to influence CMJ performance. When evaluating the CMJpre state, it is assumed that PCr and RPE have little impact on performance. However, ADP and H^+ accumulation during CMJ assessment following WanT may alter muscular contraction force. The low or fully depleted PCr concentration after WanT may partially explain the reduced performance reported in the CMJpost and CMJpost-3. Additionally, considering the chemical process of PCr resynthesis, the upward tendency to jump performance observed in CMJpost-3 is likely the result of partial resynthesis of PCr reserves [50, 51].

When the literature was examined, studies evaluating anaerobic capacity and applied in different dosages were found. According to these studies, 1 g of taurine supplementation taken 1 hour before exercise in female athletes [52] and an average of 4.3 g of taurine supplementation in elite level athletes [53] determined Wingate anaerobic capacity measurements (peak and mean power) has been found to increase. It was determined that an average of 7.5 g of taurine [54] taken 1 hour before high-intensity exercise for 1 week in healthy individuals and 1 g of taurine supplementation taken acutely in professional athletes [55], reduced blood lactate level and neuromuscular fatigue, on the contrary, 3 g of taurine supplementation daily for 8 weeks was determined to increase blood lactate level in elite swimmers [56]. Unlike these, it has been stated that 3 g of

taurine [57] given to elite athletes for 10 days has no effect on blood lactate level and countermovement jump height. Since the results obtained are different from each other, more studies are needed to understand anaerobic effects more clearly.

Notably, following TAU supplementation, WanT was performed at higher power output and lower fatigue despite no effect on CMJ. TAU has positively affected intramuscular and intermuscular coordination, resulting in improved jumping performance. As the number of studies evaluating enhanced Ca^{2+} bioavailability in myoplasm increases, and when considered with experimental studies, this may further explain these findings. Further, the participation of advanced motor units is known to serve as a synergistic process that improves jumping ability and may be altered by TAU [4, 58]. In support of these potential mechanisms, it was observed that P_{peak} and P_{mean} increased and T_P_{peak} decreased during WanT measurements in participants ingesting TAU supplementation.

WanT measurement, which lasted for 30-s, was evaluated separately in 6 splits of 5-s. P_{peak} and maximum average power were reached in the 2nd split. Phosphocreatine is limited in muscle but can regenerate ATP by creatine kinase rapidly and acts as a temporary energy buffer during high-intensity exercise [51, 59]. Further, the metabolic changes (accumulation of H^+, pH decrease, acidosis) that occur with the contraction of the muscles at maximum capacity during WanT affect muscle contraction function and cause fatigue and decreased power output production in the last seconds of the second split of WanT [60]. Further, TAU supplementation improves calcium permeability in sarcoplasmic reticulum of type I and type II muscle fibers, improves contractile function by increasing the sensitivity of myofilaments to calcium, and thus can increase power output [58, 61]. Additionally, according to an *in vivo* study, TAU supplementation assists with Ca^{2+} collection in the sarcoplasmic reticulum, likely including a rise in SR Ca^{2+} pump function or the Sarco/endoplasmic reticulum Ca-ATPase affinity for Ca^{2+} in human skeletal muscle fibers [58]. In line with these theories, TAU positively enhanced performance. However, when evaluated in terms of its effect on performance, it is unclear whether the mechanisms altered the inter or intramuscular environments [4, 58, 62].

Furthermore, TAU consumption did not alter neuromuscular fatigue; PP and MP were obtained due to CMJ measurement, peak, mean, minimum power (P_{peak}, P_{mean}, and P_{min}), and time to peak power (T_P_{peak}). Currently, limited comparison data is available regarding TAU on neuromuscular fatigue following anaerobic exercise [49, 52, 63]. According to R Warnock, et al. [49], 50 mg /kg TAU ingestion increased mean peak power (MPP), peak power (PP), and mean power (MP) outputs compared to the placebo as a result of the WanT protocol. Similarly, in another study examining the effect of taurine doses of 2, 4, and 6 g on anaerobic performance, it was reported that an increase was observed in the mean and peak power outputs measured as a result of WanT performance with 6 g TAU ingestion [63]. In contrast, 1 g TAU ingestion did not significantly increase WanT performance outputs (such as peak and mean power) compared to placebo [52].In these studies, the effects of caffeine and taurine supplementation were also examined which may have influenced the findings [64, 65].

Studies have shown that TAU affects Ca^{2+} homeostasis and K_{ATP} channel activity in different cell types, anti-oxidant properties by inhibiting ROS in mitochondria, osmoregulation, anti-inflammatory effects, and regulates glucose homeostasis. TAU is found in higher concentrations in pancreatic islets and regulating insulin secretion in response to food by increasing Ca^{2+} mobilization in pancreatic β-cells. Considering the Ca^{2+} and K_{ATP} regulatory effect of taurine, cell ATP production is initiated by stimulus-secretory coupling and glucose entry via glucose transporters (GLUT)-2 in β-cells. This is followed by the complete sugar metabolism and ATP production. An increase in the ATP/ADP ratio leads to the closure of ATP-sensitive potassium (K_{ATP}) channels, depolarization of the plasma membrane, and opening of voltage-sensitive Ca^{2+} channels. Ca^{2+} influx activates the exocytotic machinery that coordinates insulin granule migration and fusion [19, 66].

Studies show that taurine affects increasing endurance exercise performance. For example, taurine aids in sarcoplasmic reticulum Ca^{2+} transport after intramuscular entry, with muscle performance attributed to taurine-facilitated Ca^{2+} transport by cardiac and skeletal myocytes [67]. In another study, it was seen that taurine exerts a stabilizing effect by acting on the mitochondrial matrix. Thanks to this stabilizing effect, it increases the efficiency of the ATP cycle in the muscle cell [68]. Based on this result, taurine has also been shown to play a role as an anti-oxidative. Indeed, inhibition of taurine uptake in taurine transporter knockout mice significantly shortened extinction time [69].

Although taurine is known to be abundant in skeletal muscle, its specific function is currently poorly understood [70]. TAU is thought to play a role in aerobic exercise and mitochondrial function, as higher concentrations in skeletal muscle have been reported in trained (~64 mmol kg^{-1} dw) and untrained (~50 mmol kg^{-1} dw) participants [71]. However, our experimental results suggest that TAU supplementation may improve anaerobic performance. Considering the regulatory role of taurine in all these pathways, it is thought that the energy deficit, especially in athletes, can be eliminated very quickly by ATP production after taurine supplementation this way.

CONCLUSIONS

In conclusion, acute TAU supplementation augments anaerobic performance in elite speed skaters but does not alter neuromuscular recovery.

Practical Applications

The nature of short-track skating has a crouching position and due to this position, when enough oxygen does not reach the muscles, fatigue occurs. In addition, the power generation of the lower extremity in this sport is also a factor that contributes to success.

Considering that the buffering effect of taurine supplement reduces lactate level and supports power production of muscle myofibrils by increasing calcium release from the sarcoplasmic reticulum, it can be said that this supplement supports anaerobic capacity and its use can be recommended to short-track skaters.

More studies are needed to examine the effect of taurine on anaerobic sports branch performance. Increasing the number of studies; is thought that will shed light on the usability of taurine supplementation to athletes, conditioners, and trainers in the future.

Limitation and Further Research

While looking at the acute effect of taurine supplementation is the limitation of this study, its strength is to conducted with well-trained athletes. In future studies, aerobic and anaerobic effects can be examined in different sports branches in chronic use and at different doses (safe and tolerable) and studies can be expanded by comparing these effects. It is seen that there is a deficiency in the literature in terms of studies on well-trained athletes. Starting from this point, it is thought that experimental studies on taurine should focus on well-trained athletes.

Ethical approval

All protocols and procedures were carried out in according to the Declaration of Helsinki and were approved by the Atatürk University Ethics Committee (E-70400699–050.02.04–2100316289, 2021/10).

Informed consent

Informed consent was obtained from all individual participants included in the study.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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The comparison between foam rolling either combined with static or dynamic stretching on knee extensors' function and structure

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ABSTRACT: Static stretching (SS) and dynamic stretching (DS) in combination with foam rolling (FR) have been attracting attention as warm-up routines in sports. However, the combined and intervention order effects of SS or DS and FR on flexibility, muscle strength, and jump performance are still unclear. Therefore, this study aimed to compare the combined effects of FR and SS or DS with the various intervention orders (i.e., SS + FR, DS + FR, FR + SS, DS + FR) on the function and properties of the knee extensors. Using a crossover, random allocation design, 17 male university students (21.0 ± 1.1 y) performed four conditions combining FR and SS or DS. The measurement included knee flexion range of motion (ROM), pain pressure threshold (PPT), tissue hardness, maximum voluntary isometric contraction (MVC-ISO), maximum voluntary concentric contraction (MVC-CON) torque, and single-leg countermovement jump (CMJ) height of the knee extensors. All interventions significantly ($p < 0.01$) increased knee flexion ROM (SS + FR: $d = 1.29$, DS + FR: $d = 0.45$, FR + SS: $d = 0.95$, FR + DS: $d = 0.49$), and significantly ($p < 0.01$) decreased tissue hardness (SS + FR: $d = -1.11$, DS + FR: $d = -0.86$, FR + SS: $d = -1.29$, DS + FR: $d = -0.65$). There were no significant changes in MVC-ISO, MVC-CON, and CMJ height in all conditions, but a near significant, small magnitude ($p = 0.056$, $d = -0.31$) decrease of MVC-ISO was observed in the FR + SS condition. Our results showed that all the combinations of SS or DS and FR effectively decreased tissue hardness and increased ROM without decreasing muscle strength. Also, effect sizes indicated the largest increase in ROM and decrease in tissue stiffness after SS + FR without decreasing muscle strength and jump performance.

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INTRODUCTION

The warm-up before exercise typically consists of aerobic exercise and stretching, i.e., static stretching (SS) and dynamic stretching (DS) [1]. Concerning SS, previous studies showed that a single bout of SS can increase the joint range of motion (ROM) [1, 2], corresponding with a decrease in muscle stiffness [3, 4]. However, further evidence showed that more than 60 seconds of SS per muscle group in isolation (no additional warm-up activities) could decrease muscle strength and performance [1, 5, 6]. On the other hand, previous studies on DS reported no adverse effect on muscle strength or sprinting ability [1, 7] but a similar increase in flexibility compared to SS [8, 9], although no consensus has been reached [10–12]. According to these findings, it can be suggested to use DS rather than SS as a warm-up if the goal is to increase flexibility and sustain performance levels.

In addition, recent studies showed that foam rolling (FR) has been attracting attention as a new warm-up tool due to the increase in ROM, similar to SS and DS [13]. Moreover, two meta-analyses showed that the increase in ROM after FR is similar to stretching [13, 14]. In addition, a further meta-analysis showed a favorable effect on muscle performance after FR compared to SS but no advantage over DS (12). Based on these findings, the authors recommend either DS or FR but not SS as a warm-up tool when the goal is to optimize performance [15].

A meta-analysis comparing the acute effects of some stretching interventions combined with FR on ROM and physical performance showed significantly increased ROM in the combined stretching and FR intervention compared to the control condition [16]. Interestingly, the magnitude of change in performance was similar when FR

was performed after stretching compared to stretching alone. On the other hand, when FR was performed before stretching, the effect size of this observation was trivial (ES = 0.17), but the combined application slightly improved performance over stretching alone (P = 0.04). In a report examining the combined and order effects of SS and FR on knee extensors, the combined application of SS and FR increased ROM, while SS followed by FR decreased muscle strength [17].

Furthermore, a recent review comparing the combined effects of DS and FR with those of DS alone concluded that in agility and performance, the combination of DS and FR significantly increased over DS alone [18]. This is consistent with the report [19], which concluded that the combination of DS and FR might significantly increase flexibility, power, and agility. However, few reports have examined the combined effects of DS and FR, and the effects of the intervention order of FR and DS on ROM and performance are unknown.

Based on the previous studies [16, 18, 19], the combined effect of stretching and FR could be greater than SS, DS, and FR intervention alone. These studies suggest that combined stretching and FR could be effective as a pre-exercise warm-up. Still, there might be differences in the effects obtained depending on the intervention order in the combination of stretching and FR, such as the decrease in muscle strength after FR intervention followed by SS intervention [17]. Since the warm-up before exercise is intended to optimize athletic performance [7], it is essential information for athletes and coaches to establish the optimal warm-up method. However, to the best of the authors' knowledge, no study has compared the effect of the combination and intervention order effect of SS and FR or DS and FR on the same participants in random order in a crossover trial. Therefore, this study aimed to investigate the combined and intervention order effects of SS or DS and FR on knee flexion ROM, muscle strength, tissue hardness, pain pressure threshold (PPT), and single-leg countermovement jump (CMJ) height of the knee extensors. In this study, since the effects of SS and DS to increase ROM are comparable [8], it was expected that the effects of SS + FR and DS + FR to increase ROM would be comparable regardless of the intervention order. Concerning performance, the SS + FR and FR + SS suggest a difference in effect depending on the intervention order [17]. Therefore, we expected that the combination of DS + FR would be optimal as a warm-up, as it is expected to have a beneficial effect regardless of the intervention order.

MATERIALS AND METHODS

Experimental set-up

A randomized repeated-measures experimental design was used to compare the order effects of combined anterior thigh SS or DS with FR. The participants were instructed to visit the laboratory four times with a ≥ 48 h break. They were exposed to the following four conditions (Figure 1): FR + SS, FR + DS, SS + FR, and DS + FR. For each SS, DS, and FR, three 60 s bouts were performed on the dominant leg. Outcomes were measured before (PRE) and immediately after the intervention (POST) in each condition. We assessed knee flexion ROM, tissue hardness, PPT, MVC-ISO, maximal concentric (MVC-CON) torque of knee extensors, and unilateral CMJ height in this order, at both PRE and POST.

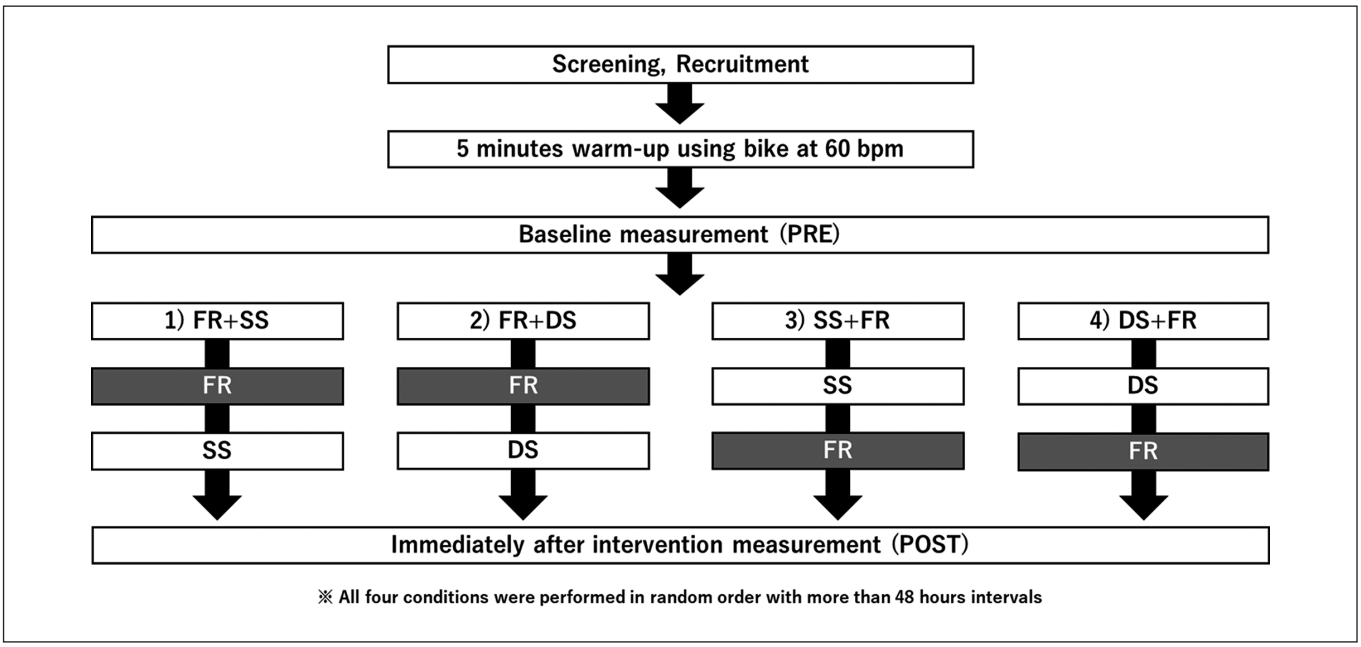


FIG. 1. The experimental set-up
SS: static stretching, FR: foam rolling, DS: dynamic stretching.

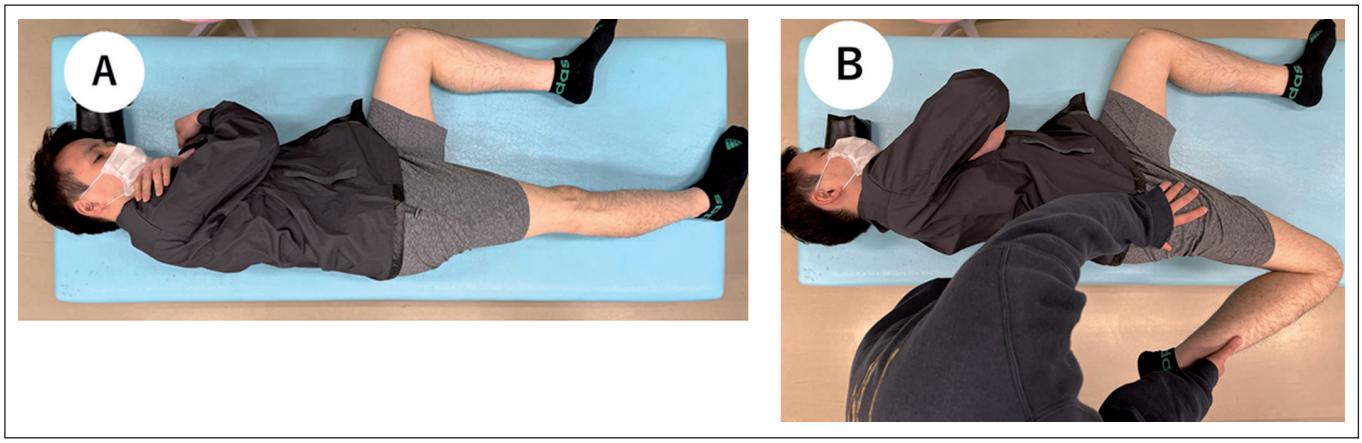


FIG. 2. The set-up for knee flexion range of motion (ROM) measurement. The participants lie in a side-lying position with the contralateral hip and knee joints flexed 90° (A). The investigator brought the dominant leg to full knee flexion with the hip joint in a neutral position (B).

Participants

Seventeen healthy, recreationally active males were enrolled (mean ± SD: age, 21.6 ± 1.1 years; height, 170.5 ± 5.8 cm; weight, 66.0 ± 8.6 kg). The participants completed the four conditions described above in random order. Individuals with a history of neuromuscular disease and musculoskeletal injury involving the lower extremities were excluded. The required sample size for a repeated-measures two-way analysis of variance (ANOVA) (effect size = 0.40 [large when considering interaction effects for 2-way ANOVAs], α error = 0.05, and power = 0.80) based on our previous study's ROM results using G* power 3.1 software (Heinrich Heine University, Düsseldorf, Germany) was 14 participants.

For the study, participants were fully informed about the procedures and aims, after which they provided written informed consent. The study complied with the requirements of the Declaration of Helsinki and was approved by the Ethics Committee of the Niigata University of Health and Welfare, Niigata, Japan (Procedure #18615).

Knee flexion ROM

Each participant was placed in a side-lying position on a massage bed with the hips as well as the knee of the non-dominant leg flexed at 90° to prevent pelvic movement (Figure 2-A) [20]. A licensed physical therapist, the investigator, brought the dominant leg to full knee flexion with the hip joint in a neutral position (Figure 2-B). A goniometer (MMI universal goniometer Todai 300 mm, Muranaka Medical Instruments, Co., Ltd., Osaka, Japan) was used to measure the knee flexion ROM three times at both PRE and POST in each condition, and the average value was used for further analysis [21].

Pain pressure threshold (PPT)

PPT measurements were conducted in the supine position using an algometer (NEUTONE TAM-22 (BT10); TRY-ALL, Chiba, Japan). The measurement location was set at the midway of the distance between the anterior superior iliac spine and the dominant side's superior border of the patella for the rectus femoris muscle. With continuously increasing pressure, the soft tissue in the measurement area was compressed with the metal rod of the algometer. The participants were instructed to immediately press a trigger when pain, rather than just pressure, was experienced. The value read from the device at this time point (kilograms per square centimeter) corresponded to the PPT. Based on previous studies [22, 23], the mean value (kilograms per square centimeter) of three repeated measurements with a 30-s interval was taken for data analysis at both PRE and POST in each condition.

Tissue hardness

Tissue hardness was measured using a portable tissue hardness meter (NEUTONE TDM-N1; TRY-ALL Corp., Chiba, Japan). The participant's measurement position and posture were similar to PPT measurements. This tissue hardness meter measured the penetration distance until a 14.71 N (1.5 kgf) pressure was reached [24]. The participants were instructed to relax while tissue hardness measurements were assessed three times at PRE and POST in each condition. The average value was used for further analysis.

Maximal voluntary isometric (MVC-ISO) and concentric contractions (MVC-CON)

MVC-ISO of the dominant leg's knee extensors was measured at 70° knee flexion using an isokinetic dynamometer (Biodex System 3.0, Biodex Medical Systems Inc., Shirley, NY, USA). The participants sat on the dynamometer chair adopting an 80° hip flexion angle, with adjusted Velcro straps fixed over the exercised limb's trunk, pelvis, and thigh. The participants were instructed to contract the knee extensors for three seconds maximally. Two repetitions with a 60-s rest between trials were performed at both PRE and POST [20]. The mean of both repetitions was used for further analysis. MVC-CON was measured at an angular velocity of 60° between 20° and 110° knee flexion. From the three trials performed at both PRE and POST

in each condition, the highest value was analyzed. During all tests, strong verbal encouragement was provided to elicit maximal effort.

Unilateral Countermovement jump (CMJ) height

Unilateral CMJ height was calculated from flight time using a contact mat (Jump mat system; 4Assist, Tokyo, Japan). The participants started with the foot of the dominant leg on the mat with their arms crossed in front of their chest. The participants were instructed to dip quickly (eccentric phase) from this position, reaching a self-selected depth to jump as high as possible in the next concentric phase. Landings were performed on both feet. The knee of the non-involved leg was held at approximately 90° flexion. After three familiarization trials, three maximal unilateral CMJ were conducted at both PRE and POST in each condition, and the greatest vertical jump height was utilized for further analysis [25].

Test-retest reliability of measurements

The test-retest reliability of knee ROM, PPT, tissue hardness, MVC-ISO, MVC-CON, and CMJ height for 12 healthy men (age, 21.8 ± 1.3 years; height, 169.9 ± 5.9 cm; weight, 67.0 ± 9.6 kg) was determined using the coefficient variation (CV) and intraclass correlation coefficient (ICC), with 10 minutes rest interval between two measures in the similar protocol in this study.

Foam rolling (FR)

The participants were instructed on how to use the foam roller (Stretch Roll SR-002, Dream Factory, Umeda, Japan) by a physical therapist. For familiarization, they were allowed to practice using the foam roller three to five times on the non-dominant leg (non-intervention leg) immediately before the FR intervention in order to verify that the participants were able to perform the FR intervention at the specified velocity and location. The participants performed three 60-s bouts of FR with a 30-s rest between sets. The participants were instructed to be in the plank position with the foam roller at the most proximal portion of the quadriceps of the dominant leg only. We defined one cycle of FR as one distal rolling plus one subsequent proximal rolling movement. FR velocity was set at 30 cycles per 60-s (90 cycles in three sets) and controlled using a metronome (Smart Metronome; Tomohiro Ihara, Japan). This procedure followed the recommendations of Behm et al. [26] to maximize the increase in ROM. The participants were asked to place as much body mass on the roller as tolerable.

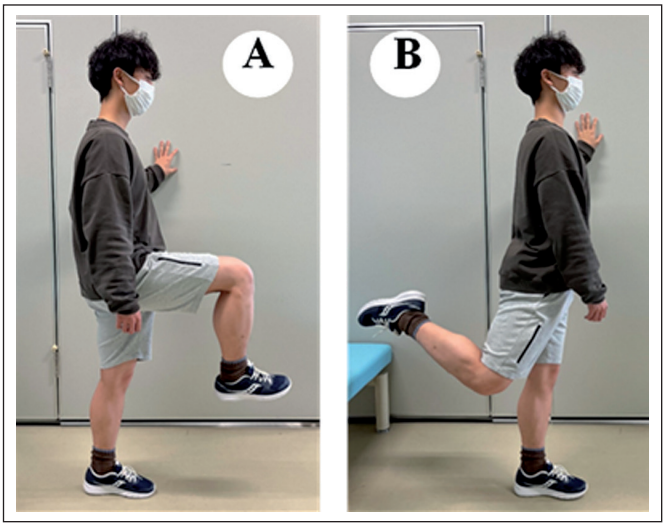


FIG. 3. The dynamic stretching (DS) intervention method. The participants performed the DS in the standing position. The participant's knee and hip joints were initially positioned at 90 degrees flexion (A) and then moved dynamically to a hip extension movement over a 1 second period (B), and then returned to the initial position over another 1-second duration (A).

Static stretching (SS)

SS was conducted similarly to the knee flexion ROM assessment (side-lying position). A well-trained investigator conducted three 60-s bouts with a 30-s rest interval. The participants were instructed to be relaxed and keep their torso upright during stretching.

Dynamic stretching (DS)

The participants performed the DS in the standing position. The participant's knee and hip joints were initially positioned at 90 degrees flexion (Figure 3-A) and then moved dynamically to a hip extension movement over a 1-s period (Figure 3-B), and then returned to the initial position over another 1-s duration (Figure 3-A). As with FR, the metronome was used to perform three 60-s exercises with 30-s rest intervals. The participants were instructed to perform the exercise through a full range of motion under control without using recoil or bouncing to distinguish this from ballistic stretching.

Statistical analysis

SPSS (version 25.0; IBM Corp., Armonk, NY, USA) was used for statistical analyses. To verify the consistency of PRE values, PRE values were tested among all conditions using a one-way ANOVA. A repeated-measures two-way ANOVA (time [PRE vs. POST] × conditions [FR + SS vs. FR + DS vs. SS + FR vs. DS + FR]) was used to identify interactions and main effects. If the interaction effect was significant, a post-hoc analysis was conducted using paired t-tests with Bonferroni correction on each condition to determine the difference between PRE and POST values. Also, POST values were tested among all conditions using paired t-tests with Bonferroni correction. Effect sizes (ES) were calculated as the mean difference between PRE and POST divided by the pooled PRE and POST standard deviation (SD). An ES of 0.00–0.19 was considered trivial, 0.20–0.49 was small, 0.50–0.79 was moderate, and ≥ 0.80 was large [27]. The significance level was set at 5%. All results are shown as mean ± SD.

RESULTS

Test-retest reliability of measurements

The CVs of measurements for knee ROM, PPT, tissue hardness, MVC-ISO, MVC-CON, and CMJ height were 0.2 ± 0.1%, 6.6 ± 3.9%,

1.7 ± 1.3%, 1.5 ± 1.4%, 2.2 ± 2.1%, 1.8 ± 1.9%, respectively, and the ICC (1, 1) for measurements were 0.993, 0.993, 0.970, 0.966, 0.939, and 0.963, respectively.

Comparison between PRE values among the four conditions

There were no significant differences in all PRE variables among the four conditions.

Changes in knee flexion ROM, PPT, tissue hardness MVC-ISO, MVC-CON, and CMJ height

Table 1 shows the changes in knee flexion ROM, PPT, tissue hardness, MVC-ISO, MVC-CON, and CMJ before and after the intervention. Significant interaction effects in knee flexion ROM ($F = 13.2$, $p < 0.01$, $\eta_p^2 = 0.38$), MVC-ISO ($F = 2.9$, $p = 0.042$, $\eta_p^2 = 0.12$) and PPT ($F = 3.2$, $p = 0.03$, $\eta_p^2 = 0.13$) were revealed. Post-hoc test results showed that knee flexion ROM significantly increased in all conditions. MVC-ISO experienced a near significant decrease (FR + SS: $p = 0.056$, $d = -0.31$), compared to non-significant changes for FR + DS: ($p = 0.46$, $d = 0.17$), SS + FR ($p = 1.00$, $d = 0.01$), and DS + FR ($p = 1.00$, $d = 0.07$). However, there were no significant differences in POST values in MVC-ISO among the four conditions. PPT significantly increased ($p < 0.01$) in FR + SS ($d = 0.33$), FR + DS ($d = 0.61$), and DS + FR ($d = 0.82$) conditions, but SS + FR condition showed no significant change ($p = 0.24$, $d = 0.31$).

Additionally, there were no significant interaction effects for MVC-CON, CMJ, or tissue hardness. However, there was a main effect of time on tissue hardness ($F = 124.2$, $p < 0.01$, $\eta_p^2 = 0.66$), which demonstrated that tissue hardness decreased after the intervention compared to PRE values in all conditions.

DISCUSSION

Previous studies have examined the effects of SS and FR and DS and FR in combination [17–19]. However, to the best of our knowledge, this was the first study to compare the combined effects of SS or DS and FR with a crossover design. The results showed a significant ROM increase and tissue hardness decrease in all conditions. Interestingly, the effect size of knee flexion ROM changes was greater for both FR + SS and SS + FR than for FR + DS or DS + FR conditions. Although there was no significant change in muscle strength in all

TABLE 1. The changes (mean ± SD) in knee flexion range of motion (ROM), pain pressure threshold (PPT), tissue hardness, maximal voluntary isometric contraction (MVC-ISO), maximal voluntary concentric contraction (MVC-CON) torques, and counter-movements jump (CMJ) height before and after the intervention. The two-way repeated ANOVA results (T: time effects, C × T: condition × time interaction effects; P- and F- value) and partial η^2 (η_p^2) are shown in the right column.

	FR + SS		FR + DS		SS + FR		DS + FR		ANOVA results
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	P value, F value, η_p^2
Knee flexion ROM (degrees)	132.7 ± 6.9	138.9 ± 6.1*	133.2 ± 5.8	136.2 ± 6.5*	132.8 ± 5.0	138.6 ± 3.9*	132.1 ± 5.0	134.4 ± 5.1*†‡	T: F = 256.0, p < 0.01, η_p^2 = 0.80
	d =	0.95	d =	0.49	d =	1.29	d =	0.45	C × T: F = 13.2, p < 0.01, η_p^2 = 0.38
PPT (kg)	2.8 ± 1.3	3.2 ± 1.2*	2.5 ± 1.1	3.1 ± 1.0*	2.9 ± 1.4	3.3 ± 1.8	2.5 ± 1.0	3.5 ± 1.5*	T: F = 49.9, p < 0.01, η_p^2 = 0.44
	d =	0.33	d =	0.61	d =	0.23	d =	0.82	C × T: F = 3.1, p = 0.03, η_p^2 = 0.13
Tissue hardness (N)	19.0 ± 3.0	15.6 ± 2.3*	18.9 ± 3.1	16.8 ± 3.4*	18.4 ± 2.3	15.0 ± 3.9*	17.9 ± 2.5	15.9 ± 2.2*	T: F = 124.2, p < 0.01, η_p^2 = 0.66
	d =	-1.29	d =	-0.65	d =	-1.11	d =	-0.86	C × T: F = 2.6, p = 0.06, η_p^2 = 0.11
MVC-ISO (Nm)	216.3 ± 42.4	203.8 ± 37.9	210.9 ± 34.5	216.7 ± 34.0	216.4 ± 42.7	216.8 ± 48.3	216.5 ± 36.7	219.0 ± 39.4	T: F = 0.2, p = 0.687, η_p^2 = 0.003
	d =	-0.31	d =	0.17	d =	0.01	d =	0.07	C × T: F = 2.9, p = 0.042, η_p^2 = 0.12
MVC-CON (Nm)	172.7 ± 25.0	165.5 ± 25.6	173.2 ± 23.5	177.3 ± 26.1	174.1 ± 31.1	173.3 ± 35.6	175.6 ± 24.8	177.3 ± 25.4	T: F = 0.1, p = 0.74, η_p^2 = 0.002
	d =	-0.29	d =	0.17	d =	-0.02	d =	0.07	C × T: F = 2.1, p = 0.12, η_p^2 = 0.09
CMJ height (cm)	21.1 ± 3.8	20.7 ± 3.7	23.2 ± 6.4	22.1 ± 3.6	21.6 ± 3.7	21.1 ± 4.0	21.6 ± 3.2	22.2 ± 3.8	T: F = 1.2, p = 0.27, η_p^2 = 0.019
	d =	-0.11	d =	-0.23	d =	-0.13	d =	0.17	C × T: F = 1.1, p = 0.34, η_p^2 = 0.05

*: Significantly ($P < 0.05$) different from the PRE-value. †: Significantly different compared to POST values for FR + SS conditions. ‡: Significantly different compared to POST values for SS + FR conditions. SS: static stretching, DS: dynamic stretching, FR: foam rolling

interventions, there was a near significant decrease in muscle strength in the SS + FR condition ($p = 0.056$, $d = -0.31$).

As shown in Table 1, all interventions in this study increased knee flexion ROM significantly. This result supports the results of Nakamura et al. [17], who investigated the combined effect of SS and FR, and Hsu et al. [19], who investigated the combined effect of DS and FR. Previous studies have suggested that changes in stretch tolerance and passive stiffness are involved in the increase in ROM after stretching interventions [28]. Indeed, a previous study showed that increased ROM with stretching could be associated with a change in stretch tolerance [29]. Similarly, stretch tolerance could contribute to change in ROM after a single FR intervention [30–32]. Concerning this study, the detailed mechanism of the increased knee flexion ROM is unknown, but changes in stretch tolerance might be involved in the increase in ROM.

Although not statistically significant, the effect sizes of DS + FR and FR + DS on ROM were small ($d = 0.45$ and $d = 0.49$, respectively), while SS + FR and FR + SS showed large effect sizes ($d = 1.29$, and $d = 0.95$, respectively). Regarding the difference in the combined effect of SS or DS with FR, several studies indicate greater ROM with SS than DS [33-38]. However, others have concluded that SS and DS have similar [8, 9] or greater [10, 11] acute increases in ROM as static stretching. Therefore, there is no consensus about the increase in ROM after SS or DS, but the results of this study indicated that SS could increase knee flexion ROM to a greater extent than DS when combined with FR. This could be related to the difference in the change in passive stiffness between SS and DS interventions. Mizuno et al. [39] showed that increased ROM after SS could be related to decreased passive stiffness and changes in stretch tolerance. Although SS interventions could decrease passive stiffness [3, 4, 40], a previous study showed that DS interventions did not produce significant changes in passive stiffness [41]. Therefore, the detailed mechanism of the difference in the increase in knee flexion ROM after combining SS or DS with FR is unclear. Still, the combination of SS and FR could have a greater effect on reducing passive stiffness than the combination of DS and FR, resulting in a larger increase in knee flexion ROM.

Interestingly, there was a significant increase in PPT in the FR + SS, FR + DS, and DS + FR conditions but not in the SS + FR condition ($p = 0.16$, $d = 0.31$). A previous study showed that mechanical stimulation by FR intervention could reduce pain perception [42]. Thus, 180-s of FR intervention could have increased PPT in combined FR and SS or DS. In addition, tissue hardness was significantly decreased in all conditions. The effect sizes on tissue hardness were greater for the combination of SS and FR (SS + FR: $d = -1.11$, FR + SS: $d = -1.29$) than for the combination of DS and FR (DS + FR: $d = -0.86$, FR + DS: $d = -0.65$). As mentioned earlier, SS intervention reduced passive stiffness [3, 4, 40], whereas DS could induce no change in passive stiffness [41]. Additionally, it was speculated that FR could induce thixotropic changes in intramuscular hyaluronic acid and alter muscle viscoelasticity [43]. Therefore, the combination of FR and SS could have produced a greater reduction in tissue hardness than the combination of FR and DS.

This study showed that MVC-ISO torque did not change in all conditions, but there was a near-significant, small magnitude decrease in the SS + FR condition ($p = 0.056$, $d = -0.31$). Previous studies pointed out that a longer duration than 60 seconds of SS could produce performance impairments [1, 6, 7]. Neurological and morphological factors have been considered as possible mechanisms [5]. Previous studies have reported that stretching may induce changes in persistent inward current (PIC) [5] and muscle spindle sensitivity [44], which could have adverse effects on muscle strength. However, the previous study suggested that FR after SS restores motoneuron excitability, resulting in recovery from a decrease in muscle strength [17]. Therefore, MVC-ISO could not change in the SS + FR condition.

On the other hand, DS is considered to increase muscle strength and/or athletic performance [45]. However, the effects of FR on muscle strength and jumping height have been shown to be negligible [26]. Therefore, we hypothesized that the combination of DS and FR would increase muscle strength and jump performance. Contrary to our expectations, however, there were no significant differences between conditions in MVC-ISO, MVC-CON, and CMJ height in the combined DS and FR conditions. These results were inconsistent with a previous study [19], in which combined DS and FR resulted in a significant increase in broad jump and medicine ball chest throw distance. This difference in results could be due to the time of DS intervention. The duration of the DS intervention in this study was 180 seconds, but eight types of DS were performed for a total of 480 seconds in the previous study [19]. DS has been shown to potentially improve performance with longer stretch times [46, 47]. Therefore, the combination of DS and FR intervention could induce increases in muscle strength and athletic performance when a longer duration of DS intervention time is applied than in the present study. Still, it is also possible that greater muscle strength and performance improvement effects may not occur when used in combination with FR. Also, no significant changes were observed in MVC-CON and CMJ height in all conditions. The previous study has shown that isometric contractions could promote recovery of muscle spindle sensitivity [44]. Since MVC-CON and CMJ were measured after MVC-ISO in this study, MVC-ISO measurement could facilitate the recovery of muscle spindle sensitivity altered by SS, resulting in no changes in MVC-CON and CMJ height in the combination of SS and FR.

There were limitations in this study. There was no control condition in this study. However, we have confirmed that the test-retest reliability of measurements is very high. Therefore, we believe that the results of this study reflect the effects of the interventions. The participants performed three 60-s bouts of FR or stretching intervention with a 30-s rest between sets, but the rest interval might affect the intervention effect. Also, the participants were recreationally active but not athletes. Previous studies investigated the effect of warm-up routine using FR and stretching intervention on athletic

performance in well-trained tennis players [19, 48]. Still, it is unclear whether the results of this research could be applied to athletes. Thus, further study is needed to investigate the effect of different rest intervals of FR and stretching interventions on ROM and athletic performance in athletes to establish an effective pre-exercise warm-up in a sports setting.

Practical implications

As a pre-exercise warm-up, a combination of SS and FR is recommended if the goal is only to increase ROM without necessarily improving performance. On the other hand, the combination of DS and FR and FR after SS intervention conditions showed no change in muscle strength and jump performance. Therefore, the SS + FR condition is the best approach when the goal is to increase ROM while maintaining muscle strength and jump performance.

CONCLUSIONS

This study aimed to compare the combined and order effects of SS or DS and FR to establish the optimal warm-up routine in sports. All interventions showed significant changes in knee flexion ROM, PTT, and tissue hardness. However, the changes in knee flexion ROM and tissue hardness after the combination of SS and FR could be superior to the combination of DS and FR regardless of an intervention order.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Acute effects of combined cycling and plyometrics on vertical jump performance in active males

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ABSTRACT: The aim of this study was to analyze the acute effects of high vs low-intensity cycling efforts, combined with plyometrics, on vertical jump performance. Twenty-four physically active men (mean ± SD: 23 ± 2 years, 72.1 ± 10.1 kg, 1.73 ± 0.07 m) were randomly divided into two groups: experimental group (EXP, n = 16) and control group (CON, n = 8). EXP competed 2 experimental trials in a random order: (a) short high-intensity interval exercise (HI + Plyo) [5 × 10 s of cycling ("all-out")/50 s active rest] or (b) low-intensity continuous exercise (LO + Plyo) [5 min of cycling at 75% of the HR_{max})], along with 3 × 10 plyometric bounds (drop jumps)/1 min rest between sets. CON used a preconditioning activity of 13 min of low intensity cycling at ~60% of HR_{max}. Both EXP interventions significantly increased ($p \leq 0.05$) the countermovement jump (CMJ) height at 1 min, 3 min, 6 min and 9 min compared to baseline, while the CON remained unchanged. There were no significant differences in CMJ performance enhancement between HI + Plyo (largest 11.2% at 9 min) and LO + Plyo (largest 15.0% at 3 min) at any time-point, suggesting that the plyometric component may be most important, with HR recovery taking slightly longer following HI + Plyo. The findings suggest that CMJ performance can be enhanced following high or low-intensity cycling combined with plyometric preconditioning activities in active males, the optimum recovery period likely to be individual-specific.

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INTRODUCTION

The ability to develop muscular power (energy output per unit of time) is critical to successful outcomes in many sports events, such as sprint races, long and high jumps and other sporting actions like swimming starts or accelerations during team-based sports [1]. Some activities or actions (e.g., sprint, heavy-load exercises or stretching) performed before sport (warm-up) have shown acute improvements in subsequent performance [2, 3]. A proposed mechanism underpinning such acute performance enhancement is post-activation potentiation (PAP). Several authors have demonstrated that muscle PAP is a phenomenon that can acutely increase muscular power and, consequently, performance [4, 5]. PAP might cause gains in power after heavy muscle preloading as a result of myosin light chain phosphorylation and increased recruitment of higher order motor units [6]. However, the efficacy of PAP mechanisms to enhance performance ultimately depends on the balance between competing and simultaneous fatigue and PAP phenomena [6]. This balance is affected by many factors, including training experience of the athletes [4, 7], recovery period [8] and the intensity of the conditioning activity performed [9].

Regarding the intensity of the conditioning activity, most studies have reported positive effects when lifting heavy weights [10, 11] or plyometric exercises prior to explosive movements (sprints or vertical jumps) [8, 12, 13]. However, while strength and plyometric exercises are generally utilized as a potentiating stimulus, less is known about the combination of these exercise modes with endurance exercise that is often also included in warm-ups (e.g., low or high-intensity cycling efforts). In addition, the post-activation performance enhancement (PAPE) concept has more recently been proposed [14, 15] for use after a voluntary muscular performance enhancement related to a high-intensity contractions, without confirmatory evidence of classical PAP, that is often not measured. Both phenomena can occur at different time points [16, 17] and PAPE was not observed despite PAP being evoked [18, 19]. For this reason, it is important to consider the time point at which an improvement of performance occurs after a conditioning activity. A recent meta-analysis [20] found that sufficient recovery occurs after 3–7 min in trained athletes. However, recreational athletes or with lower experience may need more time to recover from high-intensity protocols [16, 21]. For that reason, it is crucial to

investigate the optimal recovery time for these athletes according to the preconditioning activity.

Therefore, the main aim of this study was to analyze the acute effects of high vs low-intensity cycling efforts, combined with plyometrics, on markers of vertical jump performance and heart rate. The second aim was to analyze the influence of recovery time post-stimulus. We hypothesized that the combination of cycling with plyometrics would enhance jump performance compared to a control condition, but with a differing time-course of PAPE effects for high-intensity vs. low-intensity cycling conditions.

MATERIALS AND METHODS

Subjects

Twenty-four physically active men (mean ± SD: 23 ± 2 years, 72.1 ± 10.1 kg, 1.73 ± 0.07 m) participated in this study. Subjects were non-smokers, free from any pre-existing medical conditions and musculoskeletal injuries. They performed varied sporting activities ("gym"-based training, endurance exercises such as running and swimming, and various sports such as soccer and basketball), habitually exercising for > 6 h per week.

Using an online randomization tool, subjects were randomly divided into two groups: experimental group (EXP, n = 16; mean ± SD: 23 ± 2 years; 72.8 ± 10.9 kg and 1.73 ± 0.08 cm) and control group (CON, n = 8; mean ± SD: 23 ± 2 years; 70.6 ± 8.8 kg and 1.74 ± 0.06 cm). Prior to the study, all participants were informed about the testing protocols, possible risks involved and were invited to provide written informed consent. The study was performed in accordance with the principles of the Declaration of Helsinki (October 2008, Seoul), and the experimental protocols were approved by the local ethics committee.

Experimental design

A randomized and crossover study design was used to compare the effects of cycling efforts (high vs low-intensity) along with plyometrics on vertical jump performance and heart rate (HR) compared to a control condition. EXP competed 2 experimental trials, (a) HI + PLYO – short high-intensity interval exercise [5 × 10 s of cycling ("all-out")/50 s active rest] or (b) LO + PLYO – low-intensity continuous exercise [5 minutes of cycling at 75% (range 73–82%) of the HR_{max}, 220-age)], along with 3 sets of 10 plyometric (PLYO) bounds (drop jump [DJ]) with 1 min rest between sets, timings previously used by Turner et al. [13] with horizontal bounds. The subjects of the HI + PLYO condition were strongly encouraged to maintain a maximal effort (all-out) throughout the cycling exercise. Both experimental conditions were separated by 5 days. On the first testing day, CON performed a preconditioning activity which consisted of 13 minutes (time matched to experimental conditions) of low-intensity cycling at 60% (range: 59.4–63.5%) of HR_{max} as an example of general warm-up [22].

Procedure

All subjects visited the laboratory on two different days with 5 days apart and without performing heavy exercise in the 48 h prior to the visits. During the first visit height was measured to the nearest 0.1 cm with a portable stadiometer and body mass was measured using a calibrated balance beam scale (Seca, Bonn, Germany) to the nearest 0.1 kg. In addition, subjects completed a short survey about their previous experience in strength and endurance training (hours and days of training per week, years of experience, etc.). To control the possible PAPE effect, the following considerations were taken [23]: 1) all subjects were familiarized with the countermovement jump (CMJ) and before each warm-up condition, three maximal CMJ were performed; 2) the warm-up conditions were randomized; 3) time of day, diet, hydration, and physical activity performed and use of caffeine were controlled in the days prior to testing. Subjects refrained from caffeine use before each training session.

Then, a CMJ was performed on a force platform Kistler Quattro-Jump (Kistler, Switzerland) at 500 Hz considered as the *gold*

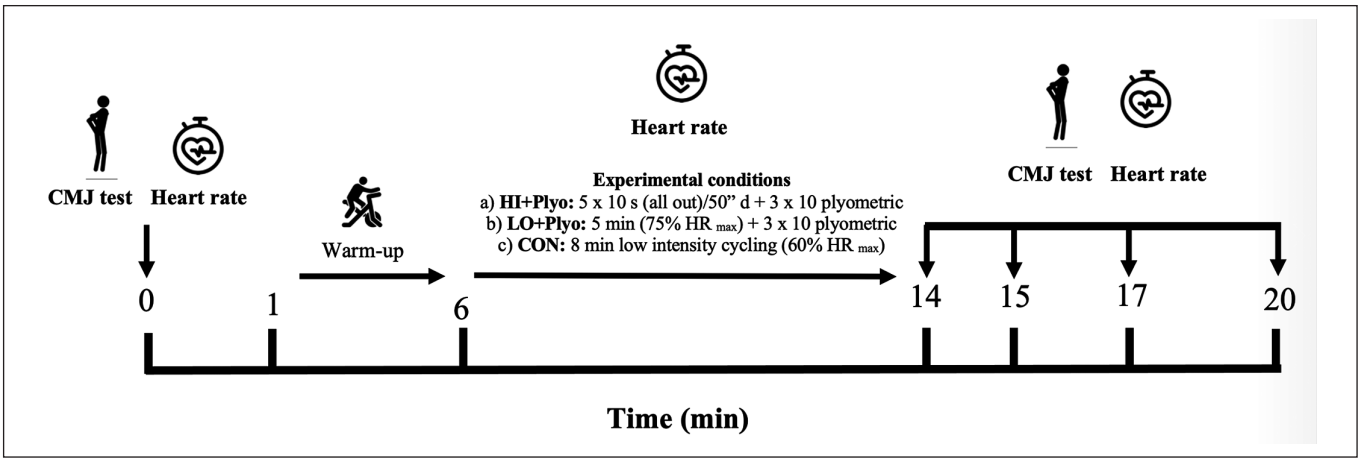


FIG. 1. Overview of experimental design, indicating the protocols and timing of measurements.

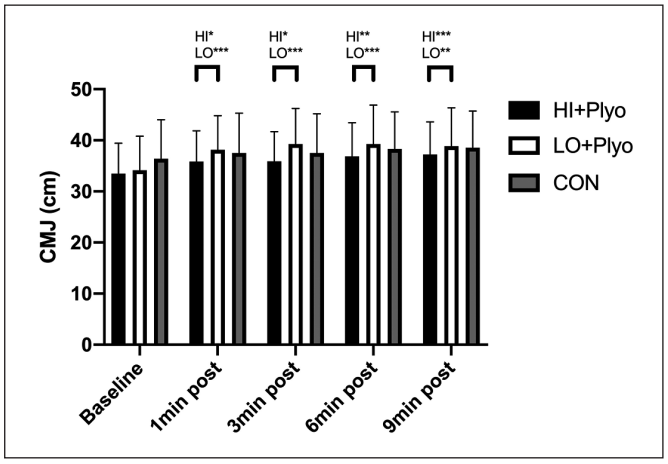


FIG. 2. Results for CMJ for each warm-up condition. $ = Different from control condition, bracket = all conditions different from baseline. *p ≤ 0.05; **p ≤ 0.01; ***p ≤ 0.001.

standard that served as baseline [24]. The force platform was calibrated according to the manufacturer's recommendations. The order of EXP conditions for each subject was determined by block randomization using an online randomization tool. After baseline CMJ, all groups performed the preconditioning activities after a standardized 5 min of cycling at 60% HR_{max}. Finally, CMJ and HR were measured at 1 min, 3 min, 6 min and 9 min of rest (Figure 1) to profile both transient fatigue and potentiation effects. Before the CMJ assessment, the subjects stood motionless on the force platform to measure their body weight [25]. Participants were instructed to perform each vertical jump "as high as possible", with both hands placed on the hip followed by a rapid decent to a self-determined squat depth. CMJ performance variables assessed were jump height (cm), relative maximal force (%BW), average power (Watts), average force (N) and average velocity (m/s) of the CMJ were recorded from a force plate. The selected variables have been described as used to assess explosive leg muscle function [26]. These variables were automatically calculated through take-off velocity using MARS software (Kistler, Winterthur, Switzerland).

The HI and LO cycling were performed on the same cycle ergometer (Technogym, Gambettola, Italy) and the plyometrics jumps from the same box of 40 cm height (Technogym, Gambettola, Italy). Finally, HR was measured continuously during the preconditioning activities and recovery periods using a Polar® watch (Vantage M, Polar, Kempele, Finland) and a heart rate sensor with a chest band (H10 sensor, Polar, Kempele, Finland). The overview of experimental design is shown in Figure 1.

Statistical analysis

Statistical analyses were performed using SPSS software (version 21; SPSS, Inc, Chicago, IL, USA). Data are presented as mean ± SD. Significance was set at p ≤ 0.05. Data were screened for normality of distribution and homogeneity of variance using a Shapiro-Wilk Normality Test. Two-way (3 × 5) mixed analyses of variance (between-groups factors: condition [HI + Plyo, LO + Plyo, CON] × time [within-groups factors: baseline, 1 min, 3 min, 6 min and 9 min]) were used. Mauchly's test was consulted and if sphericity was violated, Greenhouse-Geisser correction was applied. Post-hoc Bonferroni adjustment was applied for post-hoc pairwise comparisons. We calculated the effect size using the partial eta squared (η^2). Values of 0.01, 0.06 and above 0.15 were considered as small, medium, and large, respectively [27].

RESULTS

The results for the CMJ parameters are displayed at the Table 1.

There was no main effect of condition on CMJ height (F = 2.668, p = 0.548, partial η^2 = 0.029). However, there was a significant main effect of time (F = 39.103, p ≤ 0.001, partial η^2 = 0.488) and a significant time × condition interaction effect (F = 17.536, p ≤ 0.05, partial η^2 = 0.155), with large effect sizes. As shown in Table 1 and Figure 2, post-hoc comparisons revealed that CMJs were significantly enhanced (p ≤ 0.05) at 1 min, 3 min, 6 min and 9 min compared to baseline in HI + PLYO and LO + PLYO, with no significant differences in CON. There were no significant differences between EXP conditions at any time of recovery.

There was no main effect of condition on relative maximal force (F = 0.017, p = 0.983, partial η^2 = 0.001), with no time × condition interaction effect (F = 0.377, p = 0.929, partial η^2 = 0.038). However, there was a main effect of time (F = 6.365, p ≤ 0.001, partial η^2 = 0.408), with large effect size. Relative maximal force was significantly higher at 1 min, 3 min, 6 min and 9 min compared to baseline (p ≤ 0.01).

Similarly, there was no main effect of condition on average power (F = 0.661, p = 0.522, partial η^2 = 0.033), nor a time × condition effect (F = 0.913, p = 0.508, partial η^2 = 0.045). There was a main effect of time (F = 9.585, p ≤ 0.001, partial η^2 = 0.197), with large effect size. Average power was significantly higher at 1 min, 3 min, 6 min and 9 min compared to baseline (p ≤ 0.001).

Again, there was no main effect of condition on velocity (F = 0.359, p = 0.701, partial η^2 = 0.018), nor time × condition interaction effect (F = 0.712, p = 0.681, partial η^2 = 0.034). However, there was a main effect of time (F = 10.802, p ≤ 0.05, partial η^2 = 0.213), with large effect size. Velocity was significantly higher at 3 min, 6 min and 9 min compared to baseline (p ≤ 0.05).

In contrast, there were no main effects of condition (F = 0.410, p = 0.666, partial η^2 = 0.020), nor time × condition interaction effect (F = 0.110, p = 0.896, partial η^2 = 0.005) for average force. However, there was a main effect of time (F = 2.568, p ≤ 0.05, partial η^2 = 0.060), with medium effect size. Average force was significantly higher at 1 min, 3 min, and 9 min compared to baseline (p ≤ 0.01).

Finally, there was no main effect of condition on HR (F = 2.648, p = 0.083, partial η^2 = 0.114). However, there was a significant

TABLE 1. Results for countermovement jump performance during the study for each warm-up condition.

	Time				
	Baseline	**1 min post**	**3 min post**	**6 min post**	**9 min post**
CMJ HI + Plyo (cm)	33.46 ± 5.99	35.84 ± 6.03*	35.88 ± 5.81*	36.87 ± 6.57**	37.21 ± 6.38***
CMJ LO + Plyo (cm)	34.14 ± 6.68	38.14 ± 6.68***	39.29 ± 6.94***	39.25 ± 7.63***	38.84 ± 7.52**
CMJ CON (cm)	36.39 ± 7.65	37.50 ± 7.81	37.54 ± 7.64	38.31 ± 7.27	38.57 ± 7.15
RMF HI + Plyo (%BW)	228.63 ± 24.07	242.11 ± 30.60	242.02 ± 29.34	241.02 ± 30.66	244.90 ± 30.10
RMF LO + Plyo (%BW)	231.71 ± 25.68	243.90 ± 29.71	239.39 ± 30.09	241.07 ± 25.84	242.33 ± 28.43
RMF CON (%BW)	232.81 ± 21.80	240.86 ± 22.03	243.10 ± 22.79	243.00 ± 26.34	246.98 ± 24.86
Power HI + Plyo (W)	1847.60 ± 414.51	1903.69 ± 515.29	1926.07 ± 455.47	1943.33 ± 446.84	1955.47 ± 483.44
Power LO + Plyo (W)	1948 ± 430.32	2102.32 ± 461.82	2107.43 ± 485.98	2084.64 ± 457.18	2053.10 ± 468.14
Power CON (W)	2011.77 ± 351.22	2023.19 ± 442.98	2098.77 ± 348.08	2071.85 ± 332.52	2109.31 ± 365.40
Force HI + Plyo (N)	1296.61 ± 249.56	1331.46 ± 223.10	1332.78 ± 249.78	1265.27 ± 406.27	1356.30 ± 263.41
Force LO + Plyo (N)	1344.65 ± 252.04	1381.13 ± 256.52	1387.30 ± 268.45	1376.37 ± 243.51	1362.25 ± 256.78
Force CON (N)	1367.62 ± 155.98	1396.00 ± 155.58	1415.31 ± 168.15	1387.32 ± 151.80	1407.54 ± 156.45
Velocity HI + Plyo (m/s)	1.51 ± 0.16	1.54 ± 0.18	1.56 ± 0.15	1.58 ± 0.15	1.57 ± 0.19
Velocity LO + Plyo (m/s)	1.54 ± 0.17	1.61 ± 0.18	1.61 ± 0.18	1.61 ± 0.18	1.60 ± 0.19
Velocity CON (m/s)	1.57 ± 0.14	1.60 ± 0.14	1.60 ± 0.16	1.59 ± 0.17	1.63 ± 0.18

Data are presented as mean ± standard deviation.

CMJ countermovement jump, HI short high intensity interval exercise, LO low intensity continuous exercise, CON control condition, Plyo Plyometrics, RMF relative maximal force, %BW % body weight, W watts, bracket = all conditions different from baseline, * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

main effect of time ($F = 49.347$, $p \leq 0.001$, partial $\eta^2 = 0.839$) and time × condition interaction effect ($F = 3.044$, $p = 0.005$, partial $\eta^2 = 0.238$), with large effect sizes. As shown in Figure 2, post-hoc comparisons revealed that HRs were significantly higher ($p \leq 0.01$) at 1 min, 3 min, 6 min and 9 min compared to baseline. Furthermore, following 1 min of recovery, HRs were significantly ($p \leq 0.05$) lower in CON compared to HI + PLYO, LO + PLYO and CON. Following 6 min of recovery HRs were also significantly lower in CON than HI + PLYO ($p \leq 0.05$), with no further significant differences between conditions at other time-points (Figure 3).

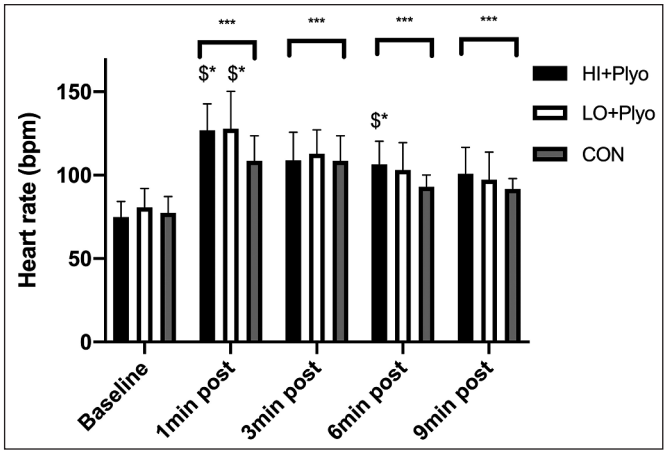


FIG. 3. Results for heart rate for each warm-up condition. $ = Different from control condition, bracket = all conditions different from baseline. *$p \leq 0.05$; ***$p \leq 0.001$.

DISCUSSION

The main findings of the present study indicate that combined cycling and plyometric activity acutely enhances CMJ height in recreationally active males between 1 min and 9 min post-stimulus, compared to no significant effect of a lower intensity cycling control condition. However, there was no evidence that one experimental condition was superior over the other, suggesting that the plyometric aspect may be the crucial component. The only slight difference between experimental conditions was that HR remained elevated 6 min post-stimulus following the higher intensity cycling intervention. It is noted that there were no differences in how elevated HR (vs. CON) was between HI + Plyo and LO + Plyo 1 min post-stimulus, again suggesting the plyometric aspect may have been predominant in dictating the intensity of the conditioning stimulus.

There is good evidence of a performance-enhancing effect from the preconditioning activities, and this could in part be due to an

increase in the peak force and rate of force development of a twitch contraction [28, 29], mainly due to an increase in calcium sensitivity of the acto-myosin complex caused by phosphorylation of the myosin regulatory light chain occurring in type II muscle fibres. PAP is a well-described phenomenon with a short half-life (~28 s) [30], usually < 3 min. However, the time course of myosin regulatory light chain phosphorylation rarely matches that of voluntary force enhancement, and other changes such as muscle temperature, muscle/cellular water content and muscle activation may underpin voluntary force enhancement [23] (called PAPE), so the time-course and mechanisms differentiate PAPE from PAP. In our study, the improvements of CMJ were found in both EXP conditions at 1 min post warm-up, in line with a PAP effect. However, improvements at later time points could be due to a PAPE effect (3–9 min). We consider it unlikely that improved CMJ performance was due to a learning effect as there was no change in the CON condition, and three maximal CMJs were performed before the baseline CMJs with no differences evident and the subjects had previous experiences in this action. It is worth noting that there has previously been mixed evidence regarding PAPE effects in less trained subjects such as ours, so the current findings are meaningful. An important contributing factor may be the specificity of force direction of the conditioning stimulus and muscles and movement involved (vertical plyometrics) to the outcome measure (vertical CMJ), as has been highlighted in more trained participants [13]. For that reason, we consider that the plyometric aspect may be the crucial component due to the specificity of preconditioning activity with the outcome measure (CMJ).

A previous meta-analysis and systematic review about PAP [4] showed that conditioning activity augmented power output, and these effects increased with training experience. In addition, potentiation was optimal following multiple sets at moderate intensities (60–85% 1RM) and using recovery period lengths between 7–10 min. Previous studies have shown a 4 min recovery duration was better than 5 min compared to baseline vertical jump height [31]. However, as we have observed in our study, a consistent optimal time did not seem to depend on the intensity of previous cycling effort, with similar cardiovascular stress between experimental conditions (Figure 2). This further emphasises that the plyometric component is likely the key aspect determining the intensity of the conditioning stimulus, rather than cycling. Plyometrics using DJ exercise with 70–75 cm box heights have shown acute increases in CMJ height between 5 to 15 min post exercise [32, 33] and in less time post exercise (1 to 5 min) using 20–60 cm [33, 34]. It remains to be determined in our participants if a change in box height from the 40 cm used in the current study would impact on optimal recovery duration.

Analysis of the CMJ kinetic and kinematic variables did not further elucidate which factors were contributing most to the CMJ height improvements. Indeed, only a main effect of time was evident, supporting an overall performance enhancement, though not statistically better than CON. It is likely that a number of factors may have contributed to this potential discrepancy, including several experimental limitations. One clear factor may relate to low statistical power, resulting in a Type II error for any effects of condition. This will have been compounded by variability in jump techniques within and between participants. Previous research on CMJs has shown that improvements in CMJ height can be explained by a variety of differences in jumping strategy and technique [35]. Given that our participants are not high-performance athletes performing CMJs as part of daily monitoring for example, although CMJ height data was consistent (e.g., CON trial data), changes in CMJ technique are likely to have occurred jump-to-jump, resulting in variations in force, velocity and power variables. A further contributing factor is likely that of individual differences, as has been reported extensively in PAP literature [23]. For example, in the HI + Plyo condition, 37.5% of the subjects achieved the higher CMJ height at 1 min, 6.25% at 3 min, 31.25% at 6 min and 25% at 9 min post conditioning activity. However, in the case of the LO + Plyo condition, 25% of the subjects achieved the higher CMJ height at 1 min, 37.5% at 3 min, and 18.75% at both 6 min and 9 min post conditioning activity. Therefore, coaches and athletes must evaluate the individual effect of PAP to achieve the best jump performance. As demonstrated here again, there is high variability between subjects in terms of the optimal recovery time. More studies are needed to analyze the causes of these differences, and therefore, the results must be considered at the individual level. Finally, our results can be applied to physically active men, as women were not included in our study due to the convenience sampling employed.

CONCLUSIONS

In conclusion, this study has shown that up to 15% CMJ performance enhancement can be elicited following high or low-intensity cycling combined with plyometric preconditioning activities in active males, with the intensity and movement specificity of the plyometric component likely the crucial component. Our results suggest that the optimal recovery time within the 1 min-9 min window may be individualized.

Practical applications

From a practical viewpoint, we recommended that coaches use combined cycling efforts (high and low-intensity) and drop jumps to acutely improve subsequent CMJ performance. Coaches may wish to explore if there is a consistent optimal recovery time on an individual basis.

Conflict of interest declaration

The authors declare no conflict of interest.

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Different time course recovery of muscle edema within the quadriceps femoris and functional performance after single- vs multi-joint exercises

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ABSTRACT: This study aimed to verify the time course recovery of muscle edema within the quadriceps femoris and functional performance after lower-body single- and multi-joint exercises. For this within-participant unilateral and contralateral experimental design, fourteen untrained young males performed a unilateral knee extension exercise (KE), and a unilateral leg press (LP) exercise in a counterbalanced order. At pre-, post-, 24 h, 48 h, 72 h, and 96 h after exercise, the peak torque (PT), unilateral countermovement jump (uCMJ) performance, and rectus femoris (RF) and vastus lateralis (VL) muscle thicknesses were recorded in both legs. The PT decreased immediately after ($p = 0.01$) both exercises (KE and LP) and was fully recovered 24 h after KE ($p = 0.38$) and 48 h after LP ($p = 0.68$). Jump height and power, in the uCMJ, followed the same PT recovery pattern after both exercises. However, vertical stiffness (Kvert) was not affected at any time point after both protocols. The RF thickness increased after both exercises ($p = 0.01$) and was fully restored 48 h after KE ($p = 0.86$) and 96 h after LP ($p = 1.00$). The VL thickness increased after both exercises ($p = 0.01$) and was fully restored 24 h after LP ($p = 1.00$) and 48 h after KE ($p = 1.00$). The LP exercise, compared to KE, induced more prolonged impairment of functional performance and delayed recovery of RF muscle edema. However, the VL edema-induced muscle swelling recovery was delayed after the KE exercise. The different recovery kinetics between functional performance and muscle damage should be taken into consideration depending on the objectives of the next training sessions.

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Muscle damage
Torque impairments
Muscle recovery

INTRODUCTION

Resistance training (RT) is an important strategy for increasing muscle strength, muscle size, and neuromuscular functional capacity [1, 2]. However, one key variable that should be considered in the prescription of RT is exercise selection [3]. Among different classifications, resistance exercises can be divided into single- and multi-joint exercises. These exercises may induce different long-term RT adaptations (e.g., muscle strength and hypertrophy), and these outcomes may be mutually dependent [4]. However, when referring to lower-body exercises there is no consensus regarding the outcomes of the single- or multi-joint exercises. For instance, some studies have previously reported that the multi-joint leg press exercise may lead to greater improvements in the knee extensor strength than the single-joint knee extension exercise and suggested that these outcomes may be due to greater neural challenges in multi-joint exercises [5, 6]. In contrast, Stien et al. [7] reported that the knee strength improvements in single- and multi-joint exercises are task-dependent (i.e., improvements in knee extensor and leg press exercises strength will be greater in single- and multi-joint exercises, respectively).

Most studies comparing single- and multi-joint exercises have focused on chronic responses [4–6]. However, the acute specific responses of lower-body single- and multi-joint exercises to muscle damage and recovery remain under discussion [4]. It is well recognized that RT-induced muscle damage is accompanied by some acute deleterious effects such as neuromuscular function impairments (e.g., decrease in muscle force), delayed onset muscle soreness (DOMS), and edema-induced muscle swelling, and elevations in biomarkers such as creatine kinase [8–10].

Recently, Maeo et al. [10] reported that eccentric knee extension exercise (i.e. single-joint) induced a longer-lasting isometric peak torque impairment than the eccentric squat exercise (i.e. multi-joint).

In addition, the authors observed greater muscle edema in the rectus femoris (RF) than the vastus muscles after eccentric knee extension exercise. In contrast, the vastus medialis showed greater muscle edema than the RF after eccentric squat exercise. In addition, Maeo et al. [10] also reported different recovery kinetics between isometric peak torque of the knee extensors and muscle edema in quadriceps muscles, which are indirect muscle damage markers, after single- and multi-joint lower-body eccentric exercises. However, the study by Maeo et al. [10] was performed with only eccentric actions, and it is well recognized that the magnitude of the induced muscle damage can be greater after eccentric than after concentric muscle actions [12, 13]. Thus, it is also important to investigate whether single- and multi-joint lower-body exercises performed during traditional RT using eccentric-concentric muscle actions would induce different knee extensor performance impairments and different magnitudes of muscle edema within the quadriceps (i.e., bi-articular RF vs. mono-articular VL).

Therefore, considering these aforementioned aspects, the purposes of this study were, first, to compare the time course recovery of indirect markers of muscle damage of the knee extensors; and second, to verify the different recovery kinetics in indirect markers of muscle damage of the knee extensors, after lower-body single- and multi-joint exercises. Based on previous evidence [2, 6, 11, 14], we hypothesized that leg press multi-joint exercise would induce greater muscle damage on the VL, and longer time course muscle performance recovery than the knee extension single-joint exercise.

MATERIALS AND METHODS

Study Design

The experimental procedures are shown in Figure 1. A within-participant unilateral and contralateral counterbalanced design was used to verify the magnitude and the time course recovery of muscle damage and functional performance after single- and multi-joint leg extension exercises. Participants visited the laboratory on eight occasions. On the first and second visits, the 10-maximum repetition (10RM) loads in unilateral leg extension and the unilateral leg press machine using the contralateral leg were determined. Moreover, the familiarization procedures with the unilateral exercises and

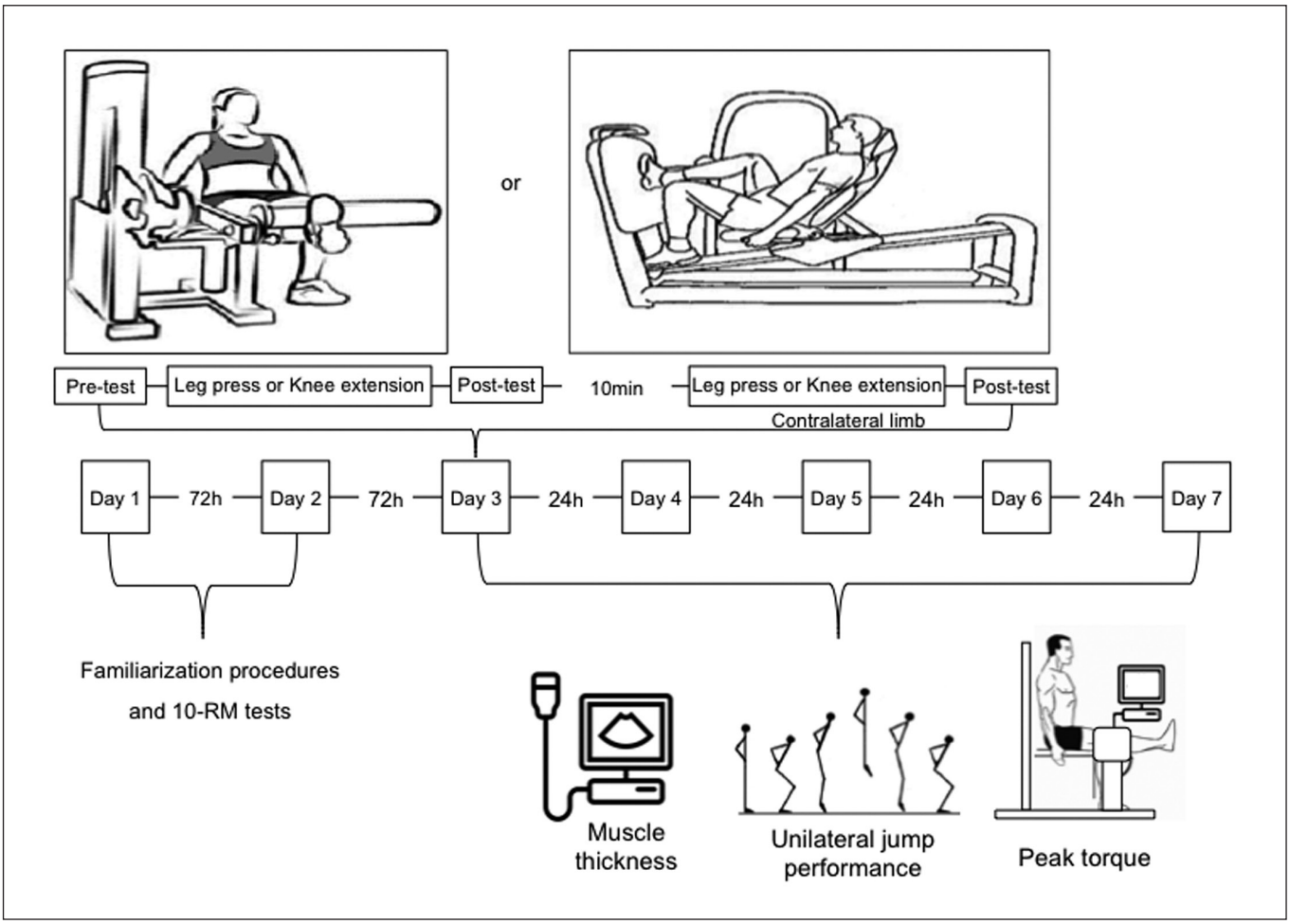


FIG. 1. Study design.

neuromuscular evaluations (i.e., peak torque and jump performances) were completed. At the subsequent visit, participants performed the unilateral exercise protocols with an evaluation of unilateral maximal peak torque (PT), unilateral countermovement jump (uCMJ), and muscle thickness measured before, immediately after, and 24, 48, 72, and 96 h after the protocols. Participants were instructed to visit the laboratory at the same time of day on all occasions to avoid circadian influences. In addition, participants were not allowed to perform any vigorous physical activity or unaccustomed exercise during the experimental period.

Participants

Fourteen healthy young men (age: 22.83 + 3.56 years; body mass 79.08 + 9.68 kg; height: 175.37 + 8.62 cm) completed all experimental sessions. To be included in this study, participants were required to have previous experience in RT with no exposure to resistance exercises for at least 6 months prior to study commencement, and to be free of cardiovascular, pulmonary, or metabolic disease. They were instructed to maintain their normal eating habits and to avoid alcohol, physical exercise, and interventions that could affect their recovery (i.e., massage, anti-inflammatory and analgesic drugs, and nutritional supplements). All procedures were approved by the University of Brasilia Committee on Human Research (CAAE No. 36351214.7.0000.0030) and were performed according to the Declaration of Helsinki. Informed consent was obtained from all participants.

Ten-Repetition Maximum Tests

10 RM tests in the unilateral leg extension and leg press exercises were used to determine the loads to be used in the training session. Participants performed 10 RM tests adapted from the Brown et al. [15] recommendations. Briefly, they warmed up by performing two sets of 10 repetitions at 40% and 60% of their estimated 10RM, with a 60 s rest interval between the sets. After the warm-up, the 10RM load in each exercise was determined with no more than three attempts. The rest intervals were 5 min for each attempt, and 10 min between exercises. After 72 hours, a retest was performed to confirm 10RM loads and ensure data reliability.

Strength Exercise Protocols

These within-subject training protocols were composed of 8 sets of 10 repetitions in the unilateral seated knee extension exercise (i.e., a single-joint exercise), and 8 sets of 10 repetitions in the unilateral leg press machine exercise (i.e., a multi-joint exercise). Each exercise was performed with a different leg in randomized order, with a 2 min rest interval between sets, and 10 min between exercises. The load of the 1st to 3rd set was 90% of the 10RM, and for the 4th set onwards, the load was 70% of the 10RM. Participants were instructed to perform each repetition in approximately 4 s, with a concentric phase of 1–2 s and the eccentric phase of 2–3 s, and it was controlled verbally by the evaluator using a metronome.

Maximal Isokinetic Knee Extension Torque

The time course of PT was used as an indirect measure of muscle damage to the knee extensors [8, 9]. The PT was recorded with an isokinetic dynamometer (Biodex Medical, Inc., Shirley, NY, USA) before, 10 min after, and 24, 48, 72, and 96 h after the exercise protocols. Participants were positioned and securely fastened in the dynamometer chair to minimize ancillary movements. The lever arm was fixed 3 cm above the lateral malleolus, and gravity correction was performed according to the manufacturer's procedures. They performed 2 sets of 4 repetitions at $60°s^{-1}$ for each leg, with 2 min rest intervals between sets, and 10 min rest intervals between legs. The range of motion was set from 5º to 90º of knee flexion (0º = full extension). The same researcher carried out the procedures for all participants and provided verbal encouragement to achieve maximal performance in every attempt. Maximal PT was defined as the highest value of the torque curve recorded during a single unilateral knee extension repetition.

Muscle Thickness Assessment

Muscle thickness was measured before, after 1 min, and 24, 48, 72, and 96 h after exercise protocols, via B-mode ultrasound (Philips-VMI, Ultra Vision Flip, model BF), which is a useful and valid tool to assess muscle edema [16]. For the measurements, participants were positioned supine on a table with the assessed knee supported from below to maintain 30° of flexion. Thereafter, they were asked to relax their limbs during the assessment. For baseline measurements, participants were evaluated in the supine position after 5 min of resting. A water-soluble transmission gel was applied on the 10 MHz ultrasound probe to provide acoustic contact without depressing the dermal surface. The ultrasound images were obtained from the middle points of the RF and vastus lateralis (VL) (i.e., 50% of the distance from the anterior superior iliac spine to the superior border of the patella) [11]. The measured sites were identified with a permanent marker at baseline to keep the same probe positioning after exercise, and for the subsequent exercise sessions. Ultrasound images were stored and further analysed using ImageJ software (National Institutes of Health, USA, version 1.49). Muscle thickness was defined as the distance between the border of the subcutaneous fascia and the deep aponeurosis [16]. All measurements were performed three times by the same investigator and the mean value was used for further analyses.

Unilateral Countermovement Jump

The participants performed three maximum attempts, separated by > 15 s, of the unilateral countermovement jump (uCMJ) on a force plate (Advanced Mechanical Technology Inc., Watertown, MA, USA) that recorded vertical forces with a sampling rate of 500 Hz. The uCMJ was used because each exercise protocol was applied to a different limb for each participant. In addition, the uCMJ has been previously reported as a useful tool to assess acute neuromuscular performance changes after different exercises [17, 18]. Both exercise

protocols and uCMJ order were performed with randomization of the limb used to avoid any interference of limb dominance and order on the results. Before each attempt, participants were instructed to stand still in the centre of the force plate with their hands placed on their hips. Subsequently, they were encouraged to jump "as high as possible". The best attempt, based on jump height, was selected for further analysis. The uCMJs were performed before, after 10 min, and 24, 48, 72, and 96 h after the exercise protocols [9, 17]. The kinetic parameters of the best jumps were obtained with the corresponding software (AccuPower version 2.0, Massachusetts, USA) or calculated from the raw data in a custom-made Excel spreadsheet: jump height (h), determined from the difference between the maximum height of the centre of mass (apex) and the last contact of the toe on the ground during the take-off; peak power (PP) during the push-off phase ($W \cdot kg^{-1}$); and normalized vertical stiffness (Kvert) ($N \cdot m^{-1} \cdot kg^{-1}$) (Kvert = $Fmax \cdot \Delta Y^{-1}$), where Fmax is peak vertical force minus body weight, and ΔY is the maximum vertical displacement of the centre of mass [19].

Statistical Analyses

Data are presented as mean + standard deviation (SD) and 95% confidence interval. The Shapiro-Wilk test was used to check the normal distribution of variables. A two-way repeated measure ANOVA 2 × 6 (exercise × time) was used to compare muscle swelling, peak torque, and jump performance parameters between single- and multi-joint exercises. A Bonferroni *post hoc* correction was applied in the case of significant differences in the ANOVA. Cohen's qualitative descriptors of standardized effect size were used to determine the magnitude of the exercise protocol changes and their recovery effects. The magnitude changes of the dependent variables before and after the exercise protocols were calculated from the formula: Post-test mean – Pre-test mean / Pre-test SD. In addition, the magnitude of the recovery parameters 24, 48, 72, and 96 h after the exercise protocols for each variable were calculated from: Post-24 mean (or 48, 72, 96) – Pre-test mean / Pre-test SD. The effect sizes (ES) < 0.4, 0.41–0.7, and > 0.7 represented small, moderate and large ES, respectively [20]. The significance level was set at $p < 0.05$. SPSS software (version 20.0; SPSS, Inc., Chicago, IL, USA) was used for all these analyses.

RESULTS

Peak Torque

The PT values are shown in Table 1. There was neither a significant effect for the factor exercise [$F(1,13) = 0.76$, $p = 0.39$] nor a significant exercise × time interaction [$F(2.16, 28.11) = 0.77$, $p = 0.48$] in the PT. However, there was a significant effect for the time factor [$F(5,65) = 43.20$, $p = 0.01$]. The Bonferroni post-hoc test revealed a significant decrease in PT immediately after both knee extension ($p = 0.01$) and leg press ($p = 0.01$) exercises. Moreover, PT was fully recovered 24 h after the knee extension exercise ($p = 0.38$), whereas it returned to baseline values 48 h after the leg press exercise ($p = 0.68$).

Muscle Thickness

The RF and VL muscle thicknesses are presented in Table 2. There was neither a significant effect for the exercise factor [$F(1,13) = 2.10$, $p = 0.17$] nor a significant exercise × time interaction [$F(2.34, 30.45) = 1.35$, $p = 0.25$] in the RF muscle thickness. However, there was a significant effect for the time factor [$F(5,65) = 82.45$, $p = 0.01$]. The Bonferroni post-hoc test showed that RF muscle thicknesses increased immediately after both knee extension and leg press exercises ($p = 0.01$) and returned to baseline values only after 96 h in the leg press exercise ($p = 1.00$) but after 48 h in the knee extension exercise ($p = 0.86$).

For the VL muscle thickness, there was neither a significant effect for the exercise factor [$F(1, 13) = 2.10$, $p = 0.85$] nor a significant exercise × time interaction [$F(4.07, 52.91) = 2.05$, $p = 0.09$]. However, there was a significant effect for the time

TABLE 1. Peak torque measures before and after both exercise protocols.

Knee Extension	PRE-	POST-	24 h	48 h	72 h	96 h
PT (Nm)	254.19 ± 29.32	206.44 ± 39.32*	242.23 ± 36.81	243.50 ± 35.00	250.21 ± 35.00	252.45 ± 26.96
95% IC	(237.3–271.0)	(183.7–229.1)	(220.9–263.4)	(223.2–263.7)	(230.0–270.4)	(236.9–268.0)
Effect Size	-	-1.63 (large)	-0.41 (moderate)	-0.36 (small)	-0.14 (small)	-0.14 (small)
Leg Press	PRE-	POST-	24 h	48 h	72 h	96 h
PT (Nm)	251.28 ± 40.75	197.15 ± 44.45*	236.04 ± 41.27*	238.44 ± 45.73	248.76 ± 44.67	252.69 ± 45.42
95% IC	(227.7–274.8)	(171.4–222.8)	(212.2–259.9)	(212.0–264.8)	(223.0–274.6)	(226.5–278.9)
Effect Size	-	-1.33 (large)	-0.37 (small)	-0.32 (small)	-0.06 (small)	-0.06 (small)

* Significant difference compared to the PRE moment with the same exercise protocol; PT = peak torque; CI = confidence interval; SD = standard deviation

TABLE 2. Rectus femoris (RF) and vastus lateralis (VL) muscle thickness measures before and after both exercise protocols.

Knee Extension	PRE-	POST-	24 h	48 h	72 h	96 h
RF (mm)	25.21 ± 2.35	33.37 ± 2.10*	27.03 ± 2.94*	26.62 ± 3.27	26.07 ± 3.07	25.52 ± 2.59
95% IC	(23.87–26.58)	(32.15–34.58)	(25.33–28.73)	(24.73–28.51)	(24.30–27.84)	(24.03–27.01)
Effect Size	-	3.47 (large)	0.77 (large)	0.60 (moderate)	0.37 (small)	0.13 (small)
VL (mm)	24.22 ± 3.23	26.68 ± 2.94*	25.70 ± 3.27*	24.78 ± 3.18	25.06 ± 2.97	24.58 ± 3.20
95% IC	(22.36–26.09)	(24.97–28.38)	(23.81–27.59)	(22.95–26.62)	(23.35–26.78)	(22.74–26.43)
Effect Size	-	0.76 (large)	0.46 (moderate)	0.17 (small)	0.26 (small)	0.11 (small)
Leg Press	PRE-	POST-	24 h	48 h	72 h	96 h
RF (mm)	25.20 ± 2.53	32.94 ± 3.23*	27.37 ± 3.32*	27.23 ± 3.01	27.07 ± 1.95*	26.11 ± 3.00
95% IC	(23.74–26.66)	(31.08–34.80)	(25.46–29.29)	(25.49–28.97)	(25.94–28.19)	(24.38–27.84)
Effect Size	-	3.06 (large)	0.86 (large)	0.80 (large)	0.74 (large)	0.36 (small)
VL (mm)	25.01 ± 2.59	26.55 ± 2.28*	24.73 ± 2.86	24.66 ± 2.99	24.75 ± 2.51	24.89 ± 3.66
95% IC	(23.52–26.51)	(25.24–27.87)	(23.08–26.38)	(22.93–26.38)	(23.30–26.20)	(22.79–27.01)
Effect Size	-	0.59 (moderate)	-0.11 (small)	-0.14 (small)	-0.10 (small)	-0.05 (small)

* Significant difference compared to the PRE moment in the same exercise protocol; # significant difference compared to knee extension exercise. RF = rectus femoris; VL = vastus lateralis; CI = confidence interval; SD = standard deviation

TABLE 3. Jump performance measures before and after both exercise protocols.

Knee Extension	PRE-	POST-	24 h	48 h	72 h	96 h
Jump (cm)	11.30 ± 3.11	8.69 ± 2.81*	10.14 ± 2.55	10.29 ± 2.92	10.52 ± 2.66	10.97 ± 2.35
95% IC	(9.51–13.10)	(7.07–10.31)	(8.67–11.61)	(8.60–11.98)	(8.99–12.06)	(9.62–12.33)
Effect Size	-	-0.84 (large)	-0.37 (small)	-0.32 (small)	-0.25 (small)	-0.11 (small)
Peak Power (W/kg)	32.32 ± 5.51	28.83 ± 5.06*	30.98 ± 4.94	30.27 ± 4.35	30.15 ± 3.44	30.94 ± 3.64
95% IC	(29.13–35.50)	(25.91–31.76)	(28.13–33.83)	(27.76–32.79)	(28.19–32.13)	(28.84–33.04)
Effect Size	-	-0.63 (moderate)	-0.24 (small)	-0.37 (small)	-0.39 (small)	-0.25 (small)
Kvert (N/m/kg)	104.34 ± 31.98	125.92 ± 43.81	108.09 ± 39.99	105.77 ± 28.68	96.14 ± 22.75	95.39 ± 22.12
95% IC	(85.87–122.80)	(100.63–151.21)	(85.00–131.18)	(89.21–122.33)	(83.00–109–28)	(82.62–108.16)
Effect Size	-	0.67 (moderate)	0.12 (small)	0.04 (small)	-0.26 (small)	-0.28 (small)
Leg Press	PRE-	POST-	24 h	48 h	72 h	96 h
Jump (cm)	11.41 ± 3.64	7.95 ± 2.44*	9.74 ± 3.16*	9.96 ± 2.74	10.58 ± 3.62	11.09 ± 3.00
95% IC	(9.32–10.50)	(6.54–9.37)	(7.92–11.57)	(8.37–11.55)	(8.49–12.67)	(9.35–12.82)
Effect Size	-	-0.95 (large)	-0.46 (moderate)	-0.40 (moderate)	-0.23 (small)	-0.09 (small)
Peak Power (W/kg)	31.21 ± 6.50	26.71 ± 5.47*	29.58 ± 6.68*	29.43 ± 6.07	30.52 ± 6.68	30.07 ± 5.35
95% IC	(27.46–34.97)	(23.55–29.87)	(25.73–33.42)	(25.93–32.94)	(26.66–34.38)	(26.98–33.16)
	-	-0.69 (moderate)	-0.25 (small)	-0.27 (small)	-0.11 (small)	-0.18 (small)
Effect Size	112.30 ± 36.78	129.39 ± 38.89	124.98 ± 77.14	133.08 ± 120.62	114.29 ± 37.68	99.86 ± 46.21
Kvert (N/m/kg)	(91.05–133.54)	(106.94–151.85)	(80.44–169.52)	(63.44–202.73)	(92.54–136.05)	(73.18–126.55)
Effect Size		0.46 (moderate)	0.34 (small)	0.56 (moderate)	0.05 (small)	-0.34 (small)

* Significant difference compared to the PRE moment in the same exercise protocol; Kvert = vertical stiffness; CI = confidence interval; SD = standard deviation

factor [F (5,65) = 82.45, p = 0.01]. The Bonferroni post-hoc test indicated that VL muscle thickness increased immediately after both knee extension and leg press exercises (p = 0.01). However, in the leg press exercise, the VL muscle thickness returned to baseline values after 24 h (p = 1.00), while it returned to baseline values after 48 h in the knee extension exercise (p = 1.00).

Jump Performance

The jump height, PP, and Kvert during the uCMJ are presented in Table 3. There was neither a significant effect for the exercise factor [F (1,13) = 0.41, p = 0.54] nor a significant exercise × time interaction [F (2.76, 35.90) = 1.25, p = 0.31] in jump height. However, there was a significant effect for the time factor [F (5,65) = 17.65, p = 0.01]. The Bonferroni post-hoc test showed that jump height decreased immediately after both knee extension and leg press exercises. However, there was a different recovery profile between exercises. Jump height returned to baseline values after 48 and 24 h in the leg press (p = 0.15) and knee extension exercises (p = 0.32), respectively.

For PP, there was neither a significant effect for the exercise factor [F (1,41.51) = 1.39, p = 0.26] nor a significant exercise × time interaction [F (5, 4.71) = 1.98, p = 0.09]. However, there was a significant effect for the time factor [F (5, 47.61) = 11.80, p = 0.01]. The Bonferroni post-hoc analysis showed that in both exercises PP was immediately decreased, but with different recovery profiles. The PP returned to baseline values 24 and 48 h after the knee extension (p = 0.76) and leg press (p = 0.08) exercises, respectively.

For the Kvert, there was no significant effect for either the exercise factor [F (1,13) = 1.67, p = 0.22] or the time factor [F (5,65) = 3.03, p = 0.07] or a significant exercise × time interaction [F (1.35, 17.53) = 0.66, p = 0.47].

DISCUSSION

The main finding of this study is that a fatiguing leg press exercise bout induced longer impairment of lower-body functional performance than the knee extension exercise. In addition, our results suggest that the leg press exercise may have induced greater RF muscle damage, as there was a longer recovery in RF edema-induced muscle swelling than the knee extension single-joint exercise. However, the VL muscle damage may be greater after knee extension exercise, as edema-induced muscle swelling recovery was longer in the knee extension exercise than in the leg press exercise. Moreover, the current findings also suggest that there were differences in recovery kinetics between indirect markers of muscle damage (i.e., functional performances and muscle-induced edema) after both exercises.

The leg press exercise induced a greater lower-body functional capacity impairment than the knee extension exercise, as confirmed by the delayed peak torque and jump height recovery. The greater impairment in the multi-joint exercise in the current study is contrary to the study by Soares et al. [8], who observed a greater peak torque impairment and longer time necessary for torque recovery in the elbow flexors after a biceps curl single-joint exercise than after the lat pull-down multi-joint exercise. In addition, Maeo et al. [10] reported a torque recovery of 48 h after an eccentric squat exercise, while the eccentric knee extension exercise showed a complete torque recovery in 72 h. These distinct responses could be due to differences in muscle structure and fibre type composition between upper and lower limb muscles [21]. Moreover, muscle action may also influence the extent of exercise-induced muscle damage [12, 13]. Therefore, the discrepancies between the current results and those of previous studies [9, 11] may be related to differences in muscles involved and type of muscle actions. Further studies are needed to test these hypotheses.

Several factors may affect the magnitude of exercise-induced muscle damage after fatiguing RT exercises, including the type of contraction, exercise load, volume, and velocity of contraction [8–10, 12, 13, 22, 23]. However, all these aforementioned factors were similar between protocols in the current study. In this regard, our results showed a longer period of torque impairment following the leg press exercise than the knee extension exercise, which may be related to the greater mechanical stress and higher neural activation imposed by the multi-joint exercise [6]. Nevertheless, further studies are needed to test these hypotheses.

An interesting result of the current study was a longer recovery in RF edema muscle swelling after the leg press exercise (i.e., 96 h) than knee extension exercise (48 h). Thus, these results may suggest that RF muscle damage is greater in lower limb multi-joint exercises because of the bi-articular nature of this muscle and the relationship between muscle lengthening and damage [24–26]. During the concentric phase of the leg press exercise, the distal portion of the RF may be gradually contracted to perform knee extension, but the proximal portion may be lengthened to induce hip extension, while the opposite happens during the eccentric phase. In contrast, in the knee extension exercise, the hip was always flexed, which in turn could limit the lengthening of the RF muscle [11]. Since muscle lengthening during an exercise is associated with greater force impairments and subsequent muscle damage [26], it may be expected that the leg press exercise could induce greater damage in RF muscle than the knee extension exercise, as confirmed in the current study.

Although the VL is a uni-articular muscle [27], which means that its activation cannot be influenced by different joint positions in both single- and multi-joint exercises [24, 25], this muscle showed a longer muscle edema recovery after the knee extension exercise than the leg press exercise. This finding suggests greater VL muscle damage in the single-joint exercise than after the multi-joint exercise. To the best of our knowledge, this is the first time this interesting finding has been reported. However, previous studies using electromyography have reported different hip joint positions' influence on VL muscle activity [28, 29]. Indeed, Ema et al. [28] demonstrated higher excitation in the sitting position, followed by an inclined and supine position for the VL. Moreover, Lewek et al. [30] previously

reported a greater VL muscle activity in the knee extension exercise than in the lunge exercise. Therefore, it may suggest greater action and mechanical stress of the VL muscle when the hip is flexed during knee extension movements, with further studies needed to confirm our findings.

In the current study, the jump and torque performances in both exercises exhibited the same recovery pattern. Nonetheless, muscle edema recovery was delayed after both protocols. Similar to our study, Maeo et al. [11]reported a full torque recovery 24–48 hours after eccentric knee extension, squat, and downhill walking exercises. Meanwhile, the time course recovery of vastus muscles and RF was longer than 72 hours after these exercises. Thus, the results of the previous [11] and the current study may indicate that muscular performance can be fully recovered in a shorter time despite the pro-inflammatory responses induced by muscle swelling [31]. In this regard, other factors may be influencing muscular performance recovery after fatiguing exercise. For instance, it has been suggested that the perception of fatigue, muscle soreness, and stiffness may influence both muscular performance and subsequent recovery after eccentric exercises [31]. While future studies should be conducted to appropriately test this hypothesis, independently of the associated mechanisms, the earlier recovery of muscular performance is relevant because muscle strength and power can be associated with functional performance [32].

Finally, the post-measures for Kvert did not show significant differences from pre- exercise measures in both exercises. However, considering the ES, Kvert and jump performance revealed a different time course with preservation of stiffness despite the impairments in jumping performance. It has been proposed that a high stiffness is favourable to improve performance in movements involving the stretch-shortening cycle [33]. Moreover, an association was previously reported [19] between Kvert and the rate of force development (RDF) during the CMJ, thus confirming the important role of Kvert in vertical jumping. Considering the current and the aforementioned studies [19, 33], the existence of a compensatory neuromuscular mechanism related to this Kvert preservation may be suggested. However, this should be interpreted with caution because these above-mentioned studies [19, 33] have a cross-sectional design. Similar to the current study, a previous study reported an increase in passive muscle stiffness after a fatiguing exercise, which may provide additional information on the recovery status of subjects [34]. Therefore, further studies should be conducted to verify whether the acute adaptations in stiffness from different exercises are associated with a compensatory mechanism linked to a recovery status.

Our study has some limitations. First, no measures of delayed onset muscle soreness were included; these might have helped to better explain the dissociated responses between functional performances and edema-induced muscle swelling. In addition, no electromyographic measures were recorded, though it would provide valuable information on the active muscles during both fatiguing and evaluation protocols.

CONCLUSIONS

The current findings indicate greater mechanical stress in the leg press exercise than in the knee extension exercise, as demonstrated by longer impairments in torque, power, and jump performance. The current results may explain the greater strength improvements after resistance training with multi-joint exercises [6]. In addition, considering the bi-articular nature of the RF [24, 25] and the relationship between muscle lengthening and muscle damage [26], it may be suggested that the RF is more damaged after the leg press exercise than the knee extension exercise. In contrast, it seems that the VL is more stressed when the hip joint is flexed, as occurred in the current and previous studies [28, 29] that investigated the hip angle position during knee extension exercise. Finally, the faster recovery of functional performance despite the presence of muscle damage should be taken into consideration depending on the objectives of the next training sessions (e.g. hypertrophy vs. power).

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Conflict of interest

The authors declare that they have no conflict of interest.

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The associations between physical-test performance and match performance in women's Rugby Sevens players

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ABSTRACT: Evaluating the relationships between physical-test and match performance in team sports could be useful for training prescription and athlete evaluation. Here we investigated these relationships in women's Rugby Sevens. Thirty provincial-representative players performed Bronco-fitness, countermovement-jump, acceleration, speed, and strength tests within two weeks before a two-day tournament. Match-running and match-action performance measures were provided by GPS units and video analysis. Generalised and general linear mixed models were employed to estimate the effect of a two standard-deviation difference in physical-test measures on match measures. Effect magnitudes were assessed via standardisation (using the between-player SD) and, for effects on tries scored, also via match winning (based on simulating matches). Evidence for substantial and trivial true magnitudes was provided by one-sided interval-hypothesis tests and Bayesian analysis. There was good evidence of positive effects of many physical-test measures on match high-intensity running, with large effects for jump height and acceleration. There was some evidence of small-moderate positive effects of speed and Bronco, and of small-moderate negative effects of maximal strength and jump height, on match total running and high intensity changes in speed. The evidence was generally inadequate for associations between physical-test measures and match actions, but there was good evidence of small-large positive effects of back squat and jump height on tries scored. Enhancing players' jump height and back-squat performance might therefore increase the likelihood of match success in women's Rugby Sevens.

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INTRODUCTION

Women's Rugby Sevens is an intermittent, field-based team sport characterised by high-intensity activities and collisions [1]. Two teams of seven players contest matches over two 7-min halves in a tournament format over 2–3 days. Similar to other team sports, a combination of technical, tactical, and physical factors determines success in women's Rugby Sevens [2]. While some of these factors (e.g., tactical awareness, decision making, and passing accuracy) are independent of physical measures, evaluating the relationships between physical-test and match performance could provide helpful information to implement specific training programs for enhancing match performance [2] and refining athlete evaluation.

In a previous study on women's Rugby Sevens across different playing levels, performance in various physical tests (10-m acceleration, 40-m sprint, Yo-Yo Intermittent Recovery Test Level 1, vertical jump) had moderate to large correlations with some match-running activities, including total distance, distance covered >5 m·s^{-1}, and maximal speed [3]. However, several other measures of match running from the women's Rugby Sevens literature such as number of sprints and accelerations [4, 5] were not included in this study; match actions were also not included. In provincial-representative and international-level men's Rugby Sevens players, moderate to large correlations were observed between numerous physical-test measures and various match actions (e.g., tries scored) [6], but no studies have tested the relationships between physical-test measures and match actions in women's Rugby Sevens. Therefore, in this study, we explored the associations of a range of physical-test measures with various match-running and match-action measures in women's Rugby Sevens players.

MATERIALS AND METHODS

Subjects

Thirty women's Rugby Sevens players (age: 22 ± 5 y, height: 1.68 ± 0.05 m, mass: 69 ± 7 kg) representing five different New Zealand Provincial Union teams participated in the study. Each

participant provided written informed consent and ethical approval was granted from the University of Waikato research ethics committee.

Study design

The association between physical-test performance and match performance in women's Rugby Sevens players was examined using a descriptive correlation design. Participants performed a battery of physical tests within the two weeks before a two-day tournament. Match-running and match-action data were collected as measures of athlete performance using GPS units and video analysis. All tests employed are commonly used in Rugby [6–8].

Acceleration and maximal speed

Acceleration and maximal speed abilities were assessed over a 40-m sprint on an outdoor artificial turf. Single beam timing lights (Brower Timing System, Utah, USA) were positioned at 0, 10, 30, and 40 m. The first gate was set at a 0.5 m height, while the remaining were set at 0.75 m. Prior to performing the sprints, participants completed a 10-minute standardised warm up comprising of jogging, dynamic stretches, running drills, and three stride-outs at increasing intensity. Participants started each sprint in a standing split position 0.5 m behind the first gate and were instructed to "run as fast as possible" past the last gate. Each participant performed two maximal effort sprints, separated by three minutes of passive rest. Sprint time was measured to the nearest 0.01 second. The fastest 10-m, 30-m, 40-m, and 30–40 m times were transformed into average running speeds and used for analysis. The speed over 10 m was used as an indicator of acceleration ability, while 30-m, 40-m, and 30–40 m speeds were used as measures of maximal speed abilities. The re-test reliability (intraclass correlation coefficient, ICC) for 10-m, 30-m, and 40-m sprint times in women's Rugby Sevens players using similar equipment was 0.90, 0.95, and 0.96 [8].

Fitness

The 1.2 km shuttle run test, also known as the Bronco test [7], was used as a measure of fitness. The test was performed outdoors, on artificial turf, in running shoes. The protocol consists of a continuous 20, 40, 60 m straight shuttle run, completed five times at maximal intensity (i.e., 20 m and back, 40 m and back, 60 m and back) [9]. Total running time was recorded with a stopwatch. Average running speed was calculated from total time and used for analysis. The ICC for Bronco time was 0.99 in men's and women's team-sport players combined [10].

Countermovement jump

Bodyweight countermovement jumps were assessed using dual-axis force plates (PASPORT force plate, PASCO, California, USA) and analysed using custom-made software (Weightroom, HPSNZ, Auckland, New Zealand) sampling at 100 Hz. Participants started from an upright standing position with their hands-on hips and were instructed to "bend their knees to a self-selected depth and to jump as high as possible". Two warm up trials were given, followed by two sets of three jumps separated by two minutes rest. The best jump height (calculated from flight time) recorded by each athlete was included in the analysis. The re-test reliability of the best jump height out of three countermovement jumps was 0.97 (ICC) and 3.6% (typical error) in women's soccer players [11].

Maximal strength

Back squat and bench press exercises were used to evaluate lower-body and upper-body maximal strength. For the back squat, athletes started from a standing position and were instructed to "lower until the thighs are parallel to the floor and then come up in the starting position". A miss was recorded if participants failed to meet the proper depth or successfully come up in a straight position. For the bench press, athletes started with the arms fully straight, and were instructed to "lower the bar to the chest and press all the way up" while keeping the glutes in contact with the bench. If an athlete bounced the bar on the chest or failed to press the bar all the way up to a fully extended arms position, a fail was given. Each participant completed two warm up sets at sub-maximal intensities. Thereafter, participants were given three attempts to reach their 2–3 repetition maximum (RM) in each lift, with three minutes rest between attempts. One repetition maximum (1RM) from the lifts was calculated using the formula of Mayhew et al. [12]. ICCs for 1RM testing were ≥0.97 in women's team-sport players [13].

Match performance

Match-running and match-action data were collected during the New Zealand National Rugby Sevens tournament, a two-day tournament between the New Zealand Provincial Unions where each team competes in 5 to 6 matches. Match data were considered for players that completed at least a full 7-minute half of a match; therefore, resulting in 1 to 6 files for each player and a total of 119 files included in the analysis (6 players = 1 match, 2 players = 2 matches, 2 players = 3 matches, 5 players = 4 matches, 7 players = 5 matches, 8 players = 6 matches).

Match running

Match running was measured using GPS units (VX Sport 220, Visuallex Sport International, Wellington, New Zealand) sampling at 10 Hz. The validity and reliability of devices with a similar sampling rate have been investigated previously [14, 15]. Each athlete wore the same GPS unit in every match in a fitted vest under the playing jersey. Data were downloaded and analysed post-tournament using the manufacturer's software (VX View software, Sport International, Wellington, New Zealand). Match files were trimmed to include only the time players were on the field. The variables analysed were based on women's Rugby Sevens research [3, 4, 16] and were described as the frequency of efforts or cumulative distance covered in different speed zones (see Table 1). Sprints were defined as running efforts that required an increase of ≥0.70 $m \cdot s^{-1}$ within a second and that

TABLE 1. Match-performance variables predicted from mixed models without a physical-test predictor.

	Mean[a]	Standard deviations[b]		
		Within-player	Between-player	Observed in matches
Match running				
Match maximal speed ($m \cdot s^{-1}$)	7.4	±8%	±6%	±10%
Distance >7.5 $m \cdot s^{-1}$ (m)	2	×/÷ 3.8	×/÷ 1.96	×/÷ 4.4
Distance >5.5 $m \cdot s^{-1}$ (m)	76	×/÷ 1.55	×/÷ 1.36	×/÷ 1.71
Distance >5.0 $m \cdot s^{-1}$ (m)	113	×/÷ 1.42	±23%	×/÷ 1.50
Distance >4.7 $m \cdot s^{-1}$ (m)	145	×/÷ 1.34	±18%	×/÷ 1.40
Distance 5.0–7.5 $m \cdot s^{-1}$ (m)	108	×/÷ 1.41	±20%	×/÷ 1.48
Distance >3.5 $m \cdot s^{-1}$ (m)	347	±18%	±15%	±24%
Distance 3.5–5.0 $m \cdot s^{-1}$ (m)	233	±22%	±23%	×/÷ 1.33
Total distance (m)	1123	±8%	±7%	±11%
Sprints	28	±13%	±9%	±16%
Accelerations	40	±13%	±12%	±18%
Decelerations	19	±22%	±13%	±26%
High-intensity accelerations	34	±15%	±15%	±21%
High-intensity decelerations	13	±25%	±18%	×/÷ 1.32
Match actions				
Tries	0.30	×/÷ 4.7	×/÷ 1.89	×/÷ 5.3
Line breaks	0.50	×/÷ 3.0	×/÷ 2.1	×/÷ 3.8
Work rate	4.91	×/÷ 1.53	×/÷ 1.34	×/÷ 1.68
Carries	0.85	×/÷ 3.0	×/÷ 1.52	×/÷ 3.2
Tackle breaks	0.40	×/÷ 3.9	×/÷ 2.6	×/÷ 5.3
Effective attacking rucks	0.25	×/÷ 5.6	×/÷ 1.52	×/÷ 5.9
Handling errors	0.38	×/÷ 5.7	±0%	×/÷ 5.7
Tackles	2.00	×/÷ 1.84	×/÷ 1.34	×/÷ 2.0
Missed tackles	0.85	×/÷ 2.9	±23%	×/÷ 3.0
Turnovers won	0.30	×/÷ 5.3	×/÷ 1.77	×/÷ 5.9

[a]Uncertainty (×/÷90% CL): for match running, 1.02–1.41; for match actions, 1.12–1.45. [b]Derived from the mixed model: within-player is the residual, between-player is from the player identity, and the observed is their combination (via variances). Values ≥30% are shown as factors. Uncertainty (×/÷90% CL): for match running, 1.01–1.43; for match actions, 1.06–1.94.

reached ≥2.8 $m \cdot s^{-1}$ [17]. High-intensity accelerations and decelerations represented the the total number of accelerations and decelerations performed ≥2.0 $m \cdot s^{-2}$.

Match actions

The first author coded match actions using video analysis. The match actions included in the analysis and their operational definitions are presented in Table 2. These measures were chosen to represent different areas of the game in agreement with previous Rugby Sevens studies [6, 18]. Intra-rater reliability for the analysis was evaluated by re-analysing 10 random matches four weeks apart and calculating the percentage error, as described by Hughes et al. [19]. Errors observed for all match activities were within a 5% error limit, which was deemed acceptable.

Statistical Analysis

Data were analysed with the Statistical Analysis System (University Edition of SAS Studio, version 9.4, SAS Institute, Cary NC). Pearson correlations between each pair of physical-test variables were derived as a correlation matrix, and the variables were ordered to reveal clusters of similar variables (higher correlations within clusters than between clusters). The same analyses were performed for match-performance variables.

For measures of match performance that were counts or proportional to counts, the association between each physical characteristic and the measure was analysed with Poisson regression using the generalised linear mixed model procedure (Proc Glimmix) with a log link. This procedure allows modelling of count variables and accounting for repeated match-performance measurements on the same

TABLE 2. Operational definitions of match actions included in the analysis.

Match action	Description
Attack	
Tries	Count of tries scored by the player
Line breaks	Count of times the ball carrier breaks the defensive line
Carries	Count of times a player carries the ball into contact
Tackle breaks	Count of tackles evaded by the ball carrier
Effective attacking rucks	Count of attacking rucks in which the player successfully clears the opposition making the ball available to play
Handling errors	Sum of knock-ons, passes to ground, and dropped balls by the player
Defence	
Tackles	Count of tackles completed by the player
Missed tackles	Count of tackles attempted and missed by the player
Turnovers won	Count of times a player turns over the ball into an offensive situation from a defensive play
Combined	
Work rate	Sum of tries, line breaks, carries, tackle breaks, effective attacking rucks, tackles, and turnovers won

player. Each physical characteristic (predictor) presented in Table 3 was entered in the model separately as a numeric linear fixed effect to allow estimation of the effect of a two standard-deviation (2-SD) difference in the predictor on match performance [6, 20]. The number of the match played by each athlete in the tournament, and the log of total match time (as a fraction of a 14-min match) for each player in each match, were included as numeric linear fixed effects to estimate the tournament trend of the dependent variable and to adjust each player's score to a mean match time, respectively. Random effects in the model were nominal variables representing player identity (to adjust for between-player differences in means), match identity (to adjust for between-match differences in means), and team identity (to adjust for between-team differences in means).

TABLE 3. Characteristics of the players in the physical tests. Data are mean[a] ± SD[b] (sample size).

10-m average speed ($m \cdot s^{-1}$)	5.30 ± 0.18 (16)
30-m average speed ($m \cdot s^{-1}$)	6.47 ± 0.23 (16)
40-m average speed ($m \cdot s^{-1}$)	6.72 ± 0.28 (16)
Maximal speed ($m \cdot s^{-1}$)	7.66 ± 0.49 (16)
Bronco average speed ($m \cdot s^{-1}$)	3.51 ± 0.27 (16)
Bench press 1RM (kg)	59 ± 10 (28)
Back squat 1RM (kg)	90 ± 15 (26)
CMJ height (cm)	32.2 ± 4.1 (20)

CMJ = Countermovement jump, 1RM = One repetition maximum. [a]Uncertainty (±90% CL): 1.5–5.7%. [b]Uncertainty (×/÷90% CL): 1.26–1.36.

Over- or under-dispersion of the residual variance was estimated, which was particularly important for measures representing counts of running bouts. Distance covered >7.5 $m \cdot s^{-1}$ produced an unrealistic estimate of over-dispersion, so it was analysed with the general linear mixed-model procedure (Proc Mixed) after log transformation, with values of 0 first set to half of the smallest non-zero value. The fixed and random effects were the same as for the Poisson-regression model. The same general linear mixed model was used to analyse the only measure of match performance that was not a count or count of bouts (maximal speed), which was also log transformed. Estimates for the tournament trend were also obtained from the generalised and the general linear mixed models without a physical-test predictor.

The qualitative magnitude of the effects was assessed using standardisation, with threshold values for small, moderate, large, very large, and extremely large calculated as 0.2, 0.6, 1.2, 2.0, and 4.0 of the observed between-player SD [20], derived by combining the variances represented by player identity (true differences between players) and the residual (within-player between match variance), and adjusted for small samples [21]. Effect magnitudes for tries were also determined as the factors associated with an increase in the number of tries scored by a team to give the team 1, 3, 5, 7, and 9 extra wins every 10 matches, representing small, moderate, large, very large, and extremely large effects [20]. The factors were estimated using a simulation based on points scored by all the teams in the tournament. There was a mean of 2.7 tries scored per team per match (5 points per try), with a 52% probability of converting a try (2 points per conversion). There were no field goals or penalties. We assumed a team had 10 try-scoring opportunities in a match on the basis of our experience (The resulting magnitude thresholds were not sensitive to the number of opportunities). An opponent team was assumed

to have an unchanging probability of scoring a try per opportunity equal to 27% (2.7 tries per 10 opportunities). The factor associated with a given increase in wins per 10 matches allowed for the affected team to have a try-scoring probability per trial <27% before the factor was applied (probability = 0.27/√factor), but it increased to >27% after the factor was applied (probability = 0.27*√factor). Simulations were performed to generate scores in 10,000 matches for the two teams before and after the factor was applied, then wins were scored as 1 and loss or draw as 0. The factors giving 1, 3, 5, 7, and 9 extra wins every 10 matches were found by "trial and error". Corresponding magnitude thresholds for factor increase/decrease were 1.20/0.83, 1.75/0.57, 2.60/0.38, 4.10/0.24, and 11.0/0.09. The spreadsheet of simulations is available on request.

Physical-test scores are shown as means and standard deviations (SDs). Means of the dependent variables are shown as the back-transformed least-squares means with SDs in back-transformed ± percent units (when <30%) or ×/÷ factor units (when >30%) derived from a model without a physical-test predictor. Effects are presented in percent units with uncertainty expressed as ±90% compatibility (or confidence) limits (CL), when either the effect or the ±90% CL were <30%; otherwise, factor effects with ×/÷90% CL are reported. Decisions about magnitudes accounting for sampling uncertainty were based on one-sided interval hypothesis tests, according to which a hypothesis of a given magnitude (substantial, non-substantial) is rejected if the 90% compatibility interval falls outside that magnitude [22, 23]. P-values for the tests were therefore the areas of the sampling t-distribution of the effect falling in the hypothesised 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. The hypothesis of non-inferiority (non-substantial-negative) or non-superiority (non-substantial-positive) was rejected if its p-value ($p_{N-} = 1–p_-$ or $p_{N+} = 1–p_+$) was <0.05, representing a decisively substantial effect in minimal-effects testing. A complementary Bayesian interpretation of sampling uncertainty was also provided, when at least one substantial hypotheses was rejected: the p-value for the other hypothesis is the posterior probability of a substantial true magnitude of the effect in a Bayesian analysis with a non-informative prior [22–24], and it was interpreted qualitatively using the following scale: >0.25, possibly; >0.75, likely; >0.95, very likely; and >0.995, most likely [20]. The probability of a trivial true magnitude ($1–p_–p_+$) was also interpreted with the same scale. Possible or likely magnitudes are categorised as some evidence for those magnitudes; very likely and most likely are categorised as good evidence. 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 $p_+>0.05$). Effects on magnitudes and probabilities of a weakly informative normally distributed prior centred on the nil effect and excluding extremely large effects at the 90% level were also investigated [24, 25].

Effects with adequate precision at the 99% level ($p_-<0.005$ or $p_+<0.005$) are highlighted in bold in tables, since these represent stronger evidence against substantial hypotheses than the 90% level and therefore incur lower inflation of error with multiple hypothesis tests. For practitioners considering implementation of a treatment based on an effect in this study (e.g., training to improve try scoring by increasing jump height), the effect needs only a modest chance of benefit (at least possibly increased try scoring, $p_+>0.25$) but a low risk of harm (most unlikely impaired try scoring, $p_-<0.005$). Substantial effects highlighted in bold therefore represent potentially implementable effects. However, it is only for effects on tries scored assessed via match winning that the outcomes have direct relevance to benefit and harm (winning and losing matches); these effects were also deemed potentially implementable when the chance of benefit outweighed an otherwise unacceptable risk of harm (the odds ratio of benefit to harm >66.3) [26]. For these effects, the potential for benefit and harm was also investigated for realistic changes in physical-test measures (less than 2 SD).

RESULTS

Physical tests and match performance

Mean values and between-subjects SD of physical-test scores are presented in Table 3, while means of the dependent variables with the within-player, between-player, and observed SD are reported in Table 1. The within-player SD represents the match-to-match within-player variation, the between-player SD is the true difference between players, and the observed SD is the combination of the within- and between-player SDs representing the observed between-player SD in a typical match.

Correlations within and between groups of variables

Correlation matrices for the physical-test and match measures are shown in the Supplementary Tables 1–4, where clusters of variables have been identified as those with correlations ≥0.50 within clusters and <0.50 between clusters. The clusters of variables in each correlation matrix are delineated in the Supplementary Table 4, because correlated variables were expected to have similar effects. There were two overlapping clusters of physical-test variables for maximal-speed running measures, one with 10-m speed and one with Bronco; there was also a well-defined cluster for strength measures (Supplementary Table 1). The correlation matrix for measures of match running revealed four clusters, representing running at high intensities, running at lower intensities (with distance >5.5 $m \cdot s^{-1}$ in both clusters), total running (with sprinting, accelerations, and decelerations contributing to this concept), and high-intensity changes in speed (Supplementary Table 2). Fewer and less well-defined clusters of variables were found for match actions, with a cluster for tries and line breaks, and a cluster (with one correlation of 0.47) for work rate, carries, and tackle breaks (Supplementary Table 3). No clusters contained match-running and match-action variables, but correlations of match running with match actions (Supplementary Table 4) revealed similar

TABLE 4. Effects of a 2-SD difference in physical characteristics on match running and match actions. Data are percent effects with ±90% compatibility limits, or factor effects with ×/÷90% compatibility limits; the observed magnitude and probability of a substantial true effect are also shown. Horizontal and vertical dashed and solid lines divide the match and physical-test measures into clusters defined by the correlations between measures within and between clusters shown in the Supplementary Tables 1–3.

	10-m speed ($m \cdot s^{-1}$)	40-m speed ($m \cdot s^{-1}$)	Bronco average speed ($m \cdot s^{-1}$)	Bench press 1RM (kg)	Back squat 1RM (kg)	CMJ height (cm)
Match running						
Match maximal speed	12.5, ±7.1%; **Large** ↑***	7.4, ±6.6%; Moderate ↑**	8.0, ±6.9%; Moderate ↑**	3.0, ±4.8%; Small ↑*^{0}	6.1, ±4.8%; **Moderate** ↑**	13.6, ±5.9%; **Large** ↑****
Distance >7.5 $m \cdot s^{-1}$	2.6, ×/÷2.4; Moderate ↑**	2.0, ×/÷2.3; Small ↑**	2.4, ×/÷2.4; Small ↑**	1.28, ×/÷1.90; Trivial	1.41, ×/÷1.91; Small ↑	3.5, ×/÷2.2; **Moderate** ↑***
Distance >5.5 $m \cdot s^{-1}$	1.59, ×/÷1.50; Moderate ↑**	1.56, ×/÷1.38; **Moderate** ↑**	1.69, ×/÷1.35; **Moderate** ↑***	1.34, ×/÷1.26; **Small** ↑**	1.44, ×/÷1.26; **Moderate** ↑***	1.95, ×/÷1.22; **Large** ↑****
Distance >5.0 $m \cdot s^{-1}$	1.42, ×/÷1.35; Moderate ↑**	1.40, ×/÷1.26; **Moderate** ↑***	1.50, ×/÷1.24; **Moderate** ↑***	29, ±23%; **Moderate** ↑**	1.31, ×/÷1.19; **Moderate** ↑***	1.63, ×/÷1.18; **Large** ↑****
Distance >4.7 $m \cdot s^{1}$	1.37, ×/÷1.27; Moderate ↑**	1.33, ×/÷1.19; **Moderate** ↑***	1.39, ×/÷1.19; **Moderate** ↑***	17, ±18%; Small ↑**	17, ±19%; Small ↑**	1.48, ×/÷1.16; **Large** ↑****
Distance 5.0–7.5 $m \cdot s^{-1}$	1.34, ×/÷1.32; Moderate ↑**	1.34, ×/÷1.23; **Moderate** ↑**	1.44, ×/÷1.22; **Moderate** ↑***	29, ±21%; **Moderate** ↑***	1.31, ×/÷1.18; **Moderate** ↑***	1.58, ×/÷1.18; **Large** ↑****
Distance >3.5 $m \cdot s^{-1}$	10, ±16%; Small ↑	11, ±11%; Small ↑**	12, ±11%; Small ↑**	-8, ±10%; Small ↓*^{0}	-7, ±11 %; Small ↓	2, ±12%; Trivial
Distance 3.5–5.0 $m \cdot s^{-1}$	-1, ±23%; Trivial	1, ±20%; Trivial	-1, ±19%; Trivial	-18, ±12%; **Moderate** ↓**	-19, ±13%; **Moderate** ↓***	-19, ±16%; Moderate ↓**
Total distance	3.4, ±9.2%; Small ↑	6.4, ±7.1%; Small ↑**	9.2, ±6.5%; **Moderate** ↑***	-5.5, ±4.8%; Small ↓**	-4.5, ±5.2%; Small ↓**	-1.1, ±7.1%; Trivial
Sprints	3.3, ±9.3%; Small ↑	6.1, ±6.7%; Small ↑**	7.0, ±6.3%; Small ↑**	-8.9, ±6.3%; **Moderate** ↓**	-7.4, ±7.2%; Small ↓**	-2.1, ±6.8%; Trivial
Accelerations	-2, ±12%; Trivial	4, ±11%; Small ↑	10, ±12%; Small ↑**	-5.7, ±8.1%; Small ↓*^{0}	-4.9, ±8.9%; Small ↓	3, ±11%; Trivial
Decelerations	9, ±15%; Small ↑	10, ±10%; Small ↑**	14.6, ±9.2%; **Moderate** ↑***	-5, ±11%; Small ↓	-3, ±12%; Trivial	-1, ±14%; Trivial
High-intensity accelerations	13, ±19%; Small ↑	9, ±15%; Small ↑	11, ±14%; Small ↑**	-12.3, ±9.0%; **Moderate** ↓**	-10, ±10%; Small ↓**	5, ±15%; Small ↑
High-intensity decelerations	9, ±21%; Small ↑	8, ±16%; Small ↑	21, ±12%; **Moderate** ↑***	-2, ±15%; Trivial	6, ±16%; Small ↑	6, ±18%; Small ↑
Match actions						
Tries via standardisation via match winning	1.3, ×/÷2.8; Trivial Small ↑	1.4, ×/÷2.3; Trivial Small ↑	1.5, ×/÷2.3; Trivial Small ↑	1.55, ×/÷1.92; Small ↑*^{0} Small ↑	2.5, ×/÷2.0; **Small** ↑** Moderate ↑***	3.8, ×/÷2.8; Moderate ↑** Large ↑***
Line breaks	2.6, ×/÷2.7; Moderate ↑**	1.2, ×/÷2.1; Trivial	1.0, ×/÷2.2; Trivial	1.37, ×/÷1.86; Small ↑	2.1, ×/÷1.9; Small ↑**	2.8, ×/÷2.3; Moderate ↑**
Work rate	0.99, ×/÷1.38; Trivial	1.21, ×/÷1.30; Small ↑*^{0}	1.31, ×/÷1.28; Small ↑**	16, ±29%; Small ↑*^{0}	1.37, ×/÷1.28; **Moderate** ↑**	20, ±29%; Small ↑*^{0}
Carries	1.12, ×/÷1.93; Trivial	1.22, ×/÷1.72; Trivial	1.70, ×/÷1.71; Small ↑**	1.10, ×/÷1.59; Trivial	1.44, ×/÷1.61; Small ↑*^{0}	1.47, ×/÷1.66; Small ↑*^{0}
Tackle breaks	0.7, ×/÷2.6; Small ↓	1.4, ×/÷2.8; Small ↑	1.4, ×/÷2.7; Trivial	1.0, ×/÷2.2; Trivial	1.7, ×/÷2.3; Small ↑*^{0}	2.9, ×/÷3.1; Small ↑**
Effective attacking rucks	0.4, ×/÷4.7; Small ↓	0.5, ×/÷4.5; Small ↓	1.2, ×/÷4.4; Trivial	1.39, ×/÷1.80; Trivial ↑^{0}*	1.19, ×/÷1.90; Trivial	1.1, ×/÷2.2; Trivial
Handling errors	1.3, ×/÷2.4; Trivial	1.5, ×/÷2.1; Small ↑*^{0}	1.8, ×/÷2.1; Small ↑*^{0}	1.03, ×/÷1.73; Trivial	1.20, ×/÷1.76; Trivial	1.73, ×/÷1.92; Small ↑*^{0}
Tackles	0.88, ×/÷1.60; Trivial	1.21, ×/÷1.52; Small ↑	1.30, ×/÷1.56; Small ↑	1.19, ×/÷1.33; Small ↑*^{0}	1.29, ×/÷1.34; Small ↑*	0.86, ×/÷1.44; Small ↓
Missed tackles	0.90, ×/÷1.75; Trivial	0.97, ×/÷1.60; Trivial	1.08, ×/÷1.68; Trivial	1.21, ×/÷1.43; Trivial ↑^{0}*	1.15, ×/÷1.46; Trivial	1.04, ×/÷1.55; Trivial
Turnovers won	1.4, ×/÷2.2; Trivial	1.24, ×/÷1.95; Trivial	1.6, ×/÷2.0; Small ↑*^{0}	0.9, ×/÷2.0; Trivial	0.6, ×/÷2.0; Small ↓*^{0}	0.5, ×/÷2.1; Small ↓**

CMJ = Countermovement jump, 1RM = One repetition maximum. With the exception of tries, magnitudes are based on the following scale for standardised changes in the mean using the observed between-player SD (Table 1): <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. Magnitude thresholds for tries are based on simulations of Rugby Sevens matches (see Methods). Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely; ****most likely. *** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+}<0.05 and <0.005 respectively). ↑ and ↓ indicate a substantial positive and negative effect, respectively. Reference-Bayesian likelihoods of trivial change: ^{0}possibly; ^{00}likely; ^{000}very likely, ^{0000}most likely. Likelihoods are not shown for effects with inadequate precision at the 90% level (failure to reject any hypotheses: p>0.05). Magnitudes in **bold** have acceptable precision with 99% compatibility limits.

magnitudes within the running and action clusters; in particular, tries and line breaks had negative correlations with measures of total running and positive correlations with high-intensity running.

Effects of physical-test scores on match performance

The effects of a 2-SD difference in physical-test scores on match running and match actions are presented in Table 4. Compatibility intervals and Bayesian probabilities are shown for a minimally informative prior, since appreciable shrinkage occurred with the weakly informative prior for only one effect, jump height on tries scored. In this instance, the factor effect reduced to 3.1, 90% compatibility limits ×/÷2.6, but the magnitude remained large, very likely substantial, and potentially implementable with the odds-ratio assessment of benefit and harm defined by thresholds for match winning.

Match running

Large positive effects were observed for jump height on match maximal speed and distance covered at high intensity, and for acceleration on match maximal speed, where the effects had sufficient precision for the true magnitudes to be very likely or most likely substantial. Acceleration, speed, Bronco, and strength scores displayed consistent moderate positive effects on distance covered at high intensity during matches, with some effects showing sufficient precision for the true magnitudes to be very likely substantial. Moderate positive effects where precision was sufficient for the true magnitude to be very likely substantial were also evident for 30-m speed on match maximal speed, for jump height on distance >7.5 $m \cdot s^{-1}$, and for Bronco on match total distance, decelerations, and high-intensity decelerations.

Measures where the effects had adequate precision but were only likely substantial included small and moderate positive effects for speed, Bronco, and back squat on match maximal speed, and for speed and Bronco on match distance covered >7.5 $m \cdot s^{-1}$ and on some measures of total running. In contrast, small to moderate negative effects were observed for strength and jump height on some variables contributing to total match running and high intensity changes in speed. Precision was consistently inadequate for speed on match distance 3.5–5.0 $m \cdot s^{-1}$, accelerations, high-intensity accelerations, high-intensity decelerations, and for strength and jump height on match decelerations and high-intensity decelerations.

Match actions

Moderate and small positive effects were observed for jump height and back squat on tries scored when assessed using standardisation, with adequate precision at the 90% and 99% levels respectively; both were likely substantial. Greater positive effects characterised the same predictors for tries scored when assessed via match winning, and the effects became very likely substantial; both effects had adequate precision only at the 90% level, hence the risk of harm was too high ($p_- > 0.005$) for a conservative assessment of implementability, but they were potentially implementable when considering the odds ratio of benefit to harm (3700 and 4200, respectively). For these predictors, changes as small as 0.25 SD predicted tries scored that were at least possibly beneficial and with negligible risk of harm, but changes of 0.2 SD were unlikely to be beneficial.

A number of predictors had small or moderate positive effects but were only likely or possibly substantial: back squat and jump height on line breaks, work rate, carries, tackle breaks; 10-m speed on line breaks; maximal speed on work rate; Bronco on work rate and carries; and strength on tackles. On the other hand, back squat and jump height displayed small negative effects on turnovers won with adequate precision, but the effect was only possibly or likely substantial. Precision was inadequate for several predictors on various match-action measures, including the observed small positive effects of measures of running speed and bench press on match winning. Changes in measures of running speed and in bench press smaller than 2 SD were either unclear or at least likely trivial.

Tournament trend

When considering the effects obtained without a physical-test predictor, the measures of match total running and high-intensity changes in speed displayed small to moderate negative trends across the tournament, with adequate precision but only possibly or likely substantial magnitudes. The trend for the match measures of high-speed running ranged from small likely reductions through to small possible increases, but three of the six measures had inadequate precision. There was a similar pattern for match actions, with seven of the 11 measures lacking adequate precision. The tournament trends sometimes changed substantially with different physical-test predictors in the model, but overall the trends were similar to those without predictors.

DISCUSSION

There was good evidence of positive effects of many physical-test measures on match high-intensity running in women's Rugby Sevens players. Furthermore, there was some evidence of positive effects of speed and Bronco on match total running and high intensity changes in speed, and of negative effects of maximal strength and jump height on match total running and high intensity changes in speed. There were fewer substantial associations between physical-test measures and match actions: good evidence of positive effects of squat and jump height on tries via standardisation and match winning, and some evidence of positive effects of various predictors on some measures. Small positive effects of measures of running speed and bench press on match winning were observed, but these were unclear. The similarity of the effects observed for some predictors and/or dependent variables reflects the high correlations observed between variables.

Improving back squat and jump height performance could be advantageous for enhancing match winning in provincial-representative women's Rugby Sevens, as the effects for these tests on tries

scored were deemed potentially implementable. In Table 4 we have presented the effect of a 2-SD difference in these tests on match performance, representing the difference of moving from a typical low to a typical high value [20]. Achieving such a difference would be unrealistic for players already displaying high test values, but a change of 0.25 SD should be achievable for most players and was still potentially beneficial. There was less evidence for a beneficial effect (small but unclear) of measures of running speed and bench press on match winning; some changes smaller than 2 SD were unclear and therefore worth further investigation for potential benefit.

The magnitudes of the positive effects (small to large) for match-running measures align with moderate to large correlations (r = ~0.3–0.7) between performance in various physical-test and match-running measures reported in the only other comparable study of women's Rugby Sevens players [3]. The authors in that study combined junior, senior, and professional levels, so the correlations within each level would therefore likely be lower. In a study of provincial-representative and international-level men's Rugby Sevens players [6], some of the associations between physical-test measures and match actions were similar to ours in magnitude. A point of difference was that tries scored was moderately correlated with 10-m momentum (sprint velocity multiplied by body mass) and repeated-sprint ability, whereas in our study the measures of running speed in the physical tests had trivial (although unclear) effects on tries scored assessed via standardisation. If this difference is not due simply to sampling variation, then the explanation must reside in differences between either the style of matches or the physiology of male and female players. Unfortunately, jump height and lower-body strength were not measured in the study of men's Rugby Sevens [6], and there have been no other studies of the effects of these test measures on tries or other match actions in Rugby Sevens.

The small to moderate negative effects of maximal strength and jump height on match measures of total running and high-intensity changes in speed contrast with the moderate to large positive effects of these physical-test measures on match winning. Total running and high-intensity changes in speed are apparently negative match performance indicators, as evidenced by moderately lower total distance and distance covered at 3.5–5.0 $m \cdot s^{-1}$ during wins compared to losses in international women's Rugby Sevens [5]. Similarly, in the current study we observed consistently negative correlations between measures of total running and tries scored (Supplementary Table 4).

For most match-running and match-action measures, there was some evidence of small to moderate negative trends over the tournament, likely a result of accumulated fatigue or muscle damage. In line with these findings, professional and state-representative women's Rugby Sevens players displayed small to very large reductions in several match-running measures over a two-day tournament, with greater reductions in state-level players [27]. Both professional and state-representative players also reported a large decline in recovery perception, a large increase in perceived soreness, and had large increases in muscle damage (creatine kinase concentration) over the tournament. No information regarding the tournament trend of match actions in women's Rugby Sevens has been reported in other studies.

Due to the fact the physical tests were undertaken within a 14-day period before competition, it is possible that different teams with different training and tapering could have different relationships. To the extent that some of the test measures might be measuring the same underlying construct, the correlations between the measures are similar to reliability correlations, and the measurement error is negligible (in terms of standardisation) only when the correlation is ~0.99 or greater [28]. On this basis, only the 30-m and 40-m speed are effectively the same measure (Supplementary Table 1), and only one needs to be measured. Measures with lower correlations could either be measuring identical constructs with substantial measurement error or they could be measuring somewhat different constructs. A parsimonious set of physical tests that assess constructs making independent contributions to match performance would be useful for practitioners, but multiple linear regression with a much larger sample size of players is needed to identify them. The small sample size precluded such an analysis. A similar analysis with more players and matches to predict tries scored with the other match-performance measures might identify a parsimonious set of match measures for predicting match performance of individual players. A greater sample size of players and matches is also required to get more evidence about the magnitude of the unclear effects observed in this study, especially those on match winning.

CONCLUSIONS

Ours is the first study to reveal potentially useful relationships between physical-test measures and match performance in women's Rugby Sevens players. In particular, enhancing players' jump height and back-squat performance could increase the likelihood of match success in women's Rugby Sevens. Valuable future research would include multiple linear regression and experimental studies investigating the effect of changes in physical-test measures on match performance to support the promising utility of these findings for enhancing performance in women's Rugby Sevens.

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Disclosure Statement

The authors declare that they have no competing interests.

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SUPPLEMENTARY TABLES

SUPPLEMENTARY TABLE 1. Correlations between physical tests mean values. The variables have been ordered and outlined to show clusters with generally higher correlations between variables within the clusters than between the clusters.

Variable	1	2	3	4	5	6	7	8
1. 10-m average speed		.70	.64	.51	.31	-.32	-.23	.05
2. 30-m average speed	.70		.99	.91	.59	-.27	-.37	.03
3. 40-m average speed	.64	.99		.96	.62	-.25	-.42	-.04
4. Maximal speed	.51	.91	.96		.62	-.19	-.46	-.13
5. Bronco average speed	.31	.59	.62	.62		.18	.09	.23
6. Bench press 1RM	-.32	-.27	-.25	-.19	.18		.76	.29
7. Back squat 1RM	-.23	-.37	-.42	-.46	.09	.76		.47
8. CMJ height	.05	.03	-.04	-.13	.23	.29	.47	

Uncertainty (90% compatibility limits): ~ ± 0.31 to ~ ± 0.03 for correlations of 0.00 to 0.95 respectively assuming a sample size of ~30.

SUPPLEMENTARY TABLE 2. Correlations between match running mean values. The variables have been ordered and outlined to show clusters with generally higher correlations between variables within the clusters than between the clusters.

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Match maximal speed		.56	.61	.49	.40	.40	.06	-.25	.03	-.09	-.11	.03	-.07	.03
2. Distance >7.5 m·s^{-1}	.56		.53	.42	.32	.22	.08	-.19	.02	.05	-.03	.03	-.03	.00
3. Distance >5.5 m·s^{-1}	.61	.53		.94	.84	.88	.38	-.16	.17	-.01	.00	.24	.03	.30
4. Distance >5.0 m·s^{-1}	.49	.42	.94		.96	.98	.56	.01	.29	.15	.13	.37	.11	.45
5. Distance >4.7 m·s^{-1}	.40	.32	.84	.96		.96	.72	.23	.42	.28	.26	.52	.14	.52
6. Distance 5.0–7.5 m·s^{-1}	.40	.22	.88	.98	.96		.58	.05	.30	.15	.15	.39	.13	.48
7. Distance >3.5 m·s^{-1}	.06	.08	.38	.56	.72	.58		.83	.76	.64	.60	.73	.16	.46
8. Distance 3.5–5.0 m·s^{-1}	-.25	-.19	-.16	.01	.23	.05	.83		.72	.67	.63	.63	.12	.26
9. Total distance	.03	.02	.17	.29	.42	.30	.76	.72		.71	.70	.56	.23	.30
10. Sprints	-.09	.05	-.01	.15	.28	.15	.64	.67	.71		.85	.61	.41	.43
11. Accelerations	-.11	-.03	.00	.13	.26	.15	.60	.63	.70	.85		.56	.55	.46
12. Decelerations	.03	.03	.24	.37	.52	.39	.73	.63	.56	.61	.56		.14	.62
13. High-intensity accelerations	-.07	-.03	.03	.11	.14	.13	.16	.12	.23	.41	.55	.14		.69
14. High-intensity decelerations	.03	.00	.30	.45	.52	.48	.46	.26	.30	.43	.46	.62	.69	

Uncertainty (90% compatibility limits): ~ ± 0.31 to ~ ± 0.03 for correlations of 0.00 to 0.95 respectively assuming a sample size of ~30.

SUPPLEMENTARY TABLE 3. Correlations between match actions mean values. The variables have been ordered and outlined to show clusters with generally higher correlations between variables within the clusters than between the clusters.

Variable	1	2	3	4	5	6	7	8	9	10
1. Tries		.53	.33	-.05	.14	-.15	.00	-.10	-.17	.05
2. Line breaks	.53		.49	.08	.31	-.08	-.05	-.15	-.20	.13
3. Work rate	.33	.49		.54	.59	.12	.06	.41	-.15	.35
4. Carries	-.05	.08	.54		.47	-.06	-.07	-.12	-.08	.03
5. Tackle breaks	.14	.31	.59	.47		-.05	.01	-.17	-.07	.09
6. Effective attacking rucks	-.15	-.08	.12	-.06	-.05		.06	.06	.07	.00
7. Handling errors	.00	-.05	.06	-.07	.01	.06		.20	.23	-.09
8. Tackles	-.10	-.15	.41	-.12	-.17	.06	.20		.06	.06
9. Missed tackles	-.17	-.20	-.15	-.08	-.07	.07	.23	.06		-.19
10. Turnovers won	.05	.13	.35	.03	.09	.00	-.09	.06	-.19	

Uncertainty (90% compatibility limits): ~ ± 0.31 to ~ ± 0.03 for correlations of 0.00 to 0.95 respectively assuming a sample size of ~30.

SUPPLEMENTARY TABLE 4. Correlations between match running and match actions mean values. The variables have been ordered and outlined to show clusters with generally higher correlations between variables within the clusters than between the clusters.

Variable	Tries	Line breaks	Work rate	Carries	Tackle breaks	Effective attacking rucks	Handling errors	Tackles	Missed tackles	Turnovers won
Match maximal speed	.38	.31	.04	-.10	-.01	-.17	-.08	-.05	.00	-.14
Distance >7.5 $m \cdot s^{-1}$	.31	.17	.13	.09	-.03	-.03	-.02	.05	-.02	-.17
Distance >5.5 $m \cdot s^{-1}$	.32	.24	.15	-.06	-.02	-.06	-.13	.11	-.10	-.07
Distance >5.0 $m \cdot s^{-1}$	.26	.22	.17	-.06	-.04	-.05	-.08	.16	-.09	.03
Distance >4.7 $m \cdot s^{-1}$	.18	.16	.16	-.07	-.06	-.03	-.06	.20	-.07	.06
Distance 5.0–7.5 $m \cdot s^{-1}$	.21	.19	.16	-.08	-.03	-.05	-.08	.16	-.09	.07
Distance >3.5 $m \cdot s^{-1}$	-.08	-.05	.05	-.15	-.13	-.01	-.05	.29	.01	.16
Distance 3.5–5.0 $m \cdot s^{-1}$	-.27	-.21	-.05	-.15	-.13	.03	.00	.24	.08	.18
Total distance	-.10	-.11	.11	-.02	-.04	-.03	.02	.28	-.03	.12
Sprints	-.15	-.07	.21	.08	-.05	.07	.06	.39	.02	.06
Accelerations	-.18	-.06	.22	.08	-.02	.03	.00	.37	.02	.16
Decelerations	-.13	-.04	.01	-.17	-.18	.11	-.04	.26	-.03	.12
High-intensity accelerations	.00	.01	.23	.15	.03	.16	.01	.15	.00	.18
High-intensity decelerations	.01	.05	.20	.04	-.06	.12	.01	.21	-.08	.20

Uncertainty (90% compatibility limits): ~ ± 0.31 to ~ ± 0.03 for correlations of 0.00 to 0.95 respectively assuming a sample size of ~30.

Predicting resting energy expenditure among athletes: a systematic review

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ABSTRACT: Resting energy expenditure (REE) is often estimated in athletes using equations developed from the general population however, the application in athletic-specific populations is questionable. The aim of this systematic review was to compare measured REE and estimations of REE obtained from non-sport participants and athletes. Inclusion criteria met PICO criteria: population – participants involved in organized sport; intervention – resting energy expenditure was obtained by calorimetry; comparator – equations to estimate REE; outcomes – comparisons between measured REE and predicted REE. The search was conducted in Web of Science all databases, PubMed and Scopus. Comparisons between measured REE and predicted REE as well the potential models to estimate REE developed among athletes were summarized. Allowing for variation among studies, equations developed within general populations were not comparable to REE measured by calorimetry in athletes. Equations across athletic samples were obtained but, few studies tested their validity across independent samples of sport participants. Nevertheless, equations developed within athlete populations seem to be widely unused in sports nutrition literature and practice. De Lorenzo and ten Haaf equations appear to present an acceptable agreement with measured REE. Finally, equations used among adults should not be generalised for youth sport participants.

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INTRODUCTION

The ability to estimate total energy expenditure (TEE) accurately is frequently desired by athletes and practitioners alike. Access to this information can help in the design of optimal fuelling strategies for training and competition, supporting training adaptation and performance [1]. There are three components of TEE: resting energy expenditure (REE), thermic effect of exercise and diet induced thermogenesis. Basal metabolic rate (BMR) and REE are often used as interchange terms but, represent different concepts. BMR is defined as the minimal amount of energy to maintain the vital functions such as respiration, heartbeat, normal body temperature while, REE represents the energy to maintain the body functions at rest. Briefly, the assessment of BMR requires more standardized conditions and it is more challenging to measure than REE [2]. REE among athletes needs particular attention given the substantial contribution of REE to determine TEE [3]. Additionally, REE has been used as a parameter to define energy deficiency in sport participants [4]. Considering the preceding, the measurement of REE needs to follow a standardized protocol. The REE is typically obtained during the morning from continuous measures of VO_2 and VCO_2 at rest and athletes are instructed to avoid exercise 12 hours before REE testing. The participant is positioned in the supine position for 30–45 minutes with a mask or mouthpiece attached and then, 5–10 additional minutes of VO_2 and VCO_2 measures are obtained to assess REE [2]. The mentioned protocol requires considerable equipment, time, exercise restriction and knowledge [2]. Therefore, indirect estimations of REE have been for non-sport participants [5] and athletes [3].

The Harris-Benedict [6] and Cunningham [7] equations emerged as potential predictive estimations of REE in athletes [1]. Additionally, metabolic active tissue, expressed by fat-free mass (FFM) or lean soft tissue (LST), accounted for 60–70% of REE [8] and by inference should be considered a key factor in estimation of REE. The Harris-Benedict equation [6] did not measure metabolic active

tissues while in the Cunningham equation [7] lean body mass was estimated based on body mass and age. The Harris-Benedict equation was developed 124 years ago, in 239 healthy participants (136 males, 103 female) and incorporated age, stature and body mass as explanatory predictors [6]. In parallel, Cunningham reanalysed the data of 223 participants from Harris and Benedict [6] and excluded 16 trained athletes. In this equation, estimated lean body mass accounted for 70% of REE [7]. Interestingly, both equations are systematically used to estimate REE but, they are not specifically design for athletes. Consequently, the generalization and application of these equations among athletes are questionable.

The development and application of athletic-specific and sport-specific equations has not received much consideration within sports nutrition literature although it has been previously recognized that population specific estimations are needed [1]. Multiple equations to predict REE has been developed among athletes that participated in different sports [9–11]. Nevertheless, the validation of sport-specific equations to estimate REE in independent samples is lacking. Considering the contribution of REE to estimate TEE and the frequent use of equations validated in general population in sport participants, the aim of this systematic review is to compare estimated REE with measured REE in athletes. This review also summarized the models used in athlete populations.

MATERIALS AND METHODS

The present systematic review followed the Cochrane guidelines [12] and it was conducted according to Preferred Reporting Items for Systematic Review (PRISMA) instructions [13].

Eligibility criteria

The manuscripts included in the current systematic review followed PICO (population, intervention, comparator and outcome) criteria [12]: population comprised of participants involved in organized sport; intervention was defined as REE measured by calorimetry – requirements for REE assessment needed to be described; equations to predict REE were used as a comparator; outcomes described comparisons between REE measured and REE estimated or potential equations to predict REE; cross-sectional and cohort studies were included in this review. Published manuscripts or abstracts in English were considered for the present study. No filter was applied to year of publication. Manuscripts that did not presented descriptive statistics for REE were eligible to the review because provide qualitative information about the accuracy of equations. Authors of the papers included in the review were contacted where relevant data were not present within the manuscript.

Information source and search strategy

Three electronic databases were consulted (i.e. Web of Science all databases, PubMed and Scopus) prior to 1th January of 2022. The search strategy included the keywords: ("resting energy expenditure" OR "resting metabolic rate" OR "basal metabolic rate" OR "basal energy expenditure" OR REE OR "basal metabolism") AND ("predictive equation*" OR "prediction equation*" OR equation* OR prediction*) AND (athlete* OR sport*). Potential search terms were identified taking into account previous words used in the titles, abstract and keywords. Two specialists (DVM/AF) developed the search strategy that was supervised by an experienced author in systematic reviews and meta-analysis (HS). Afterwards, a reference manager software (EndNoteTMX9, Clarivate Analytics, Philadelphia, PA, USA) was used to export the studies.

Selection process

The initial screening by two independent authors (DVM and HS) according to the title and abstract. Then, full-text manuscripts were assessed to check if they met eligibility criteria. Discordances between authors were solved by consensus and if necessary a third independent reviewer (AF) was consulted.

Data collection process

Data extrapolation

Two authors (DVM/HS) extracted the information from eligible studies. Data was organized and summarized on adapted template of Cochrane Consumers and Communication Review Group [14]. The list of parameters included in the previous spreadsheet were: (1) number of participants, (2) sport, (3) sex, (4) age, (5) competitive level, (6) measurement of REE, (7) equation studied, (8) potential independent variables, (9) statistical parameters about the model, (10) main findings, (11) limitations. Among adolescent Brazilian soccer players [15], means and standard deviations of WHO/FAO/UNU, Harris-Benedict, Henry and Cunningham equations were calculated consulting the supplementary material from the original study.

Data Items

The main outcomes extracted were categorized in two different groups: (1) measured and predicted REE; (2) equation to estimate REE. Moreover, any equation to predict REE was contrasted with measured REE. The agreement of predicted REE was determined within 5% or 10% intervals of the measured REE. Since authors anticipated that few equations to predict REE were developed among athletes, predictive models of REE were extracted and summarized as an outcome domain.

Study risk of bias

According to a recent study [16], the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies developed jointly the National Heart, Lung and Blood Institute (NHLBI) and Research Triangle Institute International to examine individually the quality of studies [17] and was implemented in the current manuscript. The tool included fourteen questions and an overall approach (i.e. good, fair or poor). Items reflecting the following parameters: (1) research question; (2,3) study population; (4) groups recruited from the same population and uniform eligibly criteria; (5) sample size justification; (6) exposure assessed prior to outcome of measurement; (7) sufficient

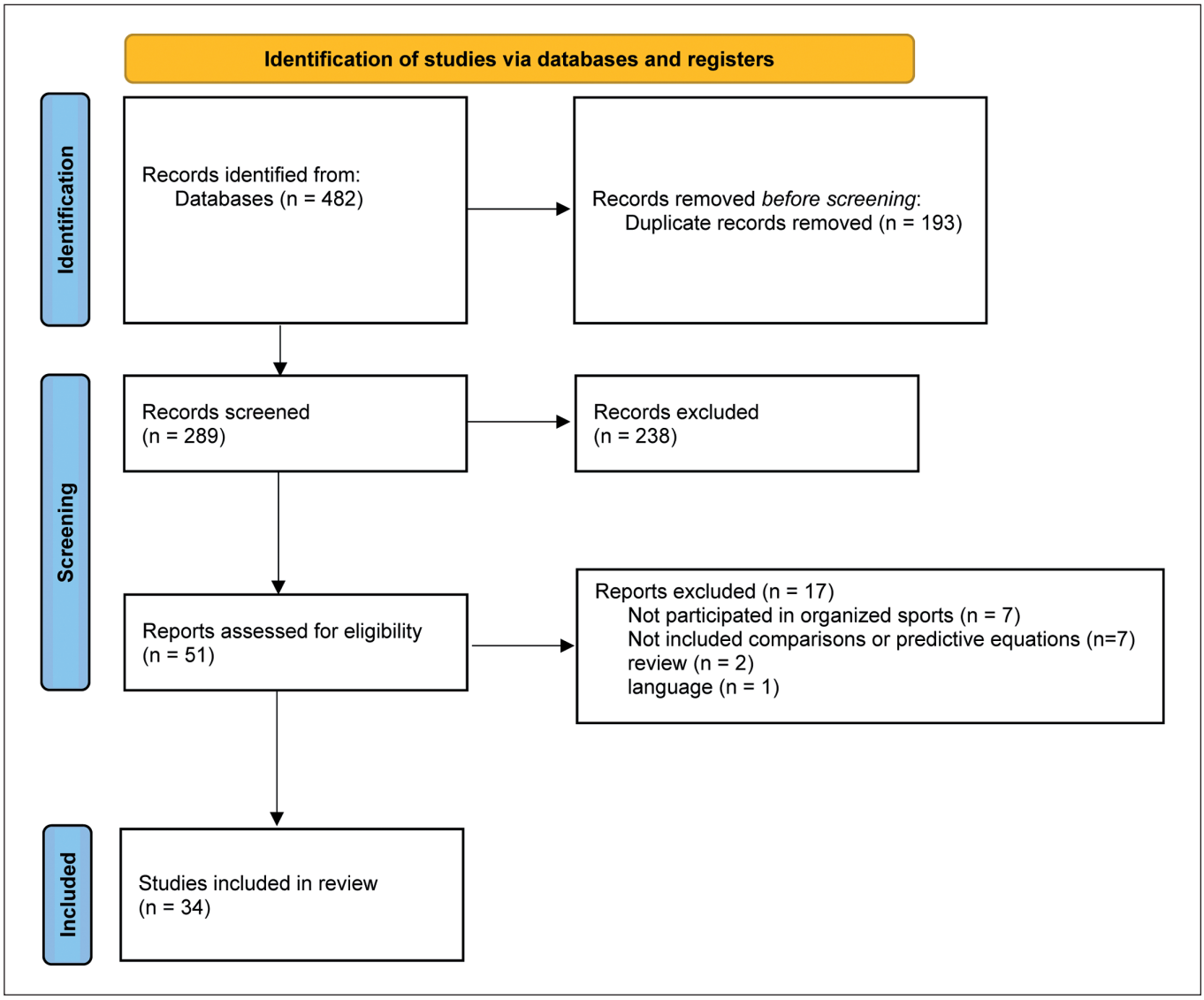


FIG. 1. Identification of studies via databases and registers.
From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

timeframe to see an effect; (8) different levels of the exposure effect; (9) exposures measurement; (10) repeated exposure assessment; (11) outcomes measurement; (12) blinding of outcomes assessors; (13) follow-up rate; (14) statistical analysis. Two independent observers completed the tool (DVM/HS) and possible disagreements were solved by a third reviewer (AF).

RESULTS

Study selection

The databases searches identified 482 entries. Subsequently, duplicates were automatically and manually removed (n = 193). A total of 289 records were screened according to title and abstract, resulting in the exclusion of 238 records. The remaining 51 articles were read in full and 17 did not follow the eligible criteria: (1) the sample not clearly described as participants involved in organized sports (n = 7); (2) the manuscript did not show any comparison with equations or present a potential model for predicting REE (n = 7); (3) manuscripts were reviews (n = 2); (4) manuscript was not written in English (n = 1). Finally, 34 studies were selected to the current systematic review (Figure 1).

Study characteristics

The characteristics of studies (sample, age, stature, body mass, FFM or LST) included in the present review are summarized separately by

TABLE 1. Mean ± standard deviation of measured REE and predicted REE considering alternative equations presented separately for adult and young athletes.

Study	Sample	Sex					
		Male			Female		
		REE measured (kcal · day^{-1})	Equation	REE predicted (kcal · day^{-1})	REE measured (kcal · day^{-1})	Equation	REE predicted (kcal · day^{-1})
ADULTS							
Balci et al. [18]	Olympic athletes	1885 ± 323	Harris-Benedict	1864 ± 180	1361 ± 232	Harris-Benedict	1483 ± 143
			Mifflin-BMSA	1778 ± 138		Mifflin-BMSA	1425 ± 148
			Mifflin-FFM	1727 ± 149		Mifflin-FFM	1149 ± 111
			Schofield	1828 ± 186		Schofield	1466 ± 198
			Cunningham (1991)	1969 ± 167		Cunningham (1991)	1534 ± 124
			Owen	1644 ± 126		Owen	1325 ± 145
			Liu	1723 ± 180		Liu	1383 ± 184
			De Lorenzo	1911 ± 147		De Lorenzo	1597 ± 164
			Bernstein	1511 ± 154		Bernstein	1597 ± 128
			Nelson	1706 ± 201		Nelson	1339 ± 1635
			Johnstone	1838 ± 187		Johnstone	1229 ± 164
			Roza	1874 ± 85		Roza	1483 ± 69
Carlsohn et al. [19]	rowing and canoe racing	2675 ± 526	Harris-Benedict	2133 ± 188	1577 ± 253	Harris-Benedict	1737 ± 200
			Cunningham (1980)	2260 ± 181		Cunningham (1980)	1734 ± 147
Cocate et al.[20]	cycling	2051 ± 169	Harris-Benedict	1699 ± 95			
			Schofield	1699 ± 85			
			FAO/WHO/UNU	1702 ± 85			
			Henry	1562 ± 76			
Devrim-Lanpir et al. [21]	endurance sports	2041 ± 301	Harris-Benedict	1701 ± 120	1788 ± 341	Harris-Benedict	1322 ± 82
			Mifflin	2038 ± 126		Mifflin	1602 ± 59
			Cunningham (1991)	1894 ± 141		Cunningham (1991)	1497 ± 61
			WHO/FAO/UNU – BMA	1726 ± 86		WHO/FAO/UNU – BMA	1321 ± 37
			WHO/FAO/UNU – BM	1755 ± 84		WHO/FAO/UNU – BM	1388 ± 41
			Wang	1744 ± 157		Wang	1289 ± 68
			Sabounchi[1]	1743 ± 137		Sabounchi[1]	1363 ± 62
			Sabounchi[1]	1662 ± 117		Sabounchi[1]	1383 ± 56
			Sabounchi[1]	1739 ± 89		Sabounchi[1]	1158 ± 30
Freire et al. [22]	high level athletes	2099 ± 400	Harris-Benedict	1896 ± 291	1577 ± 170	Harris-Benedict	1490 ± 104
			ten Haaf – BM	2082 ± 258		ten Haaf – BM	1573 ± 155
			ten Haaf – FFM	2243 ± 326		ten Haaf – FFM	1695 ± 139
			WHO/FAO/UNU	1975 ± 302		WHO/FAO/UNU	1429 ± 132
			De Lorenzo	2046 ± 242		De Lorenzo	1683 ± 165
			Wong	1969 ± 262		Wong	1505 ± 127
			Jagim	2435 ± 392		Jagim	1645 ± 205
			Cunningham (1980)	2170 ± 309		Cunningham (1980)	1650 ± 132
			Cunningham (1991)	2039 ± 309		Cunningham (1991)	1519 ± 132
Joseph et al. [26]	weightlifting	2217 ± 515	Katch-McArdle	1687 ± 198			
			Cunningham (1980)	1842 ± 202			
			WHO/FAO/UNU	1821 ± 226			
			ICMR	1727 ± 215			
			Harris-Benedict	1791 ± 221			
			Mifflin	1699 ± 172			
			Owen	1580 ± 148			
			Nelson	1294 ± 263			
Mackay et al. [41]	recreational and sub-elite athletes				1452 ± 267	Harris-Benedict	1438 ± 113
						Mifflin	1392 ± 140
						WHO/FAO/UNU	1460 ± 133
Mackenzie-Shalders et al. [27]	rugby	2389 ± 263	Cunningham	2287 ± 176			
			Harris-Benedict[2]	2242 ± 233			
			Harris-Benedict[2]	2213 ± 226			

TABLE 1. Continue

Study	Sample	Sex					
		Male			Female		
		REE measured (kcal · day^{-1})	Equation	REE predicted (kcal · day^{-1})	REE measured (kcal · day^{-1})	Equation	REE predicted (kcal · day^{-1})
Marques et al. [42]	karate				1689 ± 286	WHO/FAO/UNU	1401 ± 89
						Harris-Benedict	1449 ± 54
						Cunningham (1980)	1552 ± 122
						Henry	1326 ± 69
O'Neil et al. [43]	rugby				1651 ± 167	Cunningham (1980)	1665 ± 124
						Harris-Benedict	1545 ± 117
						ten Haaf – FFM	1690 ± 129
						ten Haaf – BM	1679 ± 166
						Jagim	1830 ± 219
						Watson – FFM	1520 ± 65
						Watson – BM	1623 ± 99
Sena et al. [30]	CrossFit	1885 ± 416	Harris-Benedict	1869 ± 188	1403 ± 258	Harris-Benedict	1397 ± 108
			WHO/FAO/UNU	1878 ± 154		WHO/FAO/UNU	1380 ± 105
			Henry	1708 ± 151		Henry	1307 ± 108
			Cunningham (1980)	2031 ± 165		Cunningham (1980)	1521 ± 126
			Cunningham (1991)	1873 ± 162		Cunningham (1991)	1373 ± 124
			Mifflin	1771 ± 147		Mifflin	1309 ± 164
Staal et al. [4]	ballet dancers	1692 ± 103	Cunningham (1980)	1967 ± 104	1215 ± 106	Cunningham (1980)	1504 ± 108
			Harris-Benedict	1896 ± 135		Harris-Benedict	1355 ± 127
			Koehler	1813 ± 73		Koehler	1378 ± 69
Tinsley et al. [31]	muscular physique	2337 ± 310[3]	Hayes	2166 ± 199	1566 ± 133[3]	Hayes	1438 ± 126
		2408 ± 350[3]	Cunningham (1980)	2245 ± 170	1633 ± 182[3]	Cunningham (1980)	1581 ± 107
			Cunningham (1991)	2083 ± 167		Cunningham (1991)	1432 ± 105
			Mifflin – FFM	1975 ± 152		Mifflin – FFM	1381 ± 96
			Mifflin – BM	1944 ± 144		Mifflin – BM	1396 ± 95
			Owen	2058 ± 172		Owen	1302 ± 96
			ten Haaf – FFM	2290 ± 176		ten Haaf – FFM	1604 ± 110
			ten Haaf – BM	2192 ± 168		ten Haaf – BM	1566 ± 112
			Harris-Benedict	2086 ± 176		Harris-Benedict	1454 ± 70
			WHO/FAO/UNU	2102 ± 160		WHO/FAO/UNU	1417 ± 77
			De Lorenzo	2032 ± 180		De Lorenzo	1677 ± 107
Watson et al. [45]	National Collegiate Athletic Association (NCAA) collegiate athletes				1466 ± 150	Harris-Benedict	1528 ± 98
						Schofield	1483 ± 132
						Mifflin	1472 ± 134
						Owen	1278 ± 64
						WHO/FAO/UNU	1496 ± 141
						Cunningham (1980)	1588 ± 129
						Taguchi	1366 ± 157
Wong et al. [24]	elite athletes	1715 ± 204	WHO/FAO/UNU	1690 ± 130	1384 ± 147	WHO/FAO/UNU	1311 ± 83
			Ismail	1461 ± 130		Ismail	1185 ± 72
			De Lorenzo	1734 ± 111		Cunningham (1980)	1451 ± 81
			Cunningham (1980)	1760 ± 163		Harris-Benedict	1387 ± 57
			Harris-Benedict	1684 ± 140			
YOUTH							
Cherian et al. [35]						IOM	1308 ± 63
	soccer	1343 ± 297	Cunningham (1980)	1375 ± 197	1135 ± 117	Cunningham (1980)	1252 ± 83
			Henry	1428 ± 205		Henry	1262 ± 73
			Soares – BMA	1357 ± 124		Soares-FFM	1135 ± 80
			Soares – FFM	1252 ± 190		Patil-BM	1085 ± 74
			Patil – BM	1402 ± 137		Patil-BMSA	1100 ± 77
			Patil – BMSA	1184 ± 186		Wong	1317 ± 119
			De Lorenzo	1429 ± 223		ten Haaf:	1263 ± 8
			Wong	1334 ± 201			
			ten Haaf	1390 ± 204			

TABLE 1. Continue

Study	Sample	Sex					
		Male			Female		
		REE measured (kcal · day^{-1})	Equation	REE predicted (kcal · day^{-1})	REE measured (kcal · day^{-1})	Equation	REE predicted (kcal · day^{-1})
Hannon et al. [36]	soccer	1858 ± 215	Cunningham (1980)	1578 ± 281			
			De Lorenzo	1769 ± 263			
			Henry	1758 ± 272			
			Kim	1466 ± 191			
			Wong	1693 ± 193			
Loureiro et al. [38]	pentathlon	1559 ± 203	WHO/FAO/UNU	1679 ± 152	1357 ± 140	WHO/FAO/UNU	1376 ± 110
			Harris-Benedict	1610 ± 149		Harris-Benedict	1366 ± 89
			Henry	1667 ± 172		Henry	1279 ± 92
			Cunningham (1980)	1580 ± 171		Cunningham (1980)	1344 ± 194
Łuszczki et al. [39]	soccer	1844 ± 328	Harris-Benedict	1513 ± 256			
			WHO/FAO/UNU	1567 ± 260			
			IMNA	1662 ± 303			
			Cunningham (1991)	1450 ± 264			
			Mifflin	1481 ± 224			
			Owen	1413 ± 147			
			Altman and Dittmer	1534 ± 283			
			Maffeis	1368 ± 150			
			Schofield	1589 ± 253			
			Molnar	1469 ± 239			
			De Lorenzo	1520 ± 298			
Kim et al. [37]	soccer	1648 ± 111	Harris-Benedict	1556 ± 58	1365 ± 186	Harris-Benedict	1418 ± 56
			WHO/FAO/UNU	1577 ± 65		WHO/FAO/UNU	1431 ± 63
			IMNA	1538 ± 70		IMNA	1367 ± 65
			Cunningham (1991)	1677 ± 95		Cunningham (1991)	1309 ± 58
			Mifflin	1543 ± 78		Mifflin	1342 ± 76
			Owen	1284 ± 38		Owen	1198 ± 37
			Altman and Dittmer	1867 ± 101		Altman and Dittmer	1640 ± 98
			Maffeis	1470 ± 60		Maffeis	1321 ± 58
			Schofield	1593 ± 63		Schofield	1431 ± 62
			De Lorenzo	1826 ± 99		De Lorenzo	1564 ± 97
			Park	1648 ± 51		Park	1590 ± 365
Oliveira et al. [15]	soccer	1717 ± 203	WHO/FAO/UNU	1854 ± 131			
			Harris-Benedict	1760 ± 126			
			Henry	1864 ± 148			
			Cunningham (1980)	1728 ± 129			

FAO/WHO/UNU (Food and Agriculture Organization/World Health/United Nations University); IMNA (Institute of Medicine of the National Academies); ICMR (Indian Council of Medical Research); IOM (Institute of Medicine); BMA (body mass, age); FFM (fat-free mass); BM (body mass); BMSA (body mass, stature, age).

[1] Specific population-equation derived from meta-regression.

[2] REE was estimated using different constants from Harris-Benedict equation.

[3] REE was measured using two calorimetry devices.

TABLE 2. Percentage of agreement and disagreement between measured REE and predicted REE.

Study	n	equation	agreement	over-predicted	under-predicted
ADULTS – MALE					
Balci et al. [18]	25	Harris-Benedict	40%	36%	24%
		Mifflin-BMSA	40%	24%	36%
		Mifflin-FFM	60%	8%	32%
		Schofield	11%	28%	28%
		Cunningham	10%	52%	8%
		Owen	12%	4%	48%
		Liu	12%	12%	40%
		De Lorenzo	10%	40%	20%
		Bernstein	5%	0%	80%
		Nelson	15%	8%	32%
		Johnstone	13%	24%	24%
		Roza	6%	44%	32%
Devrim-Lanpir et al. [21]*	15	Harris-Benedict	20%	7%	73%
		Mifflin	47%	27%	27%
		Cunningham	47%	33%	20%
		WHO/FAO/UNU – BMA	20%	7%	73%
		WHO/FAO/UNU – BM	20%	7%	73%
		Wang	27%	7%	67%
		Sabounchi[1]	27%	7%	67%
		Sabounchi[1]	13%	7%	80%
		Sabounchi[1]	20%	7%	73%
Freire et al. [22]**	58	Harris-Benedict	36%		
		ten Haaf – BM	45%		
		ten Haaf – FFM	29%		
		FAO/WHO/UNU	33%		
		De Lorenzo	38%		
		Wong	29%		
		Jagim	7%		
		Cunningham (1980)	50%		
		Cunningham (1991)	50%		
Freire et al. [22]*	58	Harris-Benedict	67%		
		ten Haaf – BM	72%		
		ten Haaf – FFM	59%		
		FAO/WHO/UNU	64%		
		De Lorenzo	69%		
		Wong	64%		
		Jagim	24%		
		Cunningham (1980)	71%		
		Cunningham (1991)	78%		
Frings-Meuthen et al. [23]	79	Harris-Benedict	48%	0%	52%
		FAO/WHO/UNU	63%	0%	37%
		Muller	66%	6%	28%
		Muller-FFM	66%	1%	33%
		Cunningham	68%	25%	7%
		De Lorenzo	72%	10%	18%
ten Haaf and Weijs [10]*	53	Cunningham	84.9%		
		De Lorenzo	77.4%		
Van Grouwn et al. [33]*	16	Mifflin	56.3%		
		Harris-Benedict	43.8%		
ADULTS – FEMALE					
Balci et al. [18]	24	Harris-Benedict	50%	42%	8%
		Mifflin	71%	17%	13%
		Mifflin	58%	17%	25%
		Schofield	54%	38%	8%
		Cunningham	54%	38%	8%
		Owen	38%	58%	4%
		Liu	67%	21%	12%
		De Lorenzo	42%	58%	0%
		Bernstein	17%	8%	75%
		Nelson	33%	8%	58%
		Johnstone	54%	29%	17%
		Roza	38%	63%	0%
Devrim-Lanpir et al. [21]*	15	Harris-Benedict	13%	0%	87%
		Mifflin	53%	13%	33%
		Cunningham	20%	13%	67%
		WHO/FAO/UNU – BMA	13%	0%	87%
		WHO/FAO/UNU – BM	27%	0%	73%
		Wang	13%	0%	87%
		Sabounchi (2013)[1]	20%	0%	80%
		Sabounchi (2013)[1]	27%	0%	73%
		Sabounchi (2013)[1]	7%	0%	93%
Freire et al. [22]**	44	Harris-Benedict	30%		
		ten Haaf – BM	39%		
		ten Haaf – FFM	25%		
		FAO/WHO/UNU	25%		
		De Lorenzo	36%		
		Wong	36%		
		Jagim	39%		
		Cunningham (1980)	41%		
		Cunningham (1991)	43%		
Freire et al. [22]*	44	Harris-Benedict	59%		
		ten Haaf – BM	66%		
		ten Haaf – FFM	59%		
		FAO/WHO/UNU	57%		
		De Lorenzo	75%		
		Wong	68%		
		Jagim	59%		
		Cunningham (1980)	70%		
		Cunningham (1991)	73%		
Frings-Meuthen et al. [23]	34	Harris-Benedict	47%	3%	50%
		FAO/WHO/UNU	41%	6%	53%
		Muller	47%	3%	50%
		Muller-FFM	46%	3%	52%
		Cunningham	64%	36%	0%
		De Lorenzo	62%	27%	12%
ten Haaf and Weijs [10]	37	Cunningham	78.4%		
		De Lorenzo	59.5%		
Van Grouwn et al. [33]*	17	Mifflin	82.2%		
		Harris-Benedict	52.3%		
YOUTH					
Cherian et al. [35]*	male	21	Cunningham	71.4%	
			Henry	57.1%	
			Soares – BMA	61.9%	
			Soares – FFM	42.9%	
			Patil – BMA	61.9%	
			Patil – BMSA	38.1%	
			De Lorenzo	61.9%	
			Wong	76.2%	
			ten Haaf	66.7%	
Cherian et al. [35]*	female	19	Cunningham	42.1%	
			Henry	47.9%	
			Soares	94.7%	
			Patil – BMA	78.9%	
			Patil – BMSA	89.5%	
			Wong	21.1%	
			ten Haaf	42.1%	

*percentage of accurate REE predictions (within 10% of the measured REE); **percentage of accurate REE predictions (within 5% of the measured REE). [1]Specific population-equation derived from meta-regression. BMA (body mass, age); FFM (fat-free mass); BMSA (body mass, stature, age); WHO/FAO/UNU (Food and Agriculture Organization/World Health). Sena et al. combined male and female CrossFit participants.

TABLE 3. Equations developed among athletes to estimate REE.

Study	sex	sample	Equation REE
Cocate et al. [20]	male	cycling	REE = -12888.2 + 485.846 × FFM – 3.7846 × FFM^{2}–24.0092 × age
De Lorenzo et al. [9]	male	water polo, judo, karate	REE = -857 + 9.0 × body mass + (11.7 × stature
Freire et al. [22]	male and female	high level athletes	REE = 729.50 + 175.64 × sex – 7.23 × age + 15.87 × body mass + 1.08 × stature
			REE = -2688.12 + 521.08 × sex + 42.86 × age + 18.98 × body mass + 16.76 × stature + 85.47 × mesomorphy + 140.54 × endomorphy – 8.24 × body mass × sex + 1.53 × body mass × endomorphy – 0.65 × body mass × age
Frings-Meuthen et al. [23]	male and female	master athletic athletes	REE = -222.088 + 18.577 × FFM + 6.753 × FM + 23.910 × temperature + 78.479 × sex
Hannon et al. [36]	male	youth soccer	REE = 1315 + 11.1 × FFM
			REE = 1254 + 9.5 × body mass
Jagim et al. [25]	male and female	National Collegiate Athletic Association (NCAA) collegiate athletes	REE = 19.46 × body mass + 775.33 (males)
			REE = 21.10 × body mass + 288.6 (females)
Joseph et al. [26]	male	weightlifting	REE = -164.065 + 0.039 × LBM
Kim et al. [37]	male and female	youth soccer	REE = 502.7 + (8.6 × body mass) + (9.7 × VO_{2max})
			REE = 730.4 + 15 × FFM
Marra et al. [11]	male	elite athletes	REE = 17.2 × body mass – 5.95 × age + 748
			REE = 16.3 × body mass + 95.4 × phase angle – 93
MacKenzie-Shalders et al. [27]	male	rugby	REE = 29.71 × LBM – 24.56 (beginning of pre-season)
			REE = 26.75 × LBM + 145.44 (prior to competition)
Midorikawa et al. [28]	male	sumo wrestlers	REE* = (13 × skeletal muscle mass) + (4.5 × adipose tissue mass) + (240 × brain mass) + (200 × liver mass) + (440 × kidney mass) + (440 × heart mass) + (12 × residual mass)
O'Neil et al. [43]	female	rugby	REE = 649.6 + 18.91 × FFM
			REE = 150.1–6.858 × age – 2.946 × stature + 11.21 × body mass
Reale et al. [40]	male and female	different sports	REE = body mass × 11.1 + stature × 8.4–339.7 (males)
			REE = FFM × 14.5 + FM + 8.6 + stature × 5.7–35.9 (males)
			REE = body mass × 11.1 + stature × 8.4–537.1 (females)
			REE = FFM × 14.5 + FM + 8.6 + stature × 5.7–203.9 (females)
Taguchi et al. [44]	female	collegiate athletes	REE = 17.8 × body mass + 243
			REE = 26.9 × FFM + 36
			REE* = (2.3 × body mass) + (4.5 × adipose tissue) + (13 × skeletal muscle) + (54 × residual mass)
ten Haaf and Weijs [10]	male and female	different sports	REE = 11.936 × body mass + 587.7 x stature – 8.129 × age + 191.027 × sex + 29.279
			REE = 22.771 × FFM + 484.264
Tinsley et al. [31]	male and female	muscular physique	REE = 25.9 × FFM + 284
			REE = 24.8 × body mass + 10
Watson et al. [45]	female	National Collegiate Athletic Association (NCAA) collegiate athletes	REE = 88.1 + 2.53 × stature + 8.42 × body mass + 19.46 × age
			REE = 120.81 + 4.88 × stature + 8.24 × FFM + 5.71 × age
Wong et al. [34]	male and female	elite athletes	REE = 669 + 13 × body mass + 192 × sex

REE (resting energy expenditure); FFM (fat-free mass); VO_{2max} (maximal oxygen uptake); LBM (lean body mass); FM (fat mass).
*These equations were developed by other authors.

age group and sex in Supplementary Table 1. Twenty-one and seven studies included male adult [4, 9–11, 18–34] and youth sport participants [15, 35–40], respectively. Female adult athletes participated in 19 studies [4, 10, 18, 19, 21–25, 30–34, 41–45] while, five studies used samples of young athletes [35, 37, 38, 40, 46].

Risk of bias in studies

Based on Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies the risk of bias of studies was individually examined as shown in Supplementary Material 2. In general, studies did not estimate a priori sample size to examine differences between

measured REE and estimated REE or to create an equation to extrapolate REE. In parallel, the inclusion criteria in each study were not described in some of the studies used in this systematic review. The overall quality rating of 28 studies was fair, 3 studies were classified as poor and 3 studies as good.

Results of individual studies

The comparison of measured REE with predicted values was noted in twelves studies of adults [4, 18, 19, 20, 21, 22, 26, 27, 30, 41, 42, 43] and analysed in seven studies of young athletes [15, 35, 36, 37, 38, 39, 46] as shown in Table 1. Of interest, Harris-Benedict, Cunningham and WHO/FAO/UNU were the main equations examined. Contrasting findings across studies are notable. For example, among ultra-endurance [21] and high-levels athletes [22], Harris-Benedict tended to underestimate measured REE while among Royal ballet dancers [4] predicted REE was overestimated in comparison to measured REE. Regarding the Cunningham equation, it tended to overestimate measured REE in Olympic male and female athletes [18] and underestimate measured REE in ultra-endurance athletes [21]. Predicted REE by WHO/FAO/UNU equation was, on average, substantially less than measured REE among Indian male weightlifters [26] and it was considered the most appropriate estimation of REE amongst adult male soccer players from Malaysia [24]. Overall, the equations developed to predict REE in general population were not comparable to measured REE in athletic samples. The percentage of agreement reported in six studies [10, 18, 21, 23, 33, 35] was often less than 60% for Harris-Benedict [10, 18, 21, 22, 23, 33] and Cunningham [21, 22] equations in athletes. Although sport-specific equations to estimate REE had received less attention, an agreement > 60% [10, 23, 25] was obtained in three studies that used De Lorenzo et al. [9] equation (Table 2). Studies which presented equations to estimate REE are summarized in Table 3 [9–11, 20, 22, 23, 25–28, 31, 34, 36, 37, 40, 43–45]. Body weight and FFM emerged as the most determinant predictors of REE. Two studies used the sum of four [44] and seven [28] body compartments to calculate REE in 93 collegiate athletes and 10 sumo wrestlers, respectively. Recently, two equations included somatotype [22] and phase angle [11] as potential determinants of REE.

DISCUSSION

The aim of the present study was to review the agreement between measured REE and predicted REE using estimative equations. Additionally, the current systemic review summarized estimations of REE obtained using participants involved in organized sports. In general, across different samples of sport participants, measured REE was not comparable with REE predicted from equations developed in general population. Consistent results were noted among participants classified as overweight and obese [47] as well in healthy older adults aged ≥ 60 years [24]. Two equations, De Lorenzo et al. [9] and ten Haaf and Weijs [10], included athletes from different sports. Although few studies tested the precision of these equations, an agreement of 72% and 68% was noted with measured REE in male [23] and female [22] athletes, respectively. Therefore, the De Lorenzo and ten Haaf equations seems to be acceptable alternatives to estimate REE in athletes. Although Harris-Benedict and Cunningham equations were claimed to estimate REE among athletes, population-specific equations are needed [1].

Among 49 Turkish Olympic athletes differences between measured REE and predicted REE by Harris-Benedict equation were, on average, negligible however, only 40% and 50% of males and females, respectively, were within 10% of the measured REE [18]. Conversely studies using the Cunningham equation provided inconsistent results – underestimating REE in 83% of adolescent athletes aged 13–19 years [40] while, among 90 adult sport participants [10] an acceptable agreement between measured REE and predicted REE was reported in males (84.9%) and females (78.4%). Recently, the application of the Cunningham equation was recommended for use in female athletes but not be considered in males [24]. The equation explained 34% of variance in measured REE and an error 15% of with Cunningham model was noted among males [24]. In general, predicted REE by the Cunningham equation should not be generalized for athletic samples. This equation estimated lean body mass based on age and body mass [48]. Studies about REE estimation in athletes applied different methods to determine body composition. ten Haaf and Weijs [10] used air displacement plethysmography technique in 90 adult athletes while a recent study in Premier League soccer academy athletes used DXA methodology obtain FFM [36]. Considering the preceding, few studies that analysed Cunningham equation adopted the same methodology to estimate metabolic active tissues as original author [7]. The Cunningham equation was reviewed in 1991 but inconsistent results to predict REE were also noted [49].

The Mifflin equation [50] also emerged as a potential model to provide sex-specific estimates of REE in sport [51]. Fat mass and FFM were estimated from skinfold subcutaneous adipose tissue measurements [52, 53] and final sex-specific equations incorporated age, body mass and stature. The original sample included 247 females (ranging 20–76 years-old) and 251 males (age ranging 19–78 years-old). Of those, 112 females and 122 males were classified as obese [50]. Not surprisingly, predicted REE by the Mifflin equation tended to underestimate -114 kcal and -94 kcal measured REE among males and females CrossFit athletes, respectively [30]. In a sample of 9 power-lifters and 3 weightlifters Mifflin equation differed 11% of measured REE and it was supported that WHO/ONU/UNU should be used to predict REE [29]. The sample of WHO/ONU/UNU derived from the 7173 European and North American data points. Even though 3338 data points were obtained from active Italian participants with an elevated REE [54] this equation seems to be not applicable in athletes. Differences between measured REE and predicted REE using WHO/ONU/UNU equation ranged 466–287 $kcal \cdot day^{-1}$ in 30 ultra-endurance athletes aged 23–55 years [21]. Overall, the equations developed in general

population should not be generalized for participants involved in organized sport. As a result, studies involving athletes proposed new predictive models to estimate REE.

Two potential equations to predict REE among athletes [9, 10] were compared with indirect calorimetry. Based on 126 male elite athletes from different sports minimal differences (21 kcal · day^{-1} and 60 kcal · day^{-1}) were reported between the De Lorenzo et al. [9] and ten Haaf and Weijs [10] equations and measured REE [11]. The latter equation successfully predicted REE (within ± 10%) in 31 out of 36 female adult rugby players [43]. However, REE was underestimated by the De Lorenzo equation in young male soccer players [34, 36]. Three particular issues need highlighting: (1) De Lorenzo and ten Haaf models were validated in sport participants but received little consideration in sports nutrition literature and practice; (2) both equations combined adult athletes from different sports; (3) equations were developed in adults should not be generalized for youth sport participants.

Although the considerable number of studies extracted in the current review, a possible limitation is the inclusion of only English records. Additionally, grey literature was not also considered. Only one estimated a priori sample size necessary to create predictive models of REE. Future studies need to cross-validate the equations which used athletes from different modalities in larger sport-specific samples. Of note, predictions of REE only using female athletes are available in the literature and future research is required. The sex-specific equation proposed by ten Haaf and Weijs [10] is also adequate to predict REE in female athletes. The equation developed by De Lorenzo et al. [9] only included male participants from different sports hence, it is a valid alternative to estimate REE in male athletes. Specific equations were developed for youth involved in different sports [16] and soccer players [39, 44] thereby, should be adopted in studies of young athletes.

Findings of current review are crucial for nutritionists and/or staff providing nutrition support within sport in order to optimise total daily energy intake. The use of indirect equations in athletes, especially those that were developed in general population, tended to produce different values of measured REE which in turn has impact on TEE (obtained by multiplying REE and an appropriate physical activity factor). In summary, De Lorenzo et al. [9] and ten Haaf and Weijs [10] seem to be the most appropriate equations to predict REE among adult athletes and needed particular attention by sport nutritionists. Validation of predictive models to estimate REE required future research particularly in sport-specific samples and youth athletes.

Conflict of interest

The authors declare no conflict of interest.

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SUPPLEMENTARY TABLE 1. Summary of sample characteristics (sport, age, body size, body composition).

Study	Sport (n)	Age (years)	Stature (cm or m)	Body mass (kg)	Fat-free mass or lean soft tissue (kg or %)
		MALE – ADULTS			
Balci et al. [18]	Olympic athletes (n = 25)	19.1 ± 1.5	178.7 ± 6.1	75.4 ± 12.4	66.7 ± 7.6
Carlsohn et al. [19]	rowing and canoe racing (n = 8)	23.0 ± 5.0	193.0 ± 7.0	92.9 ± 10.0	81.0 ± 8.0 kg
Cocate et al. [20]	cycling (n = 15)	24.4 ± 3.7	174.7 ± 4.9	67.1 ± 5.5	62.0 ± 4.1 kg
De Lorenzo et al. [9]	water polo (n = 22), judo (n = 12), karate (n = 17)	22.3 ± 3.5	178.4 ± 7.1	78.0 ± 11.5	63.4 ± 6.6 kg
Devrim-Lanpir et al. [21]	triathlon (n = 10), ultra-marathon (n = 5)	38.4 ± 5.3	178.2 ± 7.4	73.0 ± 7.4	63.4 ± 6.4 kg
Freire et al. [22]	high level athletes (n = 58)	24.6 ± 3.8	182.6 ± 8.1	85.3 ± 20.1	77.2 ± 14.3 kg
Frings-Meuthen et al. [23]	master athletic athletes (n = 79)	57.1 ± 11.7	174.9 ± 7.2	74.2 ± 10.3	60.8 ± 8.4 kg
Jagim et al. [24]	football (n = 21), track and field (n = 4), baseball (n = 3)	20.3 ± 1.6	182.0 ± 6.1	94.5 ± 16.2	79.0 ± 7.7 kg
Jagim et al. [25]	National Collegiate Athletic Association (NCAA) collegiate athletes (n = 68)	20.1 ± 1.5	181.8 ± 5.9	93.7 ± 16.3	77.3 ± 8.1 kg
Joseph et al. [26]	weightlifting (n = 30)	21.5 ± 2.9	168.8 ± 6.3	76.0 ± 14.7	61.0 ± 9.2 kg
MacKenzie-Shalders et al. [27]	rugby (n = 18)	20.2 ± 1.7	184.0 ± 8.4	101.2 ± 14.5	81.3 ± 8.0 kg
Marra et al. [11]	elite athletes (n = 126)	26.9 ± 9.1	177.0 ± 7.0	71.3 ± 10.9	
Midorikawa et al. [28]	sumo wrestlers (n = 10)	19.4 ± 1.5	172.9 ± 8.4	109.1 ± 14.7	78.6 ± 0.7 kg
Moore et al. [29]	powerlifting (n = 9), weightlifters (n = 3)	22.4 ± 2.6	175.2 ± 7.8	92.0 ± 22.1	
Staal et al. [4]	ballet dancers (n = 20)	24.5 (21.0–28.5)	183.0 ± 4.4	72.8 ± 4.6	66.7 ± 4.7 kg
Sena et al. [30]	CrossFit (n = 52)	33.1 ± 5.7	1.75 ± 0.05	83.5 ± 12.3	69.6 ± 7.5 kg
ten Haaf and Weijs [10]	different sports (n = 53)	23.5 ± 5.0	1.72 ± 0.05	62.6 ± 6.6	78.4 ± 4.7%
Tinsley et al. [31]	muscular physique (n = 17)	26.0 ± 6.5	180.4 ± 7.2	94.0 ± 9.7	
Thompson and Manore [32]	endurance athletes (n = 24)	26.0 ± 4.0	177.2 ± 5.7	69.7 ± 7.6	63.4 ± 6.8 kg
Van Grouw et al. [33]	master athletes (n = 16)				
Wong et al. [34]	elite athletes (n = 92)	21.4 ± 3.0	170.6 ± 6.5	66.1 ± 8.5	57.1 ± 7.4 kg
		MALE – YOUTH			
Cherian et al. [35]	soccer (n = 21)	11.7 ± 2.1	160.0 ± 10.9	46.0 ± 11.1	39.8 ± 8.95 kg
Hannon et al. [36]	soccer (n = 99)	under-12: 12.3 ± 0.2	157.4 ± 4.1	45.5 ± 5.9	31.6 ± 4.2 kg
		under-13: 13.2 ± 0.2	162.7 ± 6.2	47.4 ± 5.6	34.6 ± 4.7 kg
		under-14: 14.3 ± 0.2	172.5 ± 8.0	56.9 ± 10.0	43.2 ± 8.9 kg
		under-15: 15.3 ± 0.3	175.9 ± 6.7	63.1 ± 7.1	49.3 ± 6.5 kg
		under-16: 16.4 ± 0.2	182.4 ± 5.8	72.9 ± 7.9	56.3 ± 5.3 kg
		under-18: 17.6 ± 0.7	182.7 ± 4.1	73.2 ± 8.1	57.9 ± 6.6 kg
		under-23: 19.9 ± 1.5	186.4 ± 6.0	80.3 ± 8.8	62.6 ± 5.9 kg
Kim et al. [37]	soccer (n = 30)	16.7 ± 1.0	176.9 ± 5.3	68.1 ± 5.3	60.5 ± 4.5 kg
Loureiro et al. [38]	pentathlon (n = 17)	15.0 ± 2.0	169.0 ± 7.0	58.5 ± 8.7	85.0 ± 3.4%
Łuszczki et al. [39]	soccer (n = 184)	13.2 ± 2.2	162.9 ± 14.9	52.4 ± 14.4	43.2 ± 12.0 kg
Reale et al. [40]	lacrosse (n = 6), basketball (n = 22), football (n = 14), baseball (n = 20), golf (n = 9), tennis (n = 11), track and field (n = 2), soccer (n = 13)	16.5 ± 1.5	179.0 ± 9.6	76.5 ± 16.6	60.7 ± 11.6 kg
Oliveira et al. [15]	soccer (n = 45)	15.69 ± 1.41	173.0 ± 7.5	67.6 ± 7.4	53.1 ± 6.0 kg
		FEMALE – ADULTS			
Balci et al. [18]	Olympic athletes (n = 24)	20.3 ± 2.1	163.3 ± 6.6	60.6 ± 12.7	47.0 ± 5.7 kg
Carlsohn et al. [19]	rowing and canoe racing (n = 9)	23.3 ± 3.0	175.0 ± 7.0	69.3 ± 11.0	56.1 ± 7.0 kg
Devrim-Lanpir et al. [21]	triathlon (n = 6), ultra-marathon (n = 9)	37.1 ± 7.9	162.7 ± 3.7	56.5 ± 4.1	45.3 ± 2.8 kg
Freire et al. [22]	high level athletes (n = 44)	25.7 ± 4.7	167.6 ± 8.0	64.3 ± 9.7	53.2 ± 6.1 kg
Frings-Meuthen et al. [23]	master athletic athletes (n = 34)	54.9 ± 11.6	165.0 ± 6.0	62.2 ± 10.0	48.2 ± 6.4 kg
Jagim et al. [24]	soccer (n = 15), swimming (n = 4), track and field (n = 3)	19.7 ± 1.4	166.5 ± 5.4	63.2 ± 7.3	49.2 ± 4.3 kg
Jagim et al. [25]	National Collegiate Athletic Association (NCAA) collegiate athletes (n = 48)	19.4 ± 1.3	166.5 ± 6.0	63.4 ± 12.7	48.7 ± 7.3 kg

SUPPLEMENTARY TABLE 1. Continue

Study	Sport (n)	Age (years)	Stature (cm or m)	Body mass (kg)	Fat-free mass or lean soft tissue (kg or %)
Mackay et al. [41]	recreational athletes (n = 12)	27.5 ± 12.3	169.3 ± 7.3	69.0 ± 9.4	
	sub-elite athletes (n = 13)	32.5 ± 7.4	167.9 ± 7.8	60.9 ± 6.7	
Marques et al. [42]	karate (n = 7)	21.7 ± 3.0	1.63 ± 0.04	62.1 ± 6.0	47.8 ± 5.6 kg
O'Neil et a. [43]	rugby (n = 36)	25.5 ± 4.8	167.5 ± 6.0	73.0 ± 10.4	53.0 ± 5.7 kg
Staal et al. [4]	ballet dancers (n = 20)	25.1 ± 4.8	170.4 ± 4.9	55.1 ± 5.4	45.6 ± 4.4 kg
Sena et al. [30]	crossfit (n = 90)	32.8 ± 6.8	1.63 ± 0.05	62.3 ± 9.4	46.4 ± 5.7 kg
Taguchi et al. [44]	collegiate athletes (n = 93)	20.3 ± 1.2	162.8 ± 6.4	57.0 ± 9.2	45.4 ± 6.2 kg
ten Haaf and Weijs [10]	different sports (n = 37)	23.1 ± 4.7	1.82 ± 0.09	75.7 ± 7.8	88.3 ± 4.9%
Tinsley et al. [31]	muscular physique (n = 10)				
Thompson and Manore [32]	endurance athletes (n = 13)	31.0 ± 5.0	162.5 ± 4.2	52.9 ± 5.6	45.1 ± 5.3 kg
Van Grouw et al. [33]	master athletes (n = 17)	25.8 ± 5.4	167.5 ± 5.7	63.8 ± 5.7	
Watson et al. [45]	National Collegiate Athletic Association (NCAA) collegiate athletes (n = 66)	19.7 ± 1.1	169.0 ± 9.0	67.3 ± 8.9	49.5 ± 5.8 kg
Wong et al. [34]	elite athletes (n = 33)	20.4 ± 2.1	160.7 ± 4.8	55.4 ± 5.7	43.2 ± 3.7 kg
		FEMALES – YOUTH			
Branco et al [46]	gymnastics (n = 11)	16.6 ± 2.5	1.61 ± 0.06	53.3 ± 5.7	
Cherian et al. [35]	soccer (n = 19)	12.2 ± 1.8	153.6 ± 4.6	45.1 ± 6.6	34.2 ± 3.8 kg
Kim et al. [37]	soccer (n = 20)	16.4 ± 1.1	163.7 ± 5.2	56.1 ± 5.2	43.5 ± 2.7 kg
Loureiro et al [38]	pentathlon (n = 11)	14.0 ± 3.0	161.0 ± 6.0	52.6 ± 6.7	74.6 ± 9.2%
Reale et al. [40]	lacrosse (n = 3), basketball (n = 7), golf (n = 2), tennis (n = 4), track and field (n = 1), soccer (n = 11)	16.5 ± 1.2	166.8 ± 7.4	60.8 ± 10.2	43.6 ± 5.2 kg

SUPPLEMENTARY MATERIAL 2. Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies to examine risk of bias for each manuscript.

Study	Balci et al. [18]	Branco et al. [46]	Carlsohn et al. [19]	Cherian et al. [35]	Cocate et al. [20]
1. Was the research question or objective in this paper clearly stated?	Yes	Yes	No	Yes	Yes
2. Was the study population clearly specified and defined?	Yes	Yes	Yes	Yes	Yes
3. Was the participation rate of eligible persons at least 50%?	NA	NA	NA	NA	No
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	Yes	No	Yes	Yes	No
5. Was a sample size justification, power description, or variance and effect estimates provided?	Yes	No	No	No	No
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	NA	NA	NA	NA	NA
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	NA	NA	NA	NA	NA
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?	NA	NA	NA	NA	NA
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	Yes	No
10. Was the exposure(s) assessed more than once over time?	No	No	No	No	No
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	Yes	Yes
12. Were the outcome assessors blinded to the exposure status of participants?	NA	NA	NA	NA	NA
13. Was loss to follow-up after baseline 20% or less?	NA	NA	NA	NA	NA
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	Yes	YES	Yes	Yes	Yes
Quality Rating (good, fair, poor)	Good	Fair	Fair	Fair	Fair

Study	De Lorenzo et al. [9]	Devrim-Lanpir et al. [21]	Freire et al. [22]	Frings-Meuthen et al. [23]	Hannon et al. [36]
1. Was the research question or objective in this paper clearly stated?	Yes	Yes	Yes	Yes	Yes
2. Was the study population clearly specified and defined?	Yes	Yes	Yes	Yes	Yes
3. Was the participation rate of eligible persons at least 50%?	NA	NA	NA	NA	NA
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	No	Yes	Yes	Yes	No
5. Was a sample size justification, power description, or variance and effect estimates provided?	No	No	No	No	No
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	NA	NA	NA	NA	NA
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	NA	NA	NA	NA	NA
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?	NA	NA	NA	NA	NA
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	Yes	Yes
10. Was the exposure(s) assessed more than once over time?	No	No	No	No	No
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	Yes	Yes
12. Were the outcome assessors blinded to the exposure status of participants?	NA	NA	NA	NA	NA
13. Was loss to follow-up after baseline 20% or less?	NA	NA	NA	NA	NA
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	Yes	Yes	Yes	Yes	No
Quality Rating (good, fair, poor)	Fair	Fair	Fair	Fair	Fair

Study	Jagim et al. [24]	Jagim et al. [25]	Joseph et al. [26]	Kim et al. [37]	Loureiro et al. [38]
1. Was the research question or objective in this paper clearly stated?	Yes	Yes	Yes	Yes	Yes
2. Was the study population clearly specified and defined?	Yes	Yes	Yes	Yes	Yes
3. Was the participation rate of eligible persons at least 50%?	NA	NA	NA	NA	NA
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	Yes	No	No	Yes	Yes
5. Was a sample size justification, power description, or variance and effect estimates provided?	No	No	No	No	No
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	NA	NA	NA	NA	NA
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	NA	NA	NA	NA	NA
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?	NA	NA	NA	NA	NA
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	No	Yes	No
10. Was the exposure(s) assessed more than once over time?	No	No	No	No	No
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	NA	NA	NA	NA	Yes
12. Were the outcome assessors blinded to the exposure status of participants?	NA	NA	NA	NA	NA
13. Was loss to follow-up after baseline 20% or less?	NA	NA	NA	NA	NA
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	Yes	Yes	Yes	Yes	Yes
Quality Rating (good, fair, poor)	Fair	Fair	Poor	Fair	Fair

Study	Łuszczki et al. [39]	Mackay et al. [41]	MacKenzie-Shalders et al. [27]	Marques [42]	Marra et al. [11]
1. Was the research question or objective in this paper clearly stated?	Yes	Yes	Yes	Yes	No
2. Was the study population clearly specified and defined?	Yes	Yes	Yes	Yes	No
3. Was the participation rate of eligible persons at least 50%?	NA	NA	NA	NA	NA
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	Yes	Yes	No	No	No
5. Was a sample size justification, power description, or variance and effect estimates provided?	Yes	No	No	No	Yes
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	NA	NA	NA	NA	NA
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	NA	NA	Yes	NA	NA
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?	NA	NA	Yes	NA	NA
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	No	Yes	No	Yes
10. Was the exposure(s) assessed more than once over time?	No	No	Yes	No	No
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	Yes	Yes
12. Were the outcome assessors blinded to the exposure status of participants?	NA	NA	NA	NA	NA
13. Was loss to follow-up after baseline 20% or less?	NA	NA	No	NA	NA
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	Yes	Yes	Yes	Yes	Yes
Quality Rating (good, fair, poor)	Good	Fair	Good	Fair	Fair

Study	Midorikawa et al. [28]	Moore et al. [29]	Oliveira et al. [15]	O'Neil et al. [43]	Reale et al. [40]
1. Was the research question or objective in this paper clearly stated?	Yes	Yes	Yes	Yes	Yes
2. Was the study population clearly specified and defined?	Yes	Yes	Yes	Yes	Yes
3. Was the participation rate of eligible persons at least 50%?	NA	NA	NA	NA	NA
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	Yes	No	Yes	Yes	Yes
5. Was a sample size justification, power description, or variance and effect estimates provided?	No	No	No	No	No
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	NA	NA	NA	NA	NA
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	NA	NA	NA	NA	NA
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?	NA	NA	NA	NA	NA
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	No	Yes	No	No
10. Was the exposure(s) assessed more than once over time?	No	No	No	No	No
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	Yes	Yes
12. Were the outcome assessors blinded to the exposure status of participants?	NA	NA	NA	NA	NA
13. Was loss to follow-up after baseline 20% or less?	NA	NA	NA	NA	NA
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	Yes	Yes	Yes	Yes	Yes
Quality Rating (good, fair, poor)	Fair	Poor	Fair	Fair	Fair

Study	Sena et al. [30]	Staal et al. [4]	Taguchi et al. [44]	ten Haaf et al. [10]	Thompson et al. [32]
1. Was the research question or objective in this paper clearly stated?	Yes	Yes	Yes	Yes	Yes
2. Was the study population clearly specified and defined?	Yes	Yes	Yes	Yes	Yes
3. Was the participation rate of eligible persons at least 50%?	NA	NA	NA	NA	NA
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	Yes	No	No	No	Yes
5. Was a sample size justification, power description, or variance and effect estimates provided?	No	No	No	No	No
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	NA	NA	NA	NA	NA
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	NA	NA	NA	NA	NA
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?	NA	NA	NA	NA	NA
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	No	Yes
10. Was the exposure(s) assessed more than once over time?	No	No	No	No	No
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	Yes	Yes
12. Were the outcome assessors blinded to the exposure status of participants?	NA	NA	NA	NA	NA
13. Was loss to follow-up after baseline 20% or less?	NA	NA	NA	NA	NA
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	Yes	Yes	Yes	Yes	Yes
Quality Rating (good, fair, poor)	Fair	Fair	Fair	Fair	Fair

Study	Tinsley et al. [31]	Van Grouw et al. [33]	Watson et al. [45]	Wong et al. [34]
1. Was the research question or objective in this paper clearly stated?	Yes	Yes	Yes	Yes
2. Was the study population clearly specified and defined?	Yes	No	Yes	Yes
3. Was the participation rate of eligible persons at least 50%?	NA	NA	NA	NA
o4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	Yes	No	No	Yes
5. Was a sample size justification, power description, or variance and effect estimates provided?	No	No	No	No
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	NA	NA	NA	NA
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	NA	NA	NA	NA
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?	NA	NA	NA	NA
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	No	Yes	Yes
10. Was the exposure(s) assessed more than once over time?	No	No	No	No
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Yes	Yes	Yes	Yes
12. Were the outcome assessors blinded to the exposure status of participants?	NA	NA	NA	NA
13. Was loss to follow-up after baseline 20% or less?	NA	NA	NA	NA
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	Yes	Yes	Yes	Yes
Quality Rating (good, fair, poor)	Fair	Poor	Fair	Fair

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Validity of a low-cost friction encoder for measuring velocity, force and power in flywheel exercise devices

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ABSTRACT: The purpose of this study was to investigate the validity of a low-cost friction encoder against a criterion measure (strain gauge combined with a linear encoder) for assessing velocity, force and power in flywheel exercise devices. Ten young and physically active volunteers performed two sets of 14 maximal squats on a flywheel inertial device (YoYo Technology, Stockholm, Sweden) with five minutes rest between each set. Two different resistances were used (0.075 kg·m^2 for the first set; 0.025 kg·m^2 for the second). Mean velocity (V_{rep}), force (F_{rep}) and power (P_{rep}) for each repetition were assessed simultaneously via a friction encoder (Chronojump, Barcelona, Spain), and with a strain gauge combined with a linear encoder (MuscleLab 6000, Ergotest Technology, Porsgrunn, Norway). Results are displayed as (Mean [CI 90%]). Compared to criterion measures, mean bias for the practical measures of V_{rep}, F_{rep} and P_{rep} were moderate (-0.95 [-0.99 to -0.92]), small (0.53 [0.50 to 0.56]) and moderate (-0.68 [-0.71 to -0.65]) respectively. The typical error of estimate (TEE) was small for all three parameters; V_{rep} (0.23 [0.20 to 0.25]), F_{rep} (0.20 [0.18 to 0.22]) and P_{rep} (0.18 [0.16 to 0.20]). Correlations with MuscleLab were nearly perfect for all measures in all load configurations. Based on these findings, the friction encoder provides valid measures of velocity, force and power in flywheel exercise devices. However, as error did exist between measures, the same testing protocol should be used when assessing changes in these parameters over time, or when aiming to perform inter-individual comparisons.

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Key words:
Iso-inertial
Monitoring
Resistance Training
Feedback

INTRODUCTION

Quantifying training loads is an important consideration for sports scientists and practitioners. Accurate quantification can ensure that training is both appropriate and meets the programme requirements [1]. Furthermore, this information is essential for informing decision making so that negative training outcomes (e.g. overtraining, illness, and maladaptation) can be avoided [2]. For this reason, tools that are used to quantify training need to be valid so that accurate training information can be gathered. This is relevant for all training methods, including resistance training.

Traditional resistance training methods (e.g. gravity-dependent loads such as dumbbells and barbells), are often quantified through the mass and number of repetitions completed (e.g. volume load) [3]. However, alternative methods of resistance training, such as flywheel training, can be more challenging to quantify as they do not have a constant external load and rely on athletes overcoming inertia to accelerate or decelerate the mass of the wheels (i.e. isoinertial training) [4]. Despite these practical difficulties in quantifying training loads, the popularity of flywheel devices has grown in recent times due to their ability to induce positive adaptations in strength, power, and velocity [5]. Furthermore, their ability to easily apply eccentric overload (i.e. brief episodes in which eccentric output is higher compared to the concentric output) may provide benefits that can be difficult to achieve using traditional training methods [5, 6]. For an extended description of the eccentric overload concept, relevance, and the available ways for its quantification the reader is referred to a recent review on the topic [7].

Several laboratory technologies can be used for quantifying movement velocity (e.g. linear encoders or optical motion sensing systems) and force (e.g. force plates or strain gauges) during isoinertial exercises [8–12]. However, since some of the aforementioned tools are expensive laboratory-based pieces of equipment, these are not viable options for most practitioners. Another limitation is that

power measurement requires the combination of at least two sensors for being calculated as the product of force and velocity [9, 10]. Therefore, the necessary set-up of sensors and wires may not be convenient in day-to-day training.

To facilitate the quantification of isoinertial training loads, monitoring devices known as axis rotary encoders have been developed. These kinetic sensors are welded to the axis to track flywheel angular velocity and relate these data to a constant moment of inertia to estimate applied force and power in real time. Recent works have demonstrated that flywheel resistance training can be accurately quantified through the use of these sensors [9, 10, 13]. However, one of the biggest limitations is that axis rotary encoders have to be installed by the manufacturer through industrial mechanization of the pieces. In this sense, the encoder is specific to the isoinertial training system and can not be disarmed and used with different devices.

To circumnavigate this issue, rotary friction encoders have been developed. These sensors are not specific or welded to a unique isoinertial training system, but instead can be adapted and used to monitor different isoinertial machines. This is a very relevant feature, as it allows for monitoring existing non-sensorized equipment in a few minutes. Rotary friction encoders consist of a wheel which has to be tightly attached to the rotating flywheel. Due to friction between the two surfaces, the encoder shares the same linear velocity with the point where it is installed. Force, power, and velocity that is being produced by the athlete during training are calculated in real time from the encoder measures of rotational velocity, using given configuration parameters such as the moment of inertia of the wheel, additional masses, and diameters of the pieces (e.g. axis). Therefore, by introducing these set-up parameters in the software, the sensor can be adapted to different inertial training systems.

Although the practicality and relevance of rotary friction encoders is evident, their criterion validity has not been assessed, so the accuracy of the provided feedback is still unknown. Thus, the aim of this study was to assess the criterion validity of force, power, and velocity outputs that are calculated at two different isoinertial loads from a rotary friction encoder.

MATERIALS AND METHODS

Experimental Approach to the Problem

The study was designed to evaluate the criterion validity of force, velocity and power values measured with a commonly used low-cost friction encoder (Chronojump, Barcelona, Spain). In order to do so, half-squats performed on a flywheel with two different isoinertial loads (0.075 kg·m^2 and 0.025 kg·m^2) were simultaneously monitored using (I, practical measure) a friction encoder attached at a known diameter of the flywheel, and (II, criterion measure) a strain gauge combined with a linear encoder attached to the harness. The level of agreement between force, velocity and power obtained from both methods was assessed.

Subjects

Ten physically active male and female volunteers (age 27.9 ± 4.9 years, body mass 70.6 ± 11.9 kg, height 174.5 ± 8.3 cm) were recruited to take part in this study. Subjects were free of injury and illness during data collection. All subjects had previously trained with the exercise device and were familiar with the testing protocol and isoinertial loads used. All experimental procedures were approved by the Catalan Sports Council (Generalitat de Catalunya) ethics committee, and written consent was provided by all subjects before study initiation.

Procedures

An exercise protocol consisting of maximal voluntary concentric-eccentric bilateral half-squats was performed on a "YoYo squat" flywheel device (YoYo Technology, Stockholm, Sweden). An extended description of the exercise can be found elsewhere [14]. Subjects performed two sets of the exercise, consisting of three sub-maximal reps to accelerate the disk, followed by 14 repetitions with maximal intent. In order to test the validity of the friction encoder in different load configurations, two different resistances were used: The moment of inertia was 0.075 kg·m^2 for one set and 0.025 kg·m^2 for the other. These load configurations were selected because they are commonly used both in research and in the professional practice [6, 7] and have previously been described as high and low isoinertial load configurations for the squat [15]. The order that subjects completed these different isoinertial loads were randomized by a coin toss. Mean velocity (V_{rep}), force (F_{rep}) and power (P_{rep}) for each repetition were assessed simultaneously via a friction encoder, and strain gauge combined with a linear encoder.

Criterion measures of velocity, force and power were assessed by a strain gauge synchronized with a linear encoder using a MuscleLab 6000 (Ergotest Technology, Porsgrunn, Norway). This device has been used before as a measurement reference system in inertial training [10, 12]. The strain gauge (accuracy 63 g, sampling rate: 200 Hz) was attached between the strap of the flywheel and the vest; and the linear encoder (accuracy 0.019 mm; sampling rate 200 Hz) was placed on the flywheel device and attached to the vest, forming a perpendicular angle with the floor (Figure 1).

The friction encoder (Chronojump, Barcelona, Spain), (accuracy 1 mm, sampling rate 1000 Hz) was tightly attached at a known diameter of the flywheel, sharing the same linear velocity (Figure 1). The set-up parameters such as disk inertia, axis diameter, and the volunteer's body mass were entered into the associated Chronojump software (v1.8.1–95) to compute the practical measures of velocity, force and power in real time. Chronojump is an open-code software, and a complete repository of the code and formulas used can be found online [16].

As previously introduced, axis diameter is an essential parameter for computing kinematic variables from the friction encoder, because it determines the point at which the strap exerts unwinding force, and therefore modifies the moment arm and torque. In the

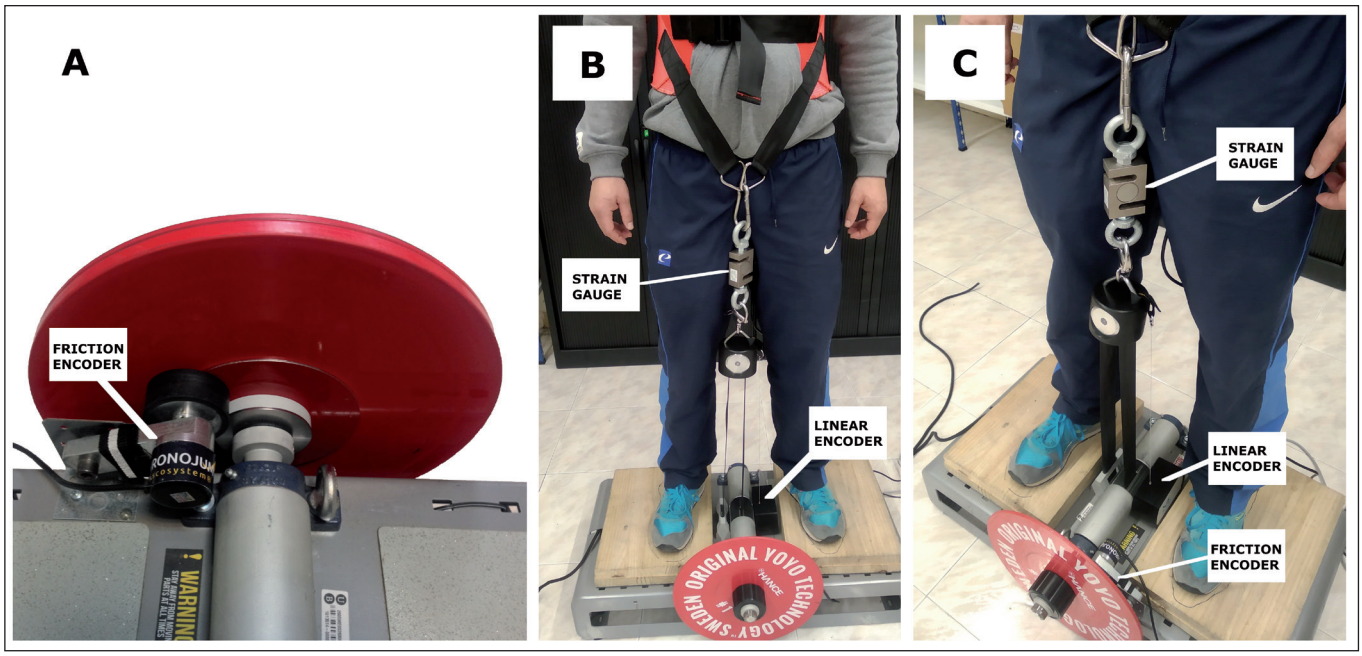


FIG. 1. Disposition of the different sensors used in the study. (A) The friction encoder was tightly attached at a known diameter of the flywheel, sharing the same linear velocity. (B) The strain gauge was attached between the strap of the flywheel and the vest, and the linear encoder was placed on the flywheel device and attached to the vest, forming a perpendicular angle with the floor. (C) General view of the setup.

TABLE 1. Comparison of V_{rep}, F_{rep} and P_{rep} between MuscleLab and Chronojump at high (0.075 kg·m^2) and low (0.025 kg·m^2) load configurations, and the total pooled data. Data is presented as mean values (± standard deviation (SD)) and mean bias, typical error of the estimate and Pearson correlation coefficient, all with 90% confidence limits.

Load	Variable	Criterion Measure	Practical Measure	Bias	TEE	Correlation
High (0.075 kg·m^2)	V_{rep}	MuscleLab 0.37 ± 0.06 m/s	Chronojump 0.28 ± 0.04 m/s	-1.44 [-1.49 to -1.39] (*large*)	0.26 [0.23 to 0.31] (*small*)	0.97 [0.96 to 0.97] (*nearly perfect*)
	F_{rep}	MuscleLab 1090.0 ± 306.1 N	Chronojump 1294.6 ± 353.2 N	0.67 [0.63 to 0.70] (*moderate*)	0.18 [0.15 to 0.20] (*small*)	0.98 [0.98 to 0.99] (*nearly perfect*)
	P_{rep}	MuscleLab 414.2 ± 160.6 W	Chronojump 312.4 ± 118.2 W	-0.63 [-0.67 to -0.59] (*moderate*)	0.13 [0.12 to 0.15] (*small*)	0.99 [0.99 to 0.99] (*nearly perfect*)
Low (0.025 kg·m^2)	V_{rep}	MuscleLab 0.55 ± 0.10 m/s	Chronojump 0.41 ± 0.07 m/s	-1.48 [-1.54 to -1.42] (*large*)	0.38 [0.33 to 0.44] (*moderate*)	0.93 [0.91 to 0.95] (*nearly perfect*)
	F_{rep}	MuscleLab 830.1 ± 222.3 N	Chronojump 942.0 ± 243.9 N	0.50 [0.46 to 0.54] (*small*)	0.27 [0.24 to 0.32] (*small*)	0.96 [0.95 to 0.97] (*nearly perfect*)
	P_{rep}	MuscleLab 478.0 ± 177.9 W	Chronojump 344.8 ± 126.5 W	-0.75 [-0.80 to -0.70] (*moderate*)	0.20 [0.17 to 0.23] (*small*)	0.98 [0.97 to 0.99] (*nearly perfect*)
Total	V_{rep}	MuscleLab 0.46 ± 0.13 m/s	Chronojump 0.34 ± 0.09 m/s	-0.95 [-0.99 to -0.92] (*moderate*)	0.23 [0.20 to 0.25] (*small*)	0.98 [0.97 to 0.98] (*nearly perfect*)
	F_{rep}	MuscleLab 960.1 ± 297.1 N	Chronojump 1118.3 ± 350.7 N	0.53 [0.50 to 0.56] (*small*)	0.20 [0.18 to 0.22] (*small*)	0.98 [0.98 to 0.98] (*nearly perfect*)
	P_{rep}	MuscleLab 446.1 ± 172.2 W	Chronojump 328.6 ± 123.3 W	-0.68 [-0.71 to -0.65] (moderate)	0.18 [0.16 to 0.20] (*small*)	0.98 [0.98 to 0.99] (*nearly perfect*)

V_{rep} = Mean repetition velocity. F_{rep} = Mean repetition force. P_{rep} = Mean repetition power

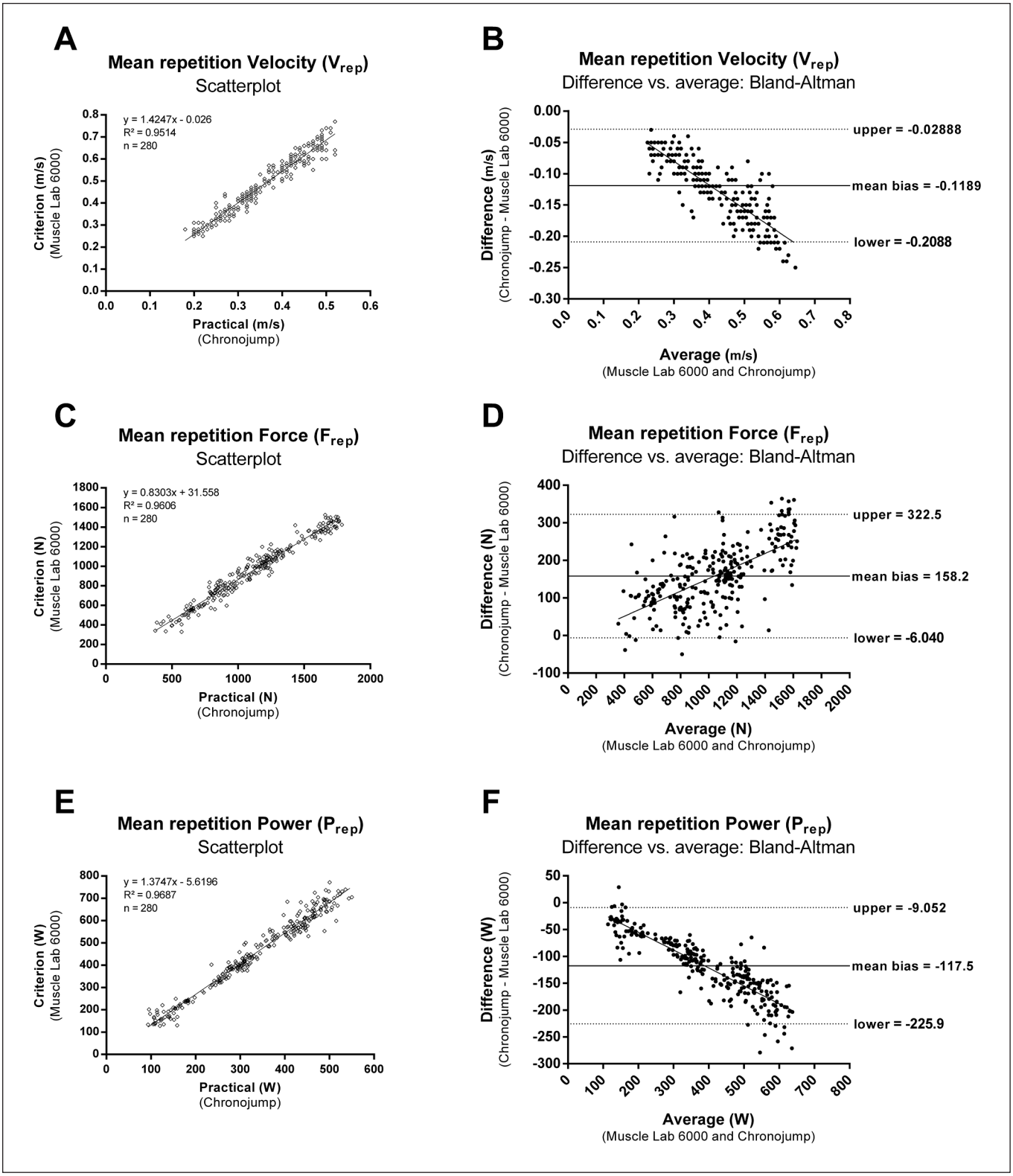


FIG. 2. Scatterplots showing the agreement between the criterion and practical measures V_{rep} (A), F_{rep} (C) and P_{rep} (E). Bland-Altman plots for V_{rep} (B), F_{rep} (D) and P_{rep} (F). The solid horizontal line within the graphs represents the mean bias. The broken horizontal lines represent the upper and lower 95% limits of agreement. The regression lines of the scattered points are shown to investigate the homoscedasticity of the errors.

particular training device used in this study, the diameter is slightly variable across the repetition, given that the strap rolls over on itself increasing the diameter. For this reason, the mean diameter value was used for the estimations.

Raw data from each of the 14 high-intensity repetitions of each set were averaged to compute repetition mean velocity (V_{rep}), force (F_{rep}) and power (P_{rep}), for both measuring systems.

Statistical Analysis

Agreement between the criterion measures (MuscleLab) and the practical measures (Chronojump) of V_{rep}, F_{rep} and P_{rep} was assessed using an excel spreadsheet for analysis of validity [17] designed to calculate the mean bias, typical error of the estimate (TEE) and Pearson correlation coefficient, all with 90% confidence limits. The standardised mean bias was rated as trivial (≤ 0.19), small (0.2–0.59), moderate (0.6–1.19) or large (1.2–1.99) [17]. The standardised typical error was rated as trivial (< 0.1), small (0.1–0.29), moderate (0.3–0.59) or large (> 0.59) [17]. The magnitude of correlation was rated as trivial (< 0.1), small (0.1–0.29), moderate (0.3–0.49), large (0.5–0.69), very large (0.7–0.89) or nearly perfect (0.9–0.99) [17]. Additionally, Bland–Altman plots were used to graphically complement the differences between the two systems [18].

RESULTS

When compared to criterion measures, mean bias for the practical measures of V_{rep}, F_{rep} and P_{rep} were moderate, small and moderate respectively. The TEE was small for all three parameters (Table 1). Correlations with MuscleLab were nearly perfect for all measures in all load configurations (Table 1).

The regression equations to estimate the criterion measures from the practical measures fitted well with data (Figure 2A, 2C, 2E) and are presented as follows:

$Y = \text{intercept} + (\text{slope} \cdot X)$

where Y is the estimated criterion measure and X is the practical measure.

The regression equation of V_{rep} is:

$Y = -0.026 + (1.4247 \cdot X)$

The regression equation of F_{rep} is:

$Y = 31.558 + (0.8303 \cdot X)$

The regression equation of P_{rep} is:

$Y = -5.6196 + (1.3747 \cdot X)$

The Bland–Altman plots visually showed the differences between the two systems for the measurement of V_{rep}, F_{rep} and P_{rep} (Figure 2B, 2D, 2F).

DISCUSSION

The primary finding of this study demonstrates acceptable levels of agreement between a low-cost, easy and versatile method (Chronojump friction encoder) and criterion measure (strain gauge combined with a linear encoder) for the assessment of velocity, force and power in a flywheel exercise device with different isoinertial loads. The friction encoder demonstrated small to moderate TEE and nearly perfect relationships across all kinetic and kinematic variables at both isoinertial loads. However, small to large bias was demonstrated, which should be acknowledged when implemented in training and future research. Considering these findings, the Chronojump friction encoder is a valid tool for the quantification of training loads when completing flywheel resistance training.

The monitoring of kinetic and kinematic variables is an important consideration for the accurate quantification of resistance training intensity. Furthermore, these external stimuli provide a greater understanding of the internal and fatigue responses that determine muscular adaptations [19]. Small to moderate TEE for all were found, which suggests that the Chronojump device can adequately provide repetition information during exercise. This will not only be of use to practitioners and scientists but also athletes, as this device can provide live augmented feedback that may enhance psychological traits during resistance training and subsequent physical adaptations [20]. However, the small to large bias that was present suggests that findings may be smaller or greater depending on the variable assessed (i.e. velocity and power may be consistently lower and force consistently higher than actual values). Thus, it is advised that, due to the lowest TEE and bias observed, power outputs are monitored in the detection of changes in neuromuscular performance.

Differences between measurement systems have also shown to be proportional to the magnitude of the value measured for all three parameters assessed, as indicated by the regression equations (see figure 2A, 2C, 2E) and the slope of the regression lines in Bland Altman plots (see figure 2B, 2D, 2F) [21]. Therefore, lower absolute bias is to be expected when the magnitude of applied V_{rep}, F_{rep} or P_{rep} are low.

One limitation of this study is that measurements have been exclusively registered from one inertial training system ("YoYo squat" – YoYo Technology, Stockholm, Sweden). Therefore, the extrapolation of the results to substantially different systems (i.e. conic pulleys) is limited. Another aspect to take into account is that the diameter of the axis of the system used was slightly variable across the range of motion, depending on the winding up of the strap (i.e. as the stap winds up over deeper layers of the strap, the diameter increases). Therefore, the mean diameter of the axis was used for the calculations. As this fact may have contributed to increasing the error of measurement, it is to be expected better accuracy in other inertial systems in which axis diameter remains constant throughout the repetition.

Despite the existence of other valid methods to monitor velocity, force and power in flywheel devices [9, 10], to our knowledge currently there are no other low-cost tools that work with free, open-code software to monitor a wide variety of flywheel resistance exercises. Given the practicality (e.g. minimal set-up), versatility (e.g. applicable to multiple systems and configurations) and cost of this sensor compared with other available options, practitioners may prefer this method for assessing V_{rep}, F_{rep} and P_{rep} in flywheel exercises.

CONCLUSIONS

In the last years, there has been a growing interest in flywheel resistance training [22]. Research in this area has shown greater increases in power and force with flywheel training [6, 23–25], improvements in changes of directions [26, 27] and other kinematics responses [28, 29], early hypertrophic adaptations [14] and changes in movement variability with functional resistance training exercises [30]. Nonetheless, only a few works have investigated the accuracy of rotary encoders for monitoring flywheel resistance training [9, 10, 13], and none had validated the use of rotary friction encoders, which can be adapted to different inertial training systems.

Inasmuch as the importance of the use of feedback [20, 31] and the control of velocity loss [32, 33] in resistance training using free weights, the validation of this rotary friction encoder and his open-code software could help strength and conditioning coaches to confidently monitor force, power and velocity in any flywheel machine, and therefore improve the control of training whenever using these resistance training devices, both with low and high training loads.

Coaches and sports scientists may confidently use a Chronojump friction encoder for assessing velocity, force and power in flywheel exercises, allowing for a simplified, accurate and versatile way of testing and monitoring athletes daily.

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Conflict of interest declaration

The authors declare no conflict of interest.

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Quercetin supplementation promotes recovery after exercise-induced muscle damage: a systematic review and meta-analysis of randomized controlled trials

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ABSTRACT: Quercetin (Q) is one of the most frequently consumed flavonoids in the human diet. The purpose of this systematic review and meta-analysis was to determine the effects of Q supplementation on muscle damage, muscle soreness and biochemical markers of inflammation, antioxidant capacity and oxidative stress after intense exercise. A literature search of SPORTDiscus, PubMed, Web of Science and Scopus was performed from inception to May 31, 2022. Forest plots were generated with fixed or random-effect models and standardized mean differences (SMD). Data extraction and quality assessment were performed independently by two authors. After application of the inclusion and exclusion criteria, 13 studies with a total of 249 sedentary to well-trained participants were included. For all studies there were some concerns about the risk of bias. All but one study used a supplementation dosage of 1000 mg/day. Q supplementation accelerated recovery of muscle function and significantly decreased muscle soreness 0/24 h after exercise (SMD: -1.33; $p = 0.03$), creatine kinase levels 24/48 h after exercise (SMD: -1.15; $p = 0.02$), and post-exercise oxidative stress (SMD: -0.92; $p = 0.03$). However, Q supplementation had no effect on IL-6 concentration. Q supplementation with a dose of 1000 mg/day for periods of more than seven days and a maximum of 12 weeks appears to be a safe and efficacious strategy to reduce muscle damage and muscle soreness, as well as to enhance recovery after intense exercise in sedentary to well-trained young men. Systematic review registration: PROSPERO CRD42021266801.

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INTRODUCTION

Phenolic compounds are abundant molecules in our diet that are synthesized exclusively by plants, and have aromatic rings with one or more attached hydroxyl groups [1]. They have received considerable attention because their dietary consumption has been linked to the prevention of chronic diseases, such as cancer, diabetes, and cardiovascular disease, due to their antioxidant and anti-inflammatory activities [1–3]. Flavonoids are an important group of phenolic compounds, consisting of two aromatic rings and an additional oxygenated heterocycle called the C ring [4]. Based on the hydroxylation type and the differences in the C ring, flavonoids can be subdivided into different subgroups, including anthocyanins, flavan-3-ols, flavones, flavanones, and flavonols [5, 6].

Flavonoids have been reported to have beneficial health effects related to their antioxidative, anti-inflammatory, anti-mutagenic, and anti-carcinogenic properties [7–9]. Quercetin (Q) is one of the most frequently consumed flavonoids in the human diet and exerts a broad range of health-promoting physiological effects in humans [10]. Important dietary sources of Q include apples, onions, berries, tomatoes, shallots, red grapes, leafy greens, and tea. The term Q should be used to describe the aglycone only (the molecule without an attached sugar); however, the name is frequently used to refer to any quercetin-type molecules [11].

The antioxidant effects associated with flavonoids are due to their free radical-scavenging abilities [8, 9]. A free radical is an unstable and highly reactive atom or molecule, due to the presence of unpaired electrons in its valence shell [12]. Free radicals are a product of cellular metabolism. Free radicals derived from oxygen are referred to as reactive oxygen species (ROS) and, at low or moderate levels, they exert beneficial effects in cells [13]. The human body naturally renders ROS inactive with the endogenous antioxidant defence system in conjunction with exogenous antioxidants consumed through a balanced diet. However, intense physical exercise increases the production of ROS, which may be highly damaging to cells [14], and may lead to an excess of ROS or oxidants over the capability of the cell to mount an effective antioxidant response. This imbalance is called oxidative stress [15].

Intense or unaccustomed physical exercise frequently causes exercise-induced muscle damage (EIMD), particularly after eccentric

actions. It is characterized by a temporary loss of force production and delayed onset muscle soreness (DOMS), and usually has a negative impact on exercise performance [16, 17]. EIMD has been described as a two-phase process [17, 18]. The first phase involves structural damage to myofibers caused by the mechanical work performed by the muscles, and an increase in the production of ROS, contributing to oxidative stress. The second phase is an inflammatory response resulting from leukocyte infiltration into the damaged tissues, initiating tissue repair and adaptation [19]. However, it increases the production of ROS and can prolong inflammation, oxidative stress and cellular damage, which may delay the complete recovery of muscle function [14].

There is growing interest in the consumption of anti-inflammatory and antioxidant food supplements to reduce inflammation and enhance recovery after exercise [20]. Although some evidence suggests that antioxidant supplements may hinder the specific cellular adaptations to exercise [21], a negative impact of antioxidant supplementation on exercise training adaptation has not been reported with natural antioxidant foods [22]. Specifically, supplementation with foods containing a high concentration of phenolic compounds, such as tart cherry, pomegranate, or curcumin, has been widely used in sports to enhance performance, attenuate symptoms from EIMD, and accelerate recovery [20, 23–26].

A large body of scientific literature has investigated the effects of Q supplementation on exercise performance, based on its antioxidant and anti-inflammatory properties [27, 28]. However, the results are contradictory and two systematic reviews and meta-analyses on Q supplementation and endurance performance draw different conclusions [29, 30]. The effects of Q supplementation on recovery after EIMD have also been extensively studied, but the results appear, likewise, inconclusive. However, to the best of our knowledge, no systematic review or meta-analysis has been performed on this subject. Therefore, this systematic review and meta-analysis was designed to determine the effects of Q supplementation on muscle damage, muscle soreness and biochemical markers of inflammation, antioxidant capacity, and oxidative stress after intense exercise based on the existing literature.

MATERIALS AND METHODS

Search strategy

This systematic review and meta-analysis was designed according to the guidelines of the Preferred Reporting of Systematic Reviews and Meta-Analyses (PRISMA) statement [31]. The protocol was registered at PROSPERO, an international database of prospectively registered reviews in health and social care (CRD42021266801). Two independent authors (D.R.O. and A.J.B.R.) performed the literature search, study selection, and data extraction. Any disagreement was resolved by consensus.

The literature search was conducted from inception to May 31, 2022, using four electronic databases: SPORTDiscus, PubMed, Web of Science and Scopus. The following search was performed: quercetin (Title) AND (muscle damage OR oxidative OR recovery OR muscle pain OR antioxidant OR inflammation OR soreness OR performance (Title)) AND (sports OR exercise OR train* OR athletes (Title/Abstract)). The search was limited to English language and journal articles. The search strategy is depicted in Figure 1.

Inclusion and exclusion criteria

The studies included in this systematic review and meta-analysis met the following inclusion criteria: (i) research conducted with human participants, (ii) original articles in peer-reviewed publications, (iii) original studies that investigated the effect of Q supplementation intervention on muscle damage and recovery after a protocol to induce muscle damage, (iv) research conducted with one control/placebo (PLA) group, and (v) articles published in the period from inception to the end of May 2022. Exclusion criteria were: (i) research conducted with animals, (ii) non-English articles, (iii) studies that involved other interventions in addition to Q supplementation, (iv) systematic reviews or meta-analyses, and (v) studies that reported results inadequately or without adequate statistical analysis.

Data extraction

The following data were extracted from each study: first author name, year of publication, intervention and placebo group characteristics, the dosage of supplements, supplementation duration, exercise protocol to induce muscle damage, and the effects of supplementation on functional measures, muscle soreness and biochemical markers of muscle damage, inflammation, antioxidant activity and oxidative stress.

Quality assessment

The quality of the selected articles was assessed by two independent reviewers (D.R.O. and A.J.B.R.), using the Cochrane Collaboration risk of bias tool, which covers bias in six domains: selection bias, performance bias, detection bias, attrition bias, reporting bias, and other bias. Within each domain, assessments are made for one or more items, which may cover different aspects of the domain, or different outcomes [32]. Discrepant results were resolved through discussion.

Statistical analysis

Review Manager software, version 5.4.1 (Cochrane Collaboration, Oxford, UK) was used to build the forest plot graphs and carry out the statistical analysis. The standardized mean difference (SMD) with a 95% confidence interval (CI) was used to present the results because units of measurements differed across studies. In the case of articles that reported the standard error of the mean (SEM), the standard deviation (SD) was calculated using the following formula: $SD = SEM \times \text{sqrt}(n)$, where n is the number of subjects. When necessary, the data were calculated from figures via WebPlotDigitizer. It is a program that converts graphical data to numerical data through manual plotting with high reliability [33] and has been used in other meta-analyses [34, 35].

TABLE 1. Characteristics of the included studies.

Study	Participants	Groups	Age (years)	Quercetin content (mg/day)	Supplementation period	Exercise protocol to induce muscle damage
Nieman et al. [38]	Trained male cyclists	20 (Q) 20 (PLA)	26.1 ± 1.8 29.1 ± 2.4	1000 mg/day	24 days (exercise on days 22, 23 and 24)	3 h cycling bout at ~57% maximal work rate
McAnulty et al. [39]	Trained male cyclist	20 (Q) 20 (PLA)	26.1 ± 1.8 29.1 ± 2.4	1000 mg/day	24 days (exercise on days 22, 23 and 24)	3 h cycling bout at ~57% maximal work rate
Abbey & Rankin [40]	Healthy male team-sport-trained athletes	15 (Q) 15 (PLA)	23.3 ± 2.6 COD	1000 mg/day	7 days (exercise on day 8)	Repeated sprint test at maximum effort (12 × 30 m)
O'Fallon et al. [41]	Sedentary to recreationally active healthy males and females	8 MEN (Q) 7 WOM (Q) 7 MEN (PLA) 8 WOM (PLA)	19.5 ± 1.1 19.6 ± 1.3 20.9 ± 1.8 20.6 ± 1.1	1000 mg/day	14 days (exercise on day 9)	24 maximal eccentric contractions of EF
Sholten & Sergeev [42]	Male runners from a local club and collegiate cross country teams	5 (Q) 3 (PLA)	24.0 ± 5.4 22.5 ± 3.0	1000 mg/day	Six weeks (exercise on days 43–44)	10 km time trial treadmill run
Demirci [43]	Healthy licensed male boxers	10 (Q) 10 (PLA)	18.90 ± 1.10 19.00 ± 1.05	500 mg/day	30 days (exercise on day 31)	2 hours of normal boxing training the last supplementation day
Duranti et al. [44]	Healthy young men	14 (Q) 14 (PLA)	25.5 ± 0.8 COD	1000 mg/day	14 days (exercise on day 15)	6 to 10 sets of 10 maximal lengthening contractions of the EF
Gholami & Ardestani [45]	Moderately trained female adolescent swimmers	10 (Q) 10 (PLA)	15.30 ± 0.17 14.90 ± 0.12	1000 mg/day	14 days (exercise on day 15)	One minute bouts of crawl swimming (> 85% of maximum HR, 30 s- rest), until exhaustion
Patrizio et al. [46]	Healthy sedentary to recreationally men	10 (Q) 10 (PLA)	22.1 ± 1.8 COD	1000 mg/day	One single dose 3 h before exercise	3 sets of 8 repetitions at 80% 1RM of eight different exercises
Bazzucchi et al. [47]	Moderately active men	12 (Q) 12 (PLA)	26.1 ± 3.1 COD	1000 mg/day	14 days (exercise on day 15)	10 bouts (30 s-rest) of 10 maximal eccentric contractions of the EF.
Bazzucchi et al. [48]	Healthy low to moderately active men	16 (Q) 16 (PLA)	25.9 ± 3.3 COD	1000 mg/day	14 days (exercise on day 15)	10 bouts (30 s-rest) of 10 maximal eccentric contractions of the EF.
Sgrò et al. [49]	Healthy moderately active men	12 (Q) 12 (PLA)	25.67 ± 3.87 COD	1000 mg/day	14 days (exercise on day 15)	10 bouts (30 s-rest) of 10 maximal eccentric contractions of the EF.
Tsao et al. [50]	Healthy physically active men	12 (Q) 12 (PLA)	20.79 ± 0.53 COD	1000 mg/day	7 days (exercise on day 8)	Cycling test to exhaustion at 75% of VO_{2max}

Q: quercetin group; PLA: placebo group; COD: cross-over design; EF: elbow flexors; HR: heart rate; RM: repetition maximum.

Statistical heterogeneity of the treatment effects among studies were assessed using Cochran's Q test and the inconsistency I^2 test, and random-effect ($I^2 > 50\%$, $P < 0.1$) or fixed-effect models were used. A sensitivity analysis using the one-study removed method was also conducted to determine the influence of each study on the overall results. The calculated effect sizes (ES) were interpreted using the conventions outlined for SMD: < 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 [36].

Publication bias

Potential publication bias was not evaluated because there were fewer than 10 studies included in each meta-analysis and this number is usually chosen as a threshold value to test publication bias [37].

RESULTS

Search results

The literature search provided a total of 129 articles identified through the combined descriptors. After examination of the titles, 33 articles were excluded because they were meta-analyses or they were not conducted in humans. After the elimination of duplicates, 37 articles were selected for abstract screening, of which 16 were excluded for not being conducted in humans, not having a PLA group, carrying out a supplementation other than solely Q, not studying recovery, or for being systematic reviews. Twenty-one studies were then selected for full-text reading, and 8 of these were excluded for not performing an exercise protocol to induce muscle damage, for reporting results inadequately, or for inadequate statistical analysis. The final number of studies included in this systematic review and meta-analysis was 13 [38–50]. A summary of the search process is depicted in Figure 1.

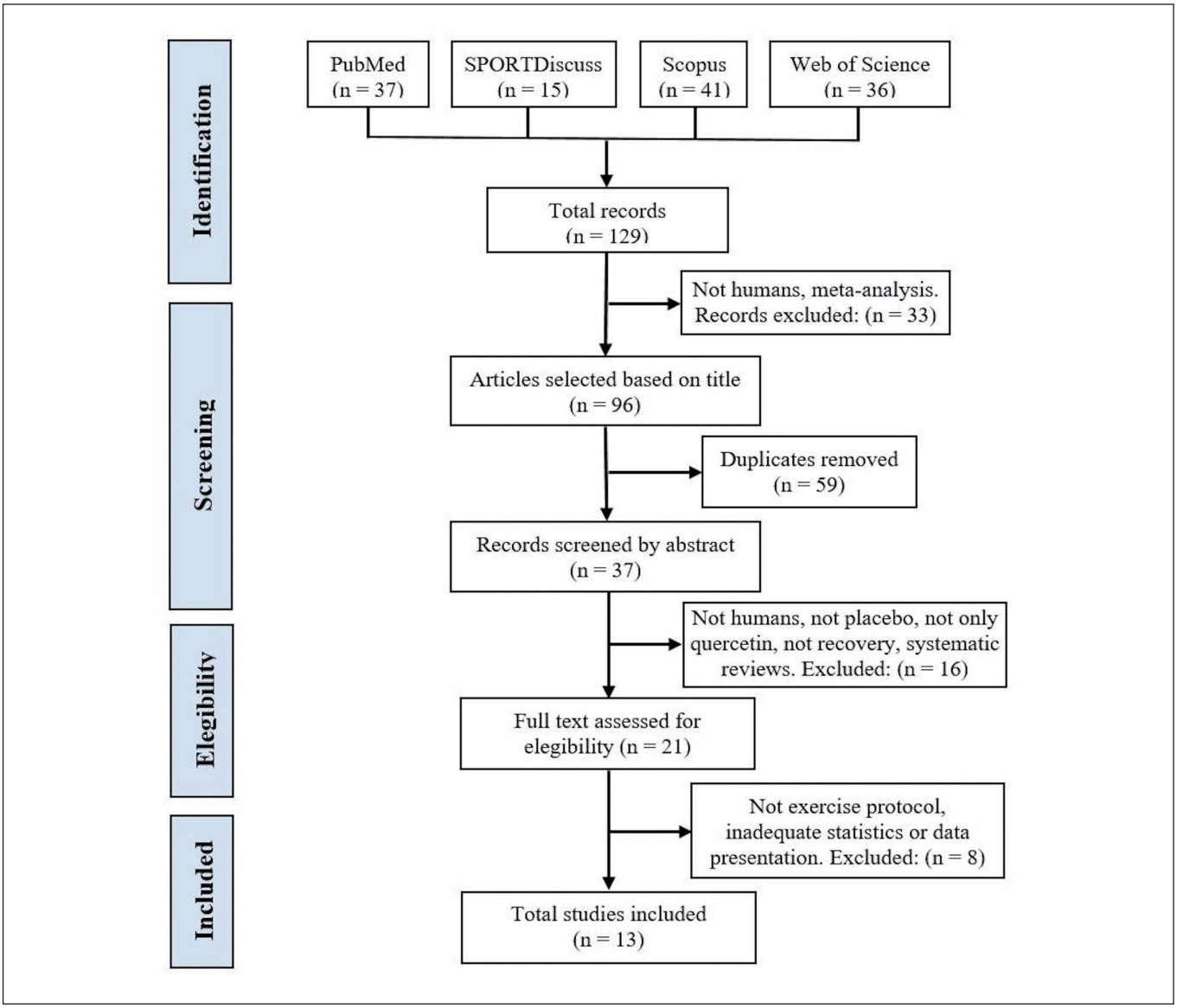


FIG. 1. Prisma flowchart of the article selection process.

TABLE 2. Variables measured and summary of findings of the included studies.

Study	Functional measures and muscle soreness	Biochemical markers of muscle damage, inflammation and oxidative stress	Significant differences between Q and PLA groups
Nieman et al. [38]		IL-1ra, IL-6, IL-8, IL-10, MCP-1, TNF-α. Measurements: each day pre and post.	↓ IL-8 and TNF-α post the three days (tendency: $p < 0.1$)
McAnulty et al. [39]	----------	CRP F2-IsoP, FRAP, TEAC Measurements: each day pre and post.	No significant differences
Abbey & Rankin [40]	----------	IL-6 XO, UA Measurements: baseline, pre, post and 1 h post.	No significant differences
O'Fallon et al. [41]	MIVC of EF, MVC of EF at 60 and 180º/s, soreness, REA. Measurements: pre, post (only MVC and REA), 24 h, 48 h, 72, 96 h and 120 h post.	CK IL-6, CRP Measurements: pre and 24 h, 48 h, 72 h, 96 h and 120 h post.	No significant differences
Sholten & Sergeev [42]	----------	MDA, PC, TAC, SOD Measurements: pre and post.	↓ PC, SOD, TAC post Significant differences between groups not really measured
Demirci [43]	----------	MDA, SOD, CAT, GSH Measurements: baseline and post.	↑ SOD, CAT, GSH ↓ MDA Significant differences between groups not really measured
Duranti et al. [44]	----------	GSSH, GSH/GSSH, TBARS Measurements: baseline, pre and post.	↓ GSSG post ↑ GSH/GSSG post ↓ TBARS post
Gholami & Ardestani [45]	----------	TNF-α Lactate Measurements: baseline, pre and post.	↓ TNF-α post
Patrizio et al. [46]	MVIC of the KE, MVC of KE at 30, 90, 180 and 240º/s, RTD200, soreness. Measurements: baseline, pre and post.	CK GSSH, GSH/GSSH Measurements: baseline, pre, post and 24 h post.	↑ MVC at 30, 90, 180 and 240 º/s post ↓ loss of MVIC of KE post ↑ RTD200 post
Bazzucchi et al. [47]	MVIC of EF, MVC of EF at 30, 60, 120 and 240 º/s, soreness, REA. Measurements: baseline, pre and post.	CK, LDH Measurements: baseline, pre, post. 24 h, 48 h and 72 h post.	↑ Relaxed EA post, ↑ MVIC pre and post ↑ MVC at 30 and 60 º/s post ↓ Soreness post (tendency) ↓ CK 48 and 72 h post ↓ LDH 24, 48 and 72 h post
Bazzucchi et al. [48]	MVIC of EF, MVC of EF at 30, 60, 120 and 240 º/s, soreness, REA. Measurements: baseline, pre, post, 24 h, 48 h, 72 h. 96 h and 7 days post.	CK, LDH Measurements: baseline, pre and 48 h, 72 h, 96 h and 7 days post.	↑ Relaxed EA post, ↑ MVIC post, 24 h, 72 h and 96 h post ↑ MVC most velocities and time-points ↓ CK 72 and 96 h post ↓ LDH 48, 72 and 96 h post
Sgrò et al. [49]	MVIC of EF Measurements: pre and 24, 48 h, 72 h, 96 h and 7 days post.	CK, LDH, MB IL-6 Measurements: pre and 24, 48 h, 72 h, 96 h and 7 days post.	↑ MVIC in all recovery time points ↓ CK 72 and 96 h post ↓ LDH in all recovery time points ↓ MB 48, 72 and 96 h post ↓ IL-6 48 and 72 h post

TABLE 2. Continue

Study	Functional measures and muscle soreness	Biochemical markers of muscle damage, inflammation and oxidative stress	Significant differences between Q and PLA groups
Tsao et al. [50]	----------	CK, MB IL-6, TNF-α, CRP Measurements: pre, post, 1 h and 24 h post. SOD, MDA, TAC. Measurements: pre, post and 1 h post.	↓ CK 24 h post ↓ IL-6 post and 1 h post ↑ TAC 1 h post ↑ SOD pre, post and 1 h post ↓ MDA post

MIVC: maximal isometric voluntary contraction; EF: elbow flexors; MVC: maximal voluntary contraction; RAA: relaxed elbow angle; KE: knee extensors; RTD200: isometric rate of torque development the first 200 ms; IL: interleukin; MCP-1: monocyte chemoattractant protein 1; TNF-α: tumor necrosis factor alpha; CRP: C-reactive protein; F2-IsoP: F2-Isoprostanes; FRAP: ferric reducing ability; TEAC: trolox equivalent antioxidant capacity; XO: xanthine oxidase; UA: uric acid; CK: creatine kinase; MDA: malondyaldehyde; PC: protein carbonyls; TAC: total antioxidant capacity; SOD: superoxide dismutase; CAT: catalase; GSH: reduced glutathione; GSSG: oxidized glutathione; GSH/GSSH: reduced to oxidized glutathione ratio; TBARS: thiobarbituric acid reactive substances; LDH: lactate dehydrogenase; MB: myoglobin.

Study characteristics

The characteristics of the included studies are summarized in Table 1. All selected studies were randomized placebo-controlled trials, except for that of Demirci [43], who did not mention whether participants were allocated at random. Six trials had a parallel-group design and the other 7 had a cross-over design. The total number of participants was 249 with sample sizes ranging from 10 to 20 participants in each group, except for Sholten and Sergeev [42], who only had 5 participants in the Q group and 3 in the PLA group. Only 5 studies [44, 46–48, 50] carried out an a priori statistical power analysis. Therefore, the other studies may not have used adequate sample sizes.

All selected studies were conducted on healthy subjects, 11 were conducted on men, 1 on women, and 1 on both women and men. The mean age of the participants ranged from 14.90 ± 0.12 to 29.1 ± 2.4 years. Nine studies evaluated the effects of Q supplementation on trained subjects, 3 on sedentary or low to moderately active subjects, and 1 did not mention the fitness level of participants. The protocol to induce muscle damage differed greatly across the included studies. One study evaluated the effects of a single dose of 1000 mg of Q taken 3 h before the protocol to induce muscle damage [46]. The remaining studies evaluated the effects of regular Q ingestion, for more than 7 days before exercise, with a dose of 1000 mg/day except for the study of Demirci [43], who used 500 mg/day.

Methodological quality

Details of the methodological quality of the studies included are shown in Figure 2. The generation of the randomization sequence and the method of concealment were not described in any of the studies. Only one study [50] had a single blind design and one study [43] did not provide information for blinding of participants and personnel. None of the studies reported information about the blinding of the outcome assessment. Results were fully reported in all studies and there was no evidence of other bias in any of the studies.

Effects of Q supplementation on functional measures and muscle soreness

Five studies [41, 46–49] measured one or more functional variables. Four studies [46–49] found a significant improvement in the Q group after supplementation in any of the variables measured after exercise or throughout the entire recovery period, when compared to the PLA group (Table 2). Four of those studies also measured muscle soreness [41, 46–48], but only Bazzucchi et al. [47] observed a trend of lower muscle soreness values after exercise in the Q group (Table 2). Meta-analysis indicated that soreness significantly decreased 0/24 h after exercise following Q supplementation (SMD: -1.33; 95% CI: [-2.57, -0.09]; $p = 0.03$; $I^2 = 87\%$; Figure 3a). The relative weight of each study in the analysis varied between 23.6% and 26.4%, demonstrating an equilibrated weight distribution. Although the results were not always significant, sensitivity analysis also showed a decrease in muscle soreness following Q supplementation.

Effects of Q supplementation on biochemical markers of muscle damage

Six studies [41, 46–50] analysed serum or plasma concentration of creatine kinase (CK), and three of them [47–49] also determined the plasma concentration of lactate dehydrogenase (LDH). Bazzucchi et al. [47, 48] and Sgrò et al. [49] found significantly lower plasma CK and LDH levels in the Q group at some point or throughout the entire recovery period after exercise, and Tsao et al. [50] also observed

lower plasma CK levels in the Q group 24 h after exercise (Table 2). The pooled ES demonstrated that CK level significantly decreased in the Q group 24/48 h after exercise (SMD: -1.15; 95% CI: [-2.09, -0.21]; p = 0.02; I^2 = 85%; Figure 3b). The relative weight of each study ranged from 15.4% to 17.7%, showing an equilibrated weight distribution. In the sensitivity analysis, the results remained consistent across all deletions.

Effects of Q supplementation on markers of inflammation

Seven studies [38–41, 45, 49, 50] measured one or more markers of inflammation in plasma or serum. Gholami and Ardestani [45] found a significantly lower plasma concentration of tumour necrosis factor alpha (TNF-α) in the Q group after exercise, and Sgrò et al. [49] and Tsao et al. [50] observed lower plasma interleukin-6 (IL-6) levels at some point of the recovery period. The details of the effects of Q supplementation on markers of inflammation are summarized in Table 2.

A meta-analysis on IL-6 concentrations showed no significant differences between groups immediately after exercise (SMD: -0.09; 95% CI: [-0.42, 0.23]; p = 0.58; I^2 = 45%; Figure 4a) and, in the sensitivity analysis, the results remained consistent across all deletions.



FIG. 2. Methodological quality assessment of included trials.

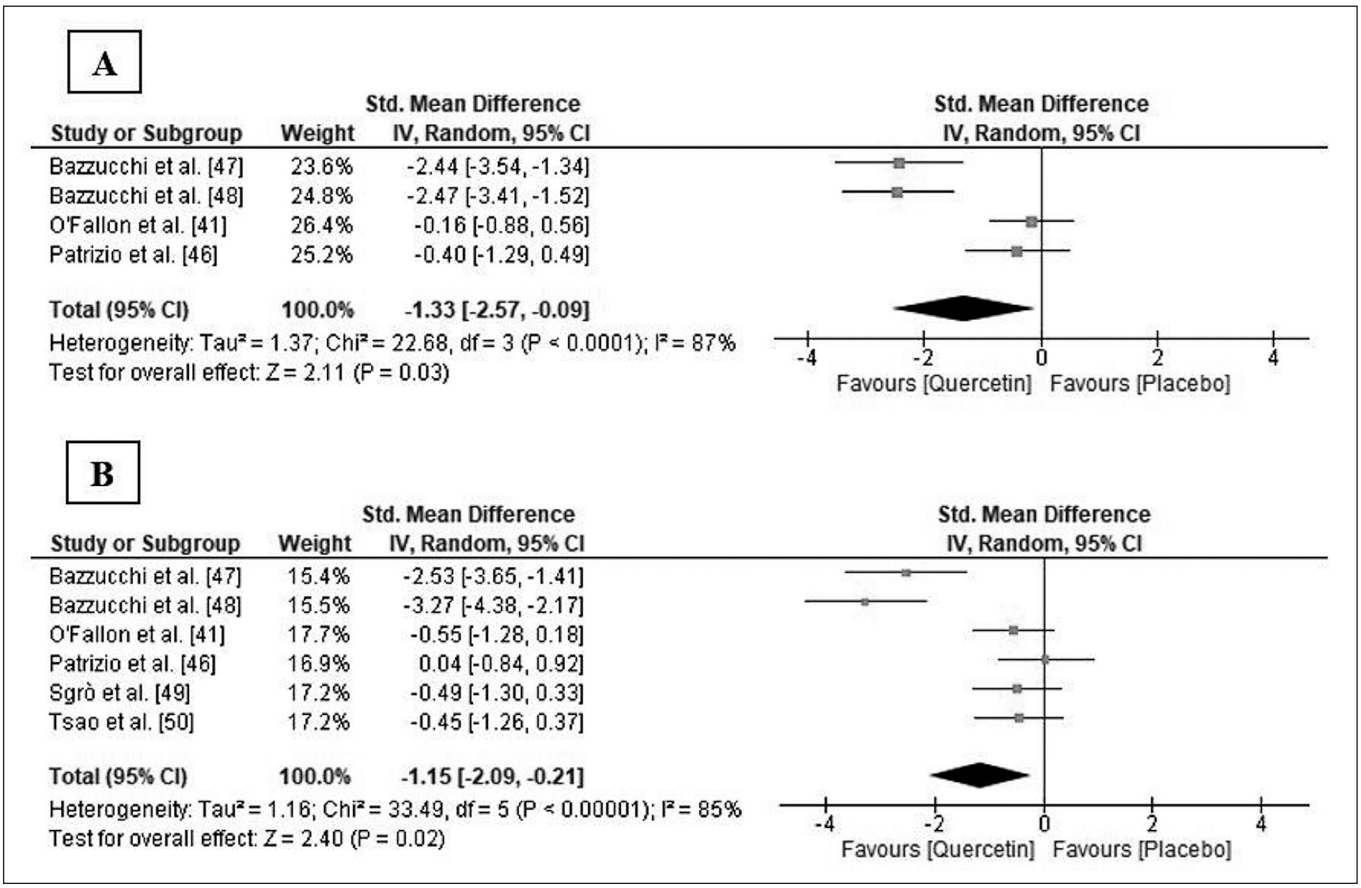


FIG. 3. Forest plot showing the standardized mean differences and 95% confidence intervals for the effects of quercetin supplementation on muscle soreness (A) and creatine kinase (B).

Effects of Q supplementation on antioxidant activity and oxidative stress

Eight studies [39, 40, 42–46, 50] measured one or more markers of antioxidant activity in plasma or serum. Only three studies [43, 44, 50] found higher antioxidant capacity in the Q group compared to the PLA group (Table 2). Seven studies [39, 40, 42–44, 46, 50] measured one or more markers of oxidative stress in plasma or serum. Four of them [42–44, 50] observed lower levels of oxidative stress in the Q group than in the PLA group.

Two meta-analyses with different non-enzymatic markers of antioxidant capacity and oxidative stress were performed. Q supplementation produced a near significant increase in antioxidant activity after exercise (SMD: 0.26; 95% CI: [-0.02, 0.54]; $p = 0.06$; $I^2 = 50\%$). Following sensitivity analysis, the results remained unchanged across all deletions and became larger and significant when the study by Sholten and Sergeev was omitted [42]. Q supplementation also decreased oxidative stress (SMD: -0.92; 95% CI: [-1.73, 0.11]; $p = 0.03$; $I^2 = 80\%$). This ES was robust in the sensitivity analysis but became nearly significant ($p = 0.06$) after the omission of the studies by Demirci [43], Duranti et al. [44] and Sholten & Sergeev [42]. Forest plots presenting the impact of Q supplementation on antioxidant activity and oxidative stress, as well as the relative weight of each study, are shown in Figures 4b and 4c.

DISCUSSION

Quercetin is one of the most frequently consumed flavonoids in the human diet and is widely distributed in fruits and vegetables. It has marked anti-inflammatory properties, as well as antioxidant activity, and exerts a protective effect against lipid peroxidation [51, 52]. Recent studies have investigated whether quercetin can reduce the extent of muscle damage and accelerate recovery after exercise in humans, but the results are not conclusive.

Consumption of Q is generally recognized as safe. According to Andres et al. [53], only mild adverse effects have been reported following high supplemental doses of isolated Q up to 1000 mg/day for a maximum duration of 12 weeks in adults. However, published data on the safety of long-term supplementation of more than 12 weeks with dosages of more than 1000 mg/day of isolated Q are currently not available, and long-term supplementation with a high dose of Q could have adverse effects in humans [53].

To the authors' knowledge, this is the first systematic review and meta-analysis to examine the effectiveness of Q supplementation for

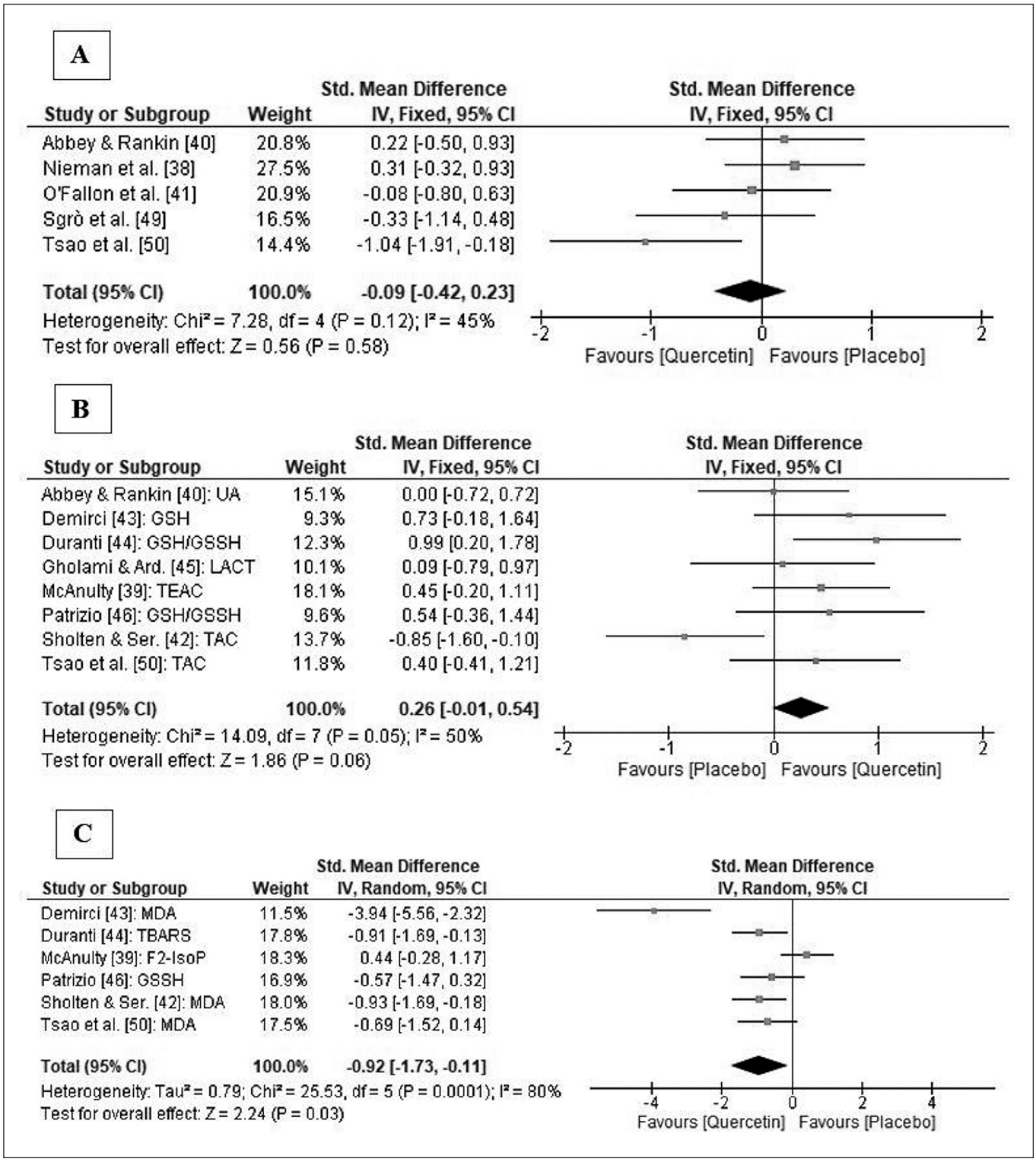


FIG. 4. Forest plot showing the standardized mean differences and 95% confidence intervals for the effects of quercetin supplementation on IL-6 (A), markers of antioxidant capacity (B) and markers of oxidative stress (C).

Note: IL-6, interleukin 6; UA, Uric Acid; GSH, reduced glutathione; GSH/GSSH, reduced to oxidized glutathione ratio; LACT, lactate; TEAC, trolox equivalent antioxidant capacity; TAC, total antioxidant capacity; MDA, malondyaldehyde; TBARS, thiobarbituric acid reactive substances; F2-IsoP, F2-isoprostanes; GSSH, oxidized glutathione.

recovery after EIMD in humans. Eleven studies met our inclusion criteria, involving a total of 249 participants. Our findings suggest that Q supplementation may accelerate recovery of muscle function and attenuate muscle damage and muscle soreness following strenuous exercise. Our results also suggest that Q supplementation is associated with reduced oxidative stress and increased antioxidant capacity. Therefore, Q supplementation is a good strategy to accelerate the recovery of muscle function.

Effects of Q supplementation on functional measures and muscle soreness

Four of the five studies that analysed functional measures [41, 47–49] used supplementation for 14 days [41, 47, 48], whereas the remaining study used a single dose 3 hours before exercise [46]. Bazzucchi et al. [47, 48] observed lower strength loss of the elbow flexors and an increased relaxed elbow angle in the Q group after exercise; Patrizio et al. [46] and Sgrò et al. [49] also observed lower strength loss of the elbow flexors and the knee extensors, respectively. However, O'Fallon et al. [41] did not find significant differences between groups after exercise, probably because the exercise protocol, comprising 24 maximal eccentric contractions of the elbow flexors, was not sufficient to induce a large magnitude of muscle damage and, consequently, supplementation conferred no benefits for recovery. Therefore, it appears that Q supplementation is an effective strategy for recovery of functional measures after EIMD, even with a single dose before exercise, in sedentary to moderately active young athletes. These results may have been due to a higher neuromuscular efficiency after Q supplementation, because Q is an adenosine receptor antagonist, which improves nerve transmission and, consequently, increases muscular strength and reduces the perceived effort of exercise and fatigue [54, 55]. Our findings are broadly in agreement with those obtained in other systematic reviews on nutritional supplements [20, 25, 56].

Four studies measured muscle soreness with a 10-cm visual analogue scale (VAS). Q supplementation produced a significant reduction of muscle soreness 24/48 h after exercise in sedentary to moderately active young men (ES = -1.33, p = 0.03). The ES can be compared with meta-analyses conducted on other ergogenic aids. Rhim et al. [35] reported that supplementation with citrulline significantly reduced feelings of muscle soreness 24 h after exercise, with an ES of -0.99, and no significant association was detected 48 h after exercise between citrulline ingestion and muscle soreness. Lv et al. [57] found that supplementation with omega-3 polyunsaturated fatty acid significantly reduced muscle soreness 48 h days after eccentric exercise, with an ES of -0.93. Finally, Jones et al. [58] reported that nitrate-rich beetroot juice significantly reduced muscle soreness 48 h after exercise, with an ES of -0.56. Therefore, Q may be more effective for reducing muscle soreness than other nutritional supplements, because of its analgesic effect, which is dependent on many mechanisms including nitric oxide production, activation of γ-aminobutyric acid and serotonin receptors [59], and inhibition of pro-nociceptive cytokine production and oxidative stress [60].

Effects of Q supplementation on markers of muscle damage

The three studies that analysed plasma LDH [47–49] found significantly lower levels in the Q group at some point or throughout the entire recovery period after exercise. In addition, the meta-analysis indicated that Q supplementation decreased CK levels 24/48 h after exercise in sedentary to physically active young men (ES = -1.15, p = 0.02). Comparisons with other meta-analyses show that Q supplementation appears to be more effective for reducing CK levels than other nutritional supplements. Jones et al. [58] noted no significant differences between the nitrate-rich beetroot juice group and the PLA 24 or 48 h after exercise, whereas Northeast and Clifford [61] observed significant differences in favour of the creatine supplementation group 48 h after exercise but with a moderate ES of -1.06. Our results may be explained by the role of Q in protecting muscle fibres from damage so that the extent of cell membrane disruption is lower, which attenuates the increase of CK [47]. However, the precise mechanism of this protective effect is still unclear.

Effects of Q supplementation on markers of inflammation

The meta-analysis on IL-6 levels showed no differences between the Q and PLA groups after exercise. Our results are in line with the meta-analysis of nitrate-rich beetroot juice supplementation conducted by Jones et al. [58], who reported no significant differences in IL-6, IL-8, or TNF-a between the experimental and placebo groups after exercise. Likewise, even though Hill et al. [62] observed that tart cherry supplementation significantly decreased IL-6 after exercise, the overall ES was small.

Effects of Q supplementation on antioxidant activity and oxidative stress

Q supplementation increased antioxidant activity after exercise in sedentary to trained young male and female athletes (ES = 0.26, p = 0.06), but the ES was small and only became significant when the study by Sholten and Sergeev [42] was removed (ES = 0.44, p = 0.004). Those authors explained that their unexpected result might have been due to subjects being randomized by maximal oxygen uptake rather than antioxidant activity, but it could also have simply been due to biological variations because the number of subjects was too low (5 in the Q group and 3 in the PLA group). The meta-analysis revealed that Q supplementation also decreased oxidative stress markers (ES = -0.92, p = 0.03). Most of the systematic reviews investigating the effects of supplementation with other ergogenic aids on recovery after EIMD did not include antioxidant activity or oxidative stress markers in their meta-analyses. Thus, we can only compare our ES with the results of Stepanyan et al. [63], but they did not observe significant protection of vitamin E against exercise-induced lipid peroxidation. Conversely, our results suggest that Q supplementation is effective for reducing oxidative stress and, to some

extent, increasing antioxidant capacity. This is potentially due to the fact that Q is the most potent scavenger of ROS within the flavonoid family [64] because it has an optimal chemical structure for free radical scavenging, particularly because of the presence and location of the hydroxyl substitutions and the catechol group in the B-ring [65, 66]. In addition, Q increases the body's antioxidant capacity by regulating the levels of glutathione, which is necessary for the enzyme SOD to catalyse the decomposition of hydrogen peroxide to non-toxic H_2O [67]. Despite Q supplementation acting directly in the secondary damage process via its antioxidant potential, it is possible to speculate that Q supplementation before exercise can reduce ROS production and limit its potentially harmful effect on cells, increasing the cell membrane resistance to the same mechanical stress [68] and therefore reducing the amount of damage caused by exercise.

Other considerations and practical applications

The results of the study by Sgrò et al. [49] suggest a new possible reason for Q to modulate damage and recovery. It is known that insulin-like growth factors 1 (IGF-I) and 2 (IGF-II) are produced during the recovery period after EIMD and both factors play an important role in skeletal muscle regeneration and remodelling [69, 70]. The authors analysed the influence of Q supplementation on circulating levels of anabolic IGF-I and IGF-2, and they concluded that Q supplementation is a good strategy to promote recovery after EIMD because it increases plasma levels of anabolic factors IGF-I and IGF-II [49]. New studies are needed to support their conclusion.

Some practical applications can be drawn from this study: 1) Regular quercetin supplementation is a good strategy to reduce muscle damage and muscle soreness caused by strenuous exercise. 2) Regular quercetin supplementation also leads to a reduction of oxidative stress and increases, to some extent, antioxidant capacity. 3) One week of quercetin supplementation in doses of 1000 mg/day seems to be enough to obtain positive results.

Study limitations

There are several limitations to the current study. First, many studies did not report the necessary data for the meta-analyses. Second, the exercise protocol varied substantially between studies, inducing different levels of muscle damage. Moreover, the different training statuses of the participants and the size of the muscles involved affected the magnitude of the muscle damage experienced. Third, most studies only included young male participants; hence, these findings are unlikely to be generalizable to females or older adults. Fourth, most studies did not perform a power analysis, and the small sample sizes were probably insufficient to detect between-group differences. In addition, though the quality of the included studies was generally acceptable, the randomization, allocation concealment, and blinding of outcome assessment procedures were inadequately described. Lastly, it was necessary to use different parameters to conduct the meta-analyses regarding antioxidant activity and oxidative stress. Although this procedure is not uncommon in the existing literature, it must be kept in mind when interpreting the results.

CONCLUSIONS

The results of our systematic review and meta-analysis support the effectiveness of Q supplementation for reducing muscle damage and accelerating recovery after intense exercise in young male athletes. However, a limited number of studies were included in the different meta-analyses and the ES were not significant for some variables except when certain studies were removed. Therefore, our findings should be interpreted cautiously. Despite these limitations, based on the studies included in this investigation and the potential risks discussed by Andres et al. [53], Q supplementation with a dose of 1000 mg/day for periods of more than seven days and a maximum of 12 weeks appears to be a safe and efficacious strategy to reduce muscle damage and muscle soreness, as well as to enhance recovery in sedentary to well-trained young men. Athletes may also benefit from ingesting a single dose before exercise, but only one study investigated acute supplementation, and further research is needed. More evidence is also required to confirm the efficacy of Q supplementation for females and older adults.

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Conflict of interest declaration

The authors declare no conflict of interest.

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Effect of 3 and 6 mg/kg of caffeine on fat oxidation during exercise in healthy active females

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ABSTRACT: The aim of this study was to investigate the effect of 3 and 6 mg of caffeine per kg of body mass (mg/kg) on whole-body substrate oxidation during an incremental cycling exercise test in healthy active women. Using a double-blind placebo-controlled counterbalanced experimental design, 14 subjects performed three identical exercise trials after the ingestion of 3 or 6 mg/kg of caffeine or placebo. The exercise trials consisted of an incremental test on a cycle ergometer with 3-min stages at workloads from 30 to 70% of maximal oxygen uptake (VO_2max). Substrate oxidation rates were measured by indirect calorimetry. During exercise, there was a significant effect of substance ($F = 5.221$; $p = 0.016$) on fat oxidation rate. In comparison to the placebo, 3 mg/kg of caffeine increased fat oxidation rates at 30 to 60% of VO_2max (all $p < 0.050$) and 6 mg/kg at 30 to 50% of VO_2max (all $p < 0.050$). There was also a significant effect of substance ($F = 5.221$; $p = 0.016$) on carbohydrate oxidation rate ($F = 9.632$; $p < 0.001$). In comparison to placebo, both caffeine doses decreased carbohydrate oxidation rates at 40 to 60% VO_2max (all $p < 0.050$). The maximal rate of fat oxidation with placebo was 0.24 ± 0.03 g/min, which increased with 3 mg/kg to 0.29 ± 0.04 g/min ($p = 0.032$) and to 0.29 ± 0.03 with 6 mg/kg of caffeine ($p = 0.042$). Acute intake of caffeine improves the utilization of fat as a fuel during submaximal aerobic exercise in healthy active women with an effect of similar magnitude after the intake of 3 and 6 mg of caffeine per kg of body mass. Thus, the use of 3 mg/kg of caffeine would be more recommended than 6 mg/kg for women seeking increased fat utilization during submaximal exercise.

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INTRODUCTION

Caffeine is one of the most widely used phytochemicals as an ergogenic aid [1], with strong evidence supporting its positive effects on sport performance [2–4]. Today there is a consensus to consider acute caffeine intake as an ergogenic supplementation protocol when caffeine is ingested in a dose of 3 to 6 mg per kg of body mass [2]. Beyond the performance benefits in the sport context, acute caffeine intake can produce other physiological changes during exercise, such as increased fat oxidation. The effect of caffeine to shift substrate oxidation towards a higher reliance on fat is present during submaximal aerobic exercise [5] and when ingested in doses ranging from 3 to 6 mg/kg [6–10]. Recently, it was found that the effect of caffeine to enhance fat oxidation during submaximal aerobic exercise is of similar magnitude with 3 and 6 mg of caffeine per kg of body mass [11]. However, was the case in the investigation of the ergogenic effect of caffeine [12], most of the findings regarding the potential effect of caffeine to augment fat utilization during aerobic exercise have been obtained in samples of male participants or mixed samples where women constituted only a small part of the sample. Hence, from the current literature on the topic, it is not possible to determine with confidence whether women benefit from acute caffeine intake to enhance fat oxidation during exercise and whether this effect is obtained in the range of 3 to 6 mg/kg as occurs in men.

To date, there are only three investigations indicating that, in women, a dose of ~6 mg/kg produces larger performance improvements than lower doses of ~3 mg/kg of caffeine or less [13–15]. Against this background, it is possible that women obtain benefits from fat oxidation during exercise of higher magnitude with 6 than with 3 mg/kg of caffeine. Therefore, the aim of this study was to investigate the effect of 3 and 6 mg of caffeine per kg of body mass (mg/kg) on whole-body substrate oxidation during an incremental cycling exercise test in healthy active women. We hypothesized that fat oxidation rates would be higher with both doses of caffeine over

a placebo, but the magnitude of the effect would be higher with 6 mg/kg than with 3 mg/kg of caffeine.

MATERIALS AND METHODS

Participants

Fourteen healthy active women volunteered to participate in this study (Table 1). Participants were considered active because all of them performed at least 60 min of exercise per day for at least 4 days per week for the two years prior to the investigation. Participants practised different aerobic sport disciplines such as road cycling, mountain biking, endurance running and triathlon. An a priori sample size calculation indicated that 14 participants were needed to obtain statistically significant differences in the maximal fat oxidation rate with caffeine with respect to the placebo. This a priori sample size was calculated to obtain an effect size of 1.01 in Cohen's d units (statistical power of 80% with type I error set at 5%), based on a previous investigation that obtained this effect when using the same dose of caffeine during an incremental exercise test [7]. The required sample size was determined using G*Power software [16]. All participants were non-smokers, had no history of cardiopulmonary diseases, suffered no musculoskeletal injuries in the previous 6 months, had a regular duration of their menstrual cycle during the previous 6 months and had no menstrual disorders such as dysmenorrhoea, amenorrhoea or strong symptoms associated with premenstrual syndrome. Participants were low caffeine consumers (i.e., < 50 mg caffeine per day in the previous 2 months) as defined by Filip et al. [17] and measured by a modified version of the validated questionnaire by Bühler et al. [18]. All participants signed a written informed consent form to participate in the research. The experimental procedure of this study was in accordance with the latest version of the Declaration of Helsinki and was approved by the local University Ethics Committee (IRB number UFV 18/2020).

TABLE 1. Participants' age, morphological characteristics, and maximal values at the end of a maximal ramp test on a cycle ergometer.

Variable (units)	Mean ± SD	Range
Age (yr)	26.0 ± 6.0	19–39
Body mass (kg)	60.7 ± 7.9	47.9–73.0
Height (m)	167 ± 6	156–175
Fat mass (%)	14.9 ± 3.6	8.02–30.5
VO_2max (ml/kg/min)	40.3 ± 5.4	32.9–50.2
Maximal heart rate (beats/min)	180 ± 7	170–197
Maximal respiratory quotient	1.22 ± 0.06	1.13–1.37
Maximal Borg's scale rating (a.u.)	20.0 ± 0.2	19–20

Arbitrary units (a.u.). Data are presented as mean ± standard deviations (SD) with minimal and maximal values (range).

Experimental design

A randomised, counterbalanced, double-blind, placebo-controlled design was used in this experimental investigation. Each participant completed 3 identical experimental trials after conducting a pre-experimental maximal oxygen consumption test. All experimental trials were separated by at least 3 days to allow for full recovery and caffeine washout. In a randomised, counterbalanced order, the participants ingested either (i) 3 mg/kg of caffeine (100% purity; CAF, Bulk Powders, UK), (ii) 6 mg/kg of caffeine or (iii) a placebo (cellulose; 100% purity, Guinama, Spain). The substances were administered in an opaque, unidentifiable capsule and ingested with 150 mL of water 60 minutes before the beginning of the experimental trials while a researcher visually verified the ingestion. An alphanumeric code was assigned to all trials and the randomization of trial order was performed by an independent investigator. All participants performed the experimental tests in the mid-luteal phase of their menstrual cycle. For this standardization, ovulation was estimated by the measurement of the dates of menstruation and the duration of the menstruation for 6 months with a commercially available mobile app (Mycalendar, Period-tracker, US).

Pre experimental trial

One week before the first trial, participants' body weight and height were obtained by a validated scale and stadiometer (Seca 700, Hammer Steindamm, Germany) and body composition was estimated by bioimpedance (Tanita InnerScan Dual, RD-901BK36, Japan). Afterwards, participants performed a ramp exercise test to assess VO_2max. The VO_2max was considered valid when the following end criteria were reached at the end of the tests: VO_2 stabilisation despite increases in ergometric power, respiratory exchange ratio greater than 1.10, and participant's rating of perceived exertion – measured with the Borg scale from 6 to 20 points – higher than 19 points and peak heart rate superior to 80% of the age-adjusted estimate of maximum heart rate [19]. To normalize exercise intensity in the experimental trials, a regression analysis was performed for each subject for the relationship between workload (in W) and VO_2 (L/min), as previously suggested [20]. With this association, the workloads were calculated to produce exercise intensities in the range of 30 to 80% VO_2max. Within the week prior to the onset of the experiment, a second pre-experimental trial was carried out to familiarise participants with the protocol. In the second pre-experimental trial, participants underwent the protocol described below for the experimental trials but without the intake of any substance.

Experimental trials

Twenty-four hours before each experimental test, participants refrained from strenuous exercise and adopted a similar diet and fluid intake regime. Participants were also required to avoid alcohol, caffeine, and other stimulants before each test. Participants were asked to complete a 24-hour dietary log the day before the first trial and to follow the same dietary pattern before the subsequent trials. In each

trial, participants arrived at the laboratory (08.00–10.00 am) in a fasted state (at least 8 hours after their last meal). Upon arrival, participants voided and proper hydration prior to testing was confirmed by urine specific gravity < 1020 g/ml. Once all the standardizations were satisfied, the participants ingested the capsule assigned for the trial and rested for 60 min. In the last 5 min of the resting period, participants' blood pressure (M6 Comfort, Omron, Japan; by triplicate) and heart rate (Wearlink+V800, Polar, Finland) were recorded. Thereafter, a urine sample was collected to assess the concentration of caffeine and paraxanthine before exercise. Then, participants performed a warm-up consisting of 10 minutes at 30% of VO_2max and the exercise intensity was increased by 10% of VO_{2max} every 3 min until they completed the workload equivalent to 80% of VO_2max. During exercise, expired gases were collected with a stationary breath-by-breath gas analyser (Ergostik, Geratherm Respiratory, Germany). The gas analyser used for this investigation has good inter-day reliability for respiratory measurements (CV = 7.7 ± 5.5% for the maximal rate of fat oxidation (MFO), and CV = 6.5 ± 8.0% for Fatmax) [21]. Throughout the trial, gas exchange data were averaged every 15 s. The rates of energy expenditure and substrate oxidation (fat and carbohydrate) were calculated using the non-protein respiratory quotient [22]. In each trial, the MFO was individually calculated for each participant as the highest value of fat oxidation rate obtained during the incremental exercise intensity test. The exercise intensity at which MFO was obtained for each individual was categorised as Fatmax.

After each trial, participants completed an *ad hoc* questionnaire regarding common side effects after acute caffeine intake. This questionnaire included a 1- to 10-point scale to assess the magnitude of each side effect [23]. This survey was completed on the following morning of the experiment once participants had completed their night's sleep [24].

Liquid chromatography–mass spectrometry (LC-MS) analysis

The assessment of urine caffeine and paraxanthine concentration was carried out through mass spectrometry coupled with an Acquity UPLC H-Class (USA). The Ultra Performance Liquid chromatography (100x2.1 mm, i.d. 1.7 μm) was performed at 30°C with an Avantor ACE (UK) C18-PFP column using a mobile phase composed of formic acid 0.1% (A) and methanol (B). Data were acquired using MRM (multiple reaction monitoring) mode. Chromatograms were integrated with MultiQuant software 1.0.3. (Sciex, Germany). Calibration curves were created using the commercial standards (caffeine VWR USA and 1.7-dimetylxanthine TCI, Japan) in the range 0.5 μg/mL-60 μg/ml.

Statistical analysis

The results of each test were entered in a blinded fashion into the SPSS v21.0 statistical package and analysed. The data are presented as mean ± standard deviation (SD). The normality of each variable was initially tested with the Shapiro-Wilk test. A one-way analysis of variance (ANOVA) was used to compare cardiovascular variables at rest, MFO, Fatmax, urine concentrations of caffeine and paraxanthine and side-effects derived from caffeine/placebo ingestion. A two-way ANOVA (substance × exercise intensity) was used to compare energy expenditure, fat, and carbohydrate oxidation rates, heart rate and the rating of perceived exertion during exercise. Cohen's effect size (ES) was calculated in all pairwise comparisons between caffeine doses and placebo [25]. The level of significance was set at $p < 0.050$.

RESULTS

In comparison to the placebo, the acute ingestion of 3 and 6 mg/kg of caffeine did not modify resting heart rate ($F_{12} = 1.130$; $p = 0.334$), systolic blood pressure ($F_{12} = 1.106$; $p = 0.372$), diastolic blood pressure ($F_{12} = 0.280$; $p = 0.757$) or mean blood pressure ($F_{12} = 0.710$; $p = 0.498$, Table 2).

Figure 1 depicts the effect of 3 and 6 mg/kg of caffeine on the rates of fat oxidation, carbohydrate oxidation and energy expenditure during exercise of increasing intensity. There were significant effects of substance ($F_{2,9} = 5.221$; $p = 0.016$) and exercise intensity ($F_{4,10} = 31.778$; $p < 0.001$), and a substance × exercise intensity interaction ($F_{8,5} = 4.321$; $p = 0.025$), on fat oxidation rate during exercise. The *post hoc* analysis revealed that, in comparison to the placebo, the rates of fat oxidation were higher with 3 mg/kg of caffeine at 30, 40, 50 and 60% of VO_2max (all $p < 0.050$, ES from 0.42 to 0.63). Similarly, the rates of fat oxidation were higher with 6 mg/kg of caffeine than with placebo at 30, 40 and 50% of VO_2max (all $p < 0.050$, ES from 0.39 to 0.58) with no differences between

TABLE 2. Cardiovascular variables at rest after the acute intake of 3 and 6 mg/kg of caffeine or a placebo.

Variable (units)	Placebo	3 mg/kg	6 mg/kg	p value
Heart rate at rest (bpm)	56 ± 9	58 ± 8	57 ± 8	0.561
Systolic blood pressure (mmHg)	104 ± 12	108 ± 9	111 ± 7	0.372
Diastolic blood pressure (mmHg)	68 ± 5	70 ± 9	70 ± 7	0.757
Mean blood pressure (mmHg)	80.3 ± 5.9	82.7 ± 5.3	84.0 ± 6.3	0.498

Data are presented as mean ± standard deviations (SD).

3 and 6 mg/kg at any exercise intensity. There were main effects of substance ($F_{2,9}$ = 9.632; p < 0.001) and exercise intensity ($F_{4,10}$ = 47.522; p < 0.001), and a substance × exercise intensity interaction ($F_{8,5}$ = 3.882; p = 0.030), on carbohydrate oxidation rate during exercise. The *post hoc* analysis revealed that the rates of carbohydrate oxidation were lower with 3 mg/kg of caffeine compared with those obtained with placebo at 40, 50 and 60% of VO_2max (all p < 0.050, ES = 0.34 to 0.58). Similar results were found when comparing the ingestion of 6 mg/kg of caffeine vs. placebo at 40, 50 and 60% of VO_2max (all p < 0.050, ES from 0.31 to 0.52). No differences between 3 and 6 mg/kg were observed for carbohydrate oxidation rate at any exercise intensity. There was a significant effect of exercise intensity ($F_{4,10}$ = 46.853; p < 0.001; Figure 1c) on energy expenditure rate, whereas no effect of substance or substance × exercise intensity interaction was observed.

Figure 2 depicts the effect both 3 and 6 mg/kg caffeine on the rating of perceived exertion and heart rate during exercise at increasing intensity. There was a significant effect of exercise intensity ($F_{4,10}$ = 82.522; p < 0.001) on the rating of perceived exertion, while no effect of substance or substance × exercise intensity interaction was observed for this variable. There was also a significant effect of exercise intensity ($F_{4,10}$ = 63.622; p < 0.001) on heart rate, whereas no effect of substance or substance × exercise intensity interaction was observed.

Figure 3 shows the effect of caffeine intake on MFO and Fatmax. There was an effect of substance on MFO (F_{12} = 5.311; p = 0.001). The *post hoc* analysis revealed that both 3 mg/kg (0.29 ± 0.03 g/min, p = 0.032, ES = 0.37) and 6 mg/kg of caffeine (0.29 ± 0.04 g/min, p = 0.042, ES = 0.34) increased MFO over the placebo condition (0.29 ± 0.03 g/min). However, the intake of caffeine did not modify the exercise intensity that elicited Fatmax (F_{12} = 0.155; p = 0.813).

Within 24 hours of caffeine ingestion, both 3 and 6 mg/kg caffeine increased the female participants' feelings of nervousness (F_{14} = 4.215; p = 0.009) and vigour (F_{14} = 3.741; p = 0.016; Table 3), while no additional side effects were observed. There was a main effect of substance on urine caffeine concentration (F_{12} = 8.794; p = 0.001). The *post hoc* analysis showed that both 3 mg/kg (p = 0.001) and 6 mg/kg (p = 0.033) increased caffeine concentrations over the placebo condition, with no differences between doses of caffeine. There was a main effect of substance on urine caffeine paraxanthine concentration (F_{12} = 21.393; p < 0.001). The *post hoc* analysis showed that both 3 and 6 mg/kg (all p < 0.001) increased urine paraxanthine concentrations over the placebo condition, and 6 mg/kg increased it more than 3 mg/kg (p < 0.001, Table 4).

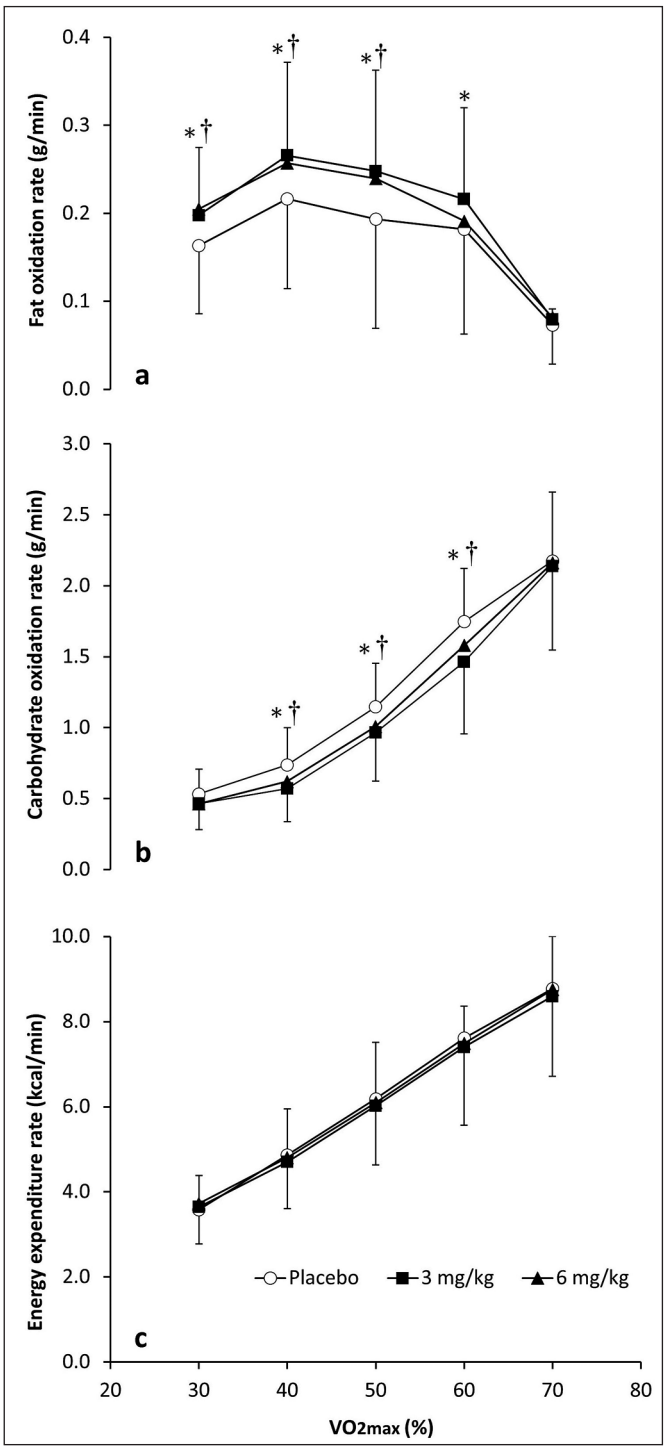


FIG. 1. Rates of fat oxidation (a), carbohydrate oxidation (b) and energy expenditure (c) during exercise of increasing intensity after the ingestion of 3 and 6 mg/kg of caffeine or a placebo.
Note: (*) Differences between placebo and 3 mg/kg (p<0.050). (†) Differences between placebo and 6 mg/kg (p<0.050).

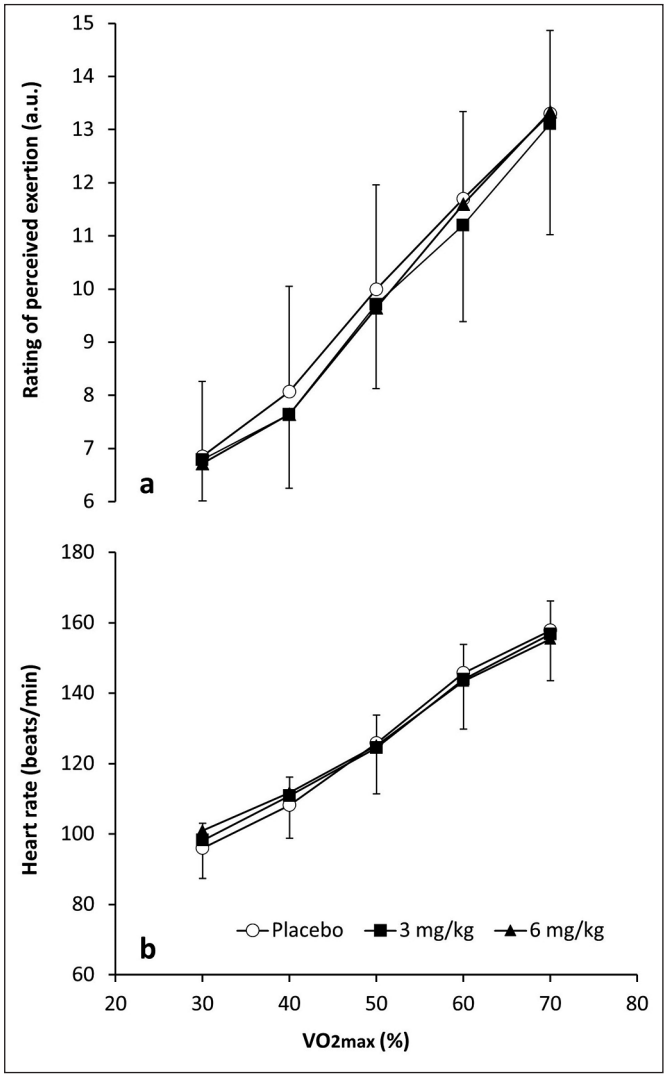


FIG. 2. Rating of perceived exertion (a) and heart rate (b) during exercise of increasing intensity after the ingestion of 3 and 6 mg/kg of caffeine or a placebo.

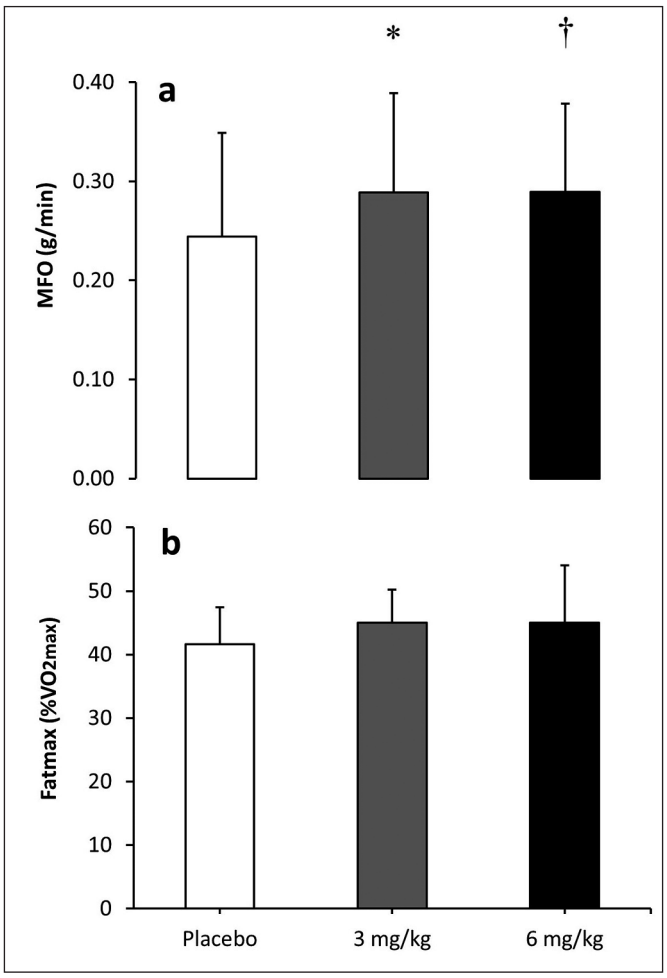


FIG. 3. Maximal fat oxidation (MFO; (a)) and exercise intensity at maximal fat oxidation (Fatmax; (b)) during exercise of increasing intensity after the ingestion of 3 and 6 mg/kg of caffeine or a placebo.
Note: (*) Differences between placebo and 3 mg/kg ($p<0.050$). (†) Differences between placebo and 6 mg/kg ($p<0.050$).

TABLE 3. Frequencies of adverse effects during the 24 hours following the test with the acute intake of 3 and 6 mg/kg of caffeine or a placebo.

Variable (units)	Placebo	3 mg/kg	6 mg/kg	p value
Nervousness (a.u.)	1.3 ± 0.6	3.3 ± 2.5*	3.0 ± 2.3†	**0.009**
Vigour (a.u.)	1.5 ± 0.8	3.2 ± 2.5*	3.5 ± 2.4†	**0.016**
Irritability (a.u.)	1.4 ± 0.7	1.5 ± 1.2	1.3 ± 0.5	0.732
Muscle pain (a.u.)	2.3 ± 1.9	1.5 ± 0.9	1.6 ± 1.4	0.184
Headache (a.u.)	2.5 ± 2.7	2.3 ± 2.4	1.1 ± 0.3	0.096
Gastrointestinal distress (a.u.)	1.3 ± 0.6	1.1 ± 0.4	1.9 ± 2.0	0.573
Diuresis (a.u.)	2.0 ± 1.4	2.3 ± 1.6	2.2 ± 1.7	0.821
Insomnia (a.u.)	2.6 ± 2.2	2.2 ± 1.3	2.3 ± 2.7	0.792
Sleep quality (a.u)	7.1 ± 1.7	6.5 ± 1.8	6.1 ± 2.2	0.219

Each side effect was self-reported by using 1–10 arbitrary units (a.u.) scale. Participants were previously informed that one point meant a minimal amount of that item and 10 points meant a maximal amount. (*) Differences between placebo and 3 mg/kg ($p < 0.050$). (†) Differences between placebo and 6 mg/kg ($p < 0.050$). Data are presented as mean ± standard deviations (SD).

TABLE 4. Urine caffeine and paraxanthine concentrations 45 minutes after of acute intake of 3 and 6 mg/kg of caffeine or a placebo.

Variable (units)	Placebo	3 mg/kg	6 mg/kg	p value
Urine caffeine concentration (μg/ml)	0.0 ± 0.0	3.4 ± 2.6*	3.7 ± 4.5†	**0.001**
Urine paraxanthine concentration (μg/ml)	0.0 ± 0.0	2.6 ± 0.9*	4.6 ± 3.5†$^{\$}$	**< 0.001**

(*) Differences between placebo and 3 mg/kg ($p < 0.050$). (†) Differences between placebo and 6 mg/kg ($p < 0.050$). ($) Differences between 3 and 6 mg/kg of caffeine ($p < 0.050$). Data are presented as mean ± standard deviations (SD).

DISCUSSION

In this double-blind, placebo-controlled study involving healthy active women, acute intake of caffeine of 3 and 6 mg of caffeine per kg of body mass modified substrate oxidation during an incremental protocol test on a cycle ergometer. Specifically, caffeine increased fat oxidation rates from 30 to 60% of VO_2max and reduced carbohydrate oxidation at these workloads, independently of the caffeine dosage. The data of this study suggest that by using an appropriate exercise intensity – one that results in maximal fat oxidation during exercise – the rate of fat oxidation can be increased by 26.5% with 3 mg/kg and by 24.7% with 6 mg/kg of this substance in healthy active women.

Several recent studies using a similar incremental exercise test performed concluded that acute intake of 3 mg/kg of caffeine was effective to increase the rate of fat oxidation during exercise of low to moderate intensities (30–60% of VO_2max) [6–8]. A recent systematic review summarizing the findings of studies published on this topic [5] concluded that caffeine was not effective to enhance fat oxidation when the dose was ≤ 3 mg/kg, while there was an increasing effect of caffeine on fat oxidation with doses of 3.1–5.9 and ≥ 6 mg/kg of caffeine. Lastly, it was found that the effect of caffeine to enhance fat oxidation during exercise is of similar magnitude with 3 and 6 mg of caffeine per kg of body mass [11]. All these reports indicate that fat oxidation enhancement can be obtained during exercise if caffeine is ingested before exercise in the dose range of 3 to 6 mg/kg. However, all these studies included samples of male participants or mixed samples where women formed a small part of the sample.

This current investigation is innovative because it is the first study on the effect of caffeine to enhance fat oxidation during exercise carried out with women. The study adds new information to the current evidence as it indicates that caffeine enhances fat oxidation during exercise in women while this effect is of similar magnitude independent of the dosing, at least in the 3 to 6 mg/kg range. From a simplistic viewpoint, the use of 3 mg/kg of caffeine would be more recommended than 6 mg/kg to those exercise enthusiasts seeking fat reduction during exercise because 3 mg/kg of caffeine produced an effect of similar magnitude to that observed for 6 mg/kg but with half the dose.

In the present investigation, pre-exercise resting heart rate and blood pressure were not affected by any caffeine dose. These findings are contrary to previous investigations where acute consumption of a moderate caffeine dose is associated with increments of 5–10 mmHg in diastolic blood pressure [26, 27]. However, the acute caffeine intake of the current study caused increased nervousness and vigour in the healthy active female participants (Table 3), showing similar data to those reported by a previous study in non-habituated women [28]. The low magnitude of these side effects and the low clinical relevance of these drawbacks suggest that caffeine can be considered a safe substance, at least for healthy individuals with no allergy to caffeine. However, participants should be aware of potential drawbacks of caffeine found in this and other investigations such as tolerance [29] and dependence [30], among others.

Caffeine is an alkaloid that undergoes extensive metabolism in the liver microsomes, with more than 25 metabolites identified [31]. However, the main metabolites of caffeine metabolism are paraxanthine, theobromine and theophylline [32]. In the context of sport, urine caffeine concentration has been measured to estimate the intake of caffeine [1, 33] and a threshold of 12 μg/ml was set to consider the use of caffeine as doping from 1984 to 2004. Although caffeine is no longer included in the list of banned substances, the measurement of urine caffeine concentration and its main metabolites may be useful to estimate the dose ingested. This is because the assessment of urinary caffeine and paraxanthine concentrations is an easy and reliable method without the need of any invasive protocol. In previous studies, 4.1 μg/ml of urinary caffeine in male soccer players [34] and 2.4 μg/ml in male rugby players [35] were found after the ingestion of 3 mg/kg of caffeine. In the present investigation, we observed urinary caffeine concentrations of ~3.4 and ~3.7 μg/ml for doses of 3 and 6 mg/kg of caffeine, without differences between doses. The lack of differences in urine caffeine concentration despite ingesting a 2-fold dose of caffeine in the 6 mg/kg trial may be due to the low portion of the ingested caffeine that is excreted in urine as caffeine. On the other hand, urine paraxanthine concentration was 1.8-fold higher with 6 than with 3 mg/kg of caffeine. Collectively, this information suggests that paraxanthine concentration was the urinary variable that best identified caffeine intake in healthy active female participants, as most of the caffeine orally ingested is excreted as urinary paraxanthine.

Despite the strengths and novelty of this investigation, the study has some limitations: i) It was only conducted with healthy active women, and therefore no extrapolation should be assumed for other

populations such as men, elite female athletes or populations with clinical conditions. (ii) No doses lower than 3 mg/kg or higher than 6 mg/kg of caffeine were tested in this investigation. The effect of caffeine on fat oxidation may be different with higher doses of caffeine, such as 9 mg/kg, as this dose produced the greatest increase in free fatty acid concentrations in the dose-response study by Graham and Spriet [15]. However, recent literature reported that 3 and 6 mg/kg of caffeine produced an effect of similar magnitude on fat oxidation during exercise [11], suggesting the absence of a dose-response effect of caffeine on the enhancement of fat utilization as a fuel during exercise. Additionally, it is necessary to establish the minimal effective doses of caffeine for enhanced fat oxidation by investigating doses below 3 mg/kg, which has not been consistently investigated in men or women. (iii) No data on the mechanism of action of caffeine to enhance fat oxidation were obtained; a future investigation should be carried out to determine the changes in free fatty acid concentration with different doses of caffeine in women. iv) All participants were low daily caffeine consumers, which could have amplified the effect of acute caffeine intake. Future investigations should determine the effect of caffeine on fat oxidation in participants with moderate and high levels of daily caffeine intake as tolerance to caffeine's benefits during exercise has been found with a 20-day chronic intake of the substance [29]. v) Recent evidence indicates that AA homozygotes in the -163C > A polymorphism of the cytochrome P450 1A2 gene (*CYP1A2*) may respond differently to acute caffeine intake during exercise than C-allele carriers [36], but no investigation has tested whether this polymorphism affects the individual responses to caffeine in terms of enhanced fat oxidation during exercise.

CONCLUSIONS

In summary, acute intake of caffeine improves the utilization of fat as a fuel during aerobic exercise at 30 to 60% VO_2max in healthy active women. The effect of caffeine on fat oxidation was of similar magnitude with 3 and 6 mg of caffeine per kg of body mass. Thus, the ingestion of at least 3 mg/kg seems to be necessary to obtain noteworthy changes in substrate oxidation during low-to-moderate intensity exercise.

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Conflict of interest declaration

The authors declare no conflict of interest.

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Global disease burden attributed to low physical activity in 204 countries and territories from 1990 to 2019: Insights from the Global Burden of Disease 2019 Study

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ABSTRACT: The purpose of this investigation is to estimate the global disease burden attributable to low physical activity (PA) in 204 countries and territories from 1990 to 2019 by age, sex, and Socio-Demographic Index (SDI). Detailed information on global deaths and disability-adjusted life years (DALYs) attributable to low PA were collected from the Global Burden of Disease Study 2019. The ideal exposure scenario of PA was defined as 3000-4500 metabolic equivalent minutes per week and low PA was considered to be less than this threshold. Age-standardization was used to improve the comparison of rates across locations or between time periods. In 2019, low PA seems to contribute to 0.83 million [95% uncertainty interval (UI) 0.43 to 1.47] deaths and 15.75 million (95% UI 8.52 to 28.62) DALYs globally, an increase of 83.9% (95% UI 69.3 to 105.7) and 82.9% (95% UI 65.5 to 112.1) since 1990, respectively. The age-standardized rates of low-PA-related deaths and DALYs per 100,000 people in 2019 were 11.1 (95% UI 5.7 to 19.5) and 198.4 (95% UI 108.2 to 360.3), respectively. Of all age-standardized DALYs globally in 2019, 0.6% (95% UI 0.3 to 1.1) may be attributable to low PA. The association between SDI and the proportion of age-standardized DALYs attributable to low PA suggests that regions with the highest SDI largely decreased their proportions of age-standardized DALYs attributable to low PA during 1990-2019, while other regions tended to have increased proportions in the same timeframe. In 2019, the rates of low-PA-related deaths and DALYs tended to rise with increasing age in both sexes, with no differences between males and females in the age-standardized rates. An insufficient accumulation of PA across the globe occurs together with a considerable public health burden. Health initiatives to promote PA within different age groups and countries are urgently needed.

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INTRODUCTION

It is well documented that regular physical activity (PA) is beneficial for health through risk-reduction of diseases and premature mortality [1, 2]. However, despite the development and implementation of country-specific PA guidelines (e.g., Great Britain, Canada, Australia, USA), as well as through the World Health Organization (WHO) and the European Union, 27.5% of adults worldwide do not accumulate sufficient PA to meet current public health guidelines [3]. The consequences of physical inactivity on disease burden have been assessed in several countries, such as Great Britain [4] and South Africa [5]. Overall, physical inactivity increases the risk of many diseases, while subsequently decreasing life expectancy [4, 5]. In a large-scale, global investigation using data from 2009 and before, Lee et al. [6] estimated that by eliminating physical inactivity, life expectancy of the world's population is estimated to increase by 0.68 (0.41 to 0.95) years.

An up-to-date and detailed report using the best available evidence is urgently needed in order to evaluate the impact of previous policies and help influence future policy decisions. The Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) is a continuous and robust effort to evaluate the disease burden of more than 80 risk factors for 204 countries and territories across the globe [7–9], and provides a unique opportunity to understand the landscape of low PA. In this study, we evaluated the impact of low PA on global disease burden in 204 countries and territories from 1990 to 2019 by age, sex, and Socio-demographic Index (SDI), using the estimates from the most recent GBD 2019.

MATERIALS AND METHODS

Overview and data sources

This study is part of GBD 2019, which is currently the most comprehensive and systematic report to date estimating the levels and trends of burden caused by 369 diseases and injuries, as well as 87 risk factors from 1990 to 2019. Seven super-regions, 21 regions, and 204 countries and territories were involved in GBD 2019. The general methodology of GBD 2019 and the comparative risk assessment specifically for low PA have been described in previous publications [10, 11]. In the present study, data on the disease burden attributable to low PA were extracted through a result tool available on the website of Institute for Health Metrics and Evaluation (IHME)[http://ghdx.healthdata.org/gbd-results-tool]. The original data sources used for the estimations of low PA can be found on the GBD 2019 Data Input Sources Tool website [http://ghdx.healthdata.org/gbd-2019/data-input-sources]. Since no identifiable data were used in GBD 2019, a waiver of informed consent was reviewed and approved by the University of Washington Institutional Review Board.

Definition of low physical activity

PA was quantified using total metabolic equivalent (MET) minutes per week, which was calculated by summating the frequency and duration per activity and the METs corresponding to the intensity of each activity. One MET is defined as the energy cost of sitting quietly and is equivalent to 1 kcal/kg/hour [12]. Although the accepted threshold/definition for physical inactivity is <600 MET-minutes/week, this threshold may not capture all increased mortality risk caused by inadequate PA [13]. In GBD studies, the counterfactual level of risk exposure used is the risk exposure that is both theoretically possible and minimizes risk in the exposed population that consequently captures the maximum population attributable burden [11]. For PA in GBD 2019, best available epidemiological evidence from published and unpublished relative risks by PA level and the lowest observed PA level from cohorts were used to select a single PA exposure level that minimizes risk for all causes of deaths combined to establish the theoretical minimum-risk exposure level (TMREL) [11]. The TMREL for PA was estimated as 3000-4500 MET minutes per week, at which minimal deaths across outcomes occurred [11, 13]. Thus, low PA was defined as less than the TMREL in GBD studies.

Analysis strategies

Random sampling studies of the general adult population (aged ≥ 25 years) that captured PA across all domains of life (leisure/recreation, work/household and transport) were selected for the analysis. Only durations of at least ten minutes at a time were included. PA data were primarily derived from two standardized questionnaires: The Global Physical Activity Questionnaire (GPAQ) and the International Physical Activity Questionnaire (IPAQ). Other survey instruments that asked about duration, frequency, and intensity of PA performed across all activity domains were also included.

Deaths and disability-adjusted life years (DALYs) related to low PA were estimated using the GBD comparative risk assessment framework. The framework pairs low PA with known disease-specific outcomes. To be paired, sufficient evidence for a causal relationship between low PA and disease outcome is required. According to the results of pooled cohort studies [10], ischemic heart disease, ischemic stroke, type 2 diabetes mellitus, colon and rectum cancer and breast cancer were proved to be significantly associated with low PA. Disability-adjusted life-years (DALYs) were a summary that quantifies the overall health loss due to low PA and were calculated by summing years lived with disability and years of life lost. One DALY represents the loss of the equivalent of one year in full health [14]. DisMod-MR 2.1, a Bayesian meta-regression tool developed for the GBD study, was used to simultaneously derive the estimates of deaths and DALYs attributable to low PA. The proportion of deaths and DALYs attributable to low PA was estimated using population attributable fraction (PAF), which represents the corresponding proportions that would be reduced if the exposure to low PA was increased to an ideal exposure scenario. More details on the modeling strategies can be obtained elsewhere [10, 11].

Socio-Demographic Index (SDI)

SDI was a composite indicator quantifying the development status for each location-year [10, 11]. SDI ranged from 0 (less developed) to 1 (most developed) and was calculated based on lag-distributed income per capita, mean educational attainment for individuals aged ≥ 15 years, and total fertility rate under 25 years. Based on SDI quintiles, the 204 countries and territories included in this paper were classified into five groups: low-SDI, low-middle-SDI, middle-SDI, high-middle-SDI, and high-SDI quintile [15].

Complementary Analyses

Age standardization was considered necessary when comparing rates across multiple locations or between different time periods. In GBD 2019, age-standardized rate was computed by direct standardization using the global age structure. The association between SDI and proportions of age-standardized deaths and DALYs attributable to low PA was assessed using a LOESS regression [16]. Uncertainty was propagated by sampling 1000 draws at each step of the calculation process [10, 11]. Final estimates were calculated as the mean across 1000 draws, and the 95% uncertainty intervals (UIs) were determined as the 2.5^{th} and 97.5^{th} percentiles of all 1000 draws. For all estimates, a 95% UI excluding zero was considered statistically significant.

RESULTS

Overall impact of low PA

In 2019, low PA potentially contributed to 0.83 million (95% UI 0.43 to 1.47) deaths and 15.75 million (95% UI 8.52 to 28.62) DALYs globally, corresponding an increase of 83.9% (95% UI 69.3 to 105.7) and 82.9% (95% UI 65.5 to 112.1) since 1990, respectively. The age-standardized rates of low-PA-related deaths and DALYs

TABLE 1. Age-standardized deaths and DALYs attributable to low physical activity in 2019 and percentage change from 1990 to 2019, overall and by sex.

	Deaths				DALYs			
	2019 age-standardized rates per 100 000 people	Percentage change in age-standardized rates, 1990–2019	2019 age-standardized PAF	Percentage change in age-standardized PAF, 1990–2019	2019 age-standardized rates per 100 000 people	Percentage change in age-standardized rates, 1990–2019	2019 age-standardized PAF	Percentage change in age-standardized PAF, 1990–2019
Both sexes								
All causes	11.1 (5.7 to 19.5)	-25.9% (-30.9 to -17.0)	1.5% (0.8 to 2.6)	12.2% (5.4 to 25.0)	198.4 (108.2 to 360.3)	-18.3% (-25.2 to -5.5)	0.6% (0.3 to 1.1)	24.5% (14.0 to 44.0)
Ischemic heart disease	6.5 (2.4 to 13.3)	-31.0% (-35.2 to -24.3)	5.5% (2.0 to 11.3)	-0.4% (-4.7 to 7.9)	96.4 (33.5 to 210.8)	-30.2% (-35.1 to -23.0)	4.3% (1.5 to 9.3)	-2.3% (-6.9 to 6.2)
Ischemic stroke	2.1 (0.4 to 5.3)	-32.8% (-38.3 to -23.7)	4.8% (1.0 to 12.3)	1.2% (-4.1 to 12.3)	31.2 (5.7 to 82.0)	-28.4% (-34.3 to -19.7)	3.9% (0.7 to 10.4)	0.0% (-5.9 to 9.8)
Type 2 diabetes mellitus	1.6 (0.8 to 2.7)	9.3% (2.6 to 17.3)	8.8% (4.4 to 14.5)	-1.4% (-4.6 to 3.8)	55.9 (27.2 to 97.6)	24.3% (16.8 to 32.3)	7.0% (3.4 to 12.0)	-2.6% (-6.2 to 2.5)
Colon and rectum cancer	0.8 (0.2 to 1.5)	-6.7% (-13.1 to 3.2)	5.6% (1.6 to 10.7)	-2.4% (-7.1 to 6.6)	12.6 (3.4 to 24.2)	-7.5% (-13.9 to 2.3)	4.3% (1.1 to 8.3)	-3.3% (-8.5 to 5.8)
Breast cancer	0.1 (0.1 to 0.2)	-13.7% (-20.9 to -3.9)	1.2% (0.6 to 2.1)	-1.8% (-7.0 to 7.3)	2.4 (1.2 to 4.2)	-12.7% (-20.4 to -2.3)	1.0% (0.5 to 1.7)	-2.9% (-8.5 to 6.4)
Male								
All causes	11.3 (5.5 to 21.3)	-22.1% (-28.3 to -9.9)	1.3% (0.6 to 2.4)	16.3% (7.8 to 34.3)	205.5 (102.9 to 388.8)	-15.3% (-23.6 to 2.6)	0.6% (0.3 to 1.1)	28.6% (16.4 to 54.7)
Ischemic heart disease	6.9 (2.3 to 15.2)	-28.4% (-33.6 to -18.7)	4.8% (1.6 to 10.4)	1.5% (-4.0 to 14.6)	108.0 (34.5 to 251.4)	-27.8% (-33.6 to -17.8)	3.7% (1.2 to 8.5)	-0.4% (-6.9 to 13.1)
Ischemic stroke	2.0 (0.3 to 5.5)	-27.6% (-35.2 to -13.9)	4.1% (0.6 to 11.4)	1.7% (-5.0 to 17.6)	29.9 (4.5 to 85.1)	-24.4% (-32.3 to -10.9)	3.4% (0.5 to 9.7)	0.8% (-6.5 to 14.8)
Type 2 diabetes mellitus	1.6 (0.8 to 2.7)	19.8% (11.1 to 30.6)	8.1% (4.0 to 13.9)	2.7% (-1.7 to 10.7)	54.3 (25.0 to 97.6)	34.2% (25.6 to 45.2)	6.3% (2.9 to 11.1)	1.1% (-3.5 to 8.5)
Colon and rectum cancer	0.8 (0.2 to 1.6)	3.3% (-6.5 to 19.9)	4.9% (1.2 to 9.7)	0.5% (-6.3 to 14.9)	13.3 (3.1 to 26.4)	2.9% (-6.9 to 19.0)	3.7% (0.9 to 7.3)	-0.7% (-7.9 to 14.2)
Breast cancer	—	—	—	—	—	—	—	—
Female								
All causes	10.8 (5.9 to 17.7)	-28.2% (-33.6 to -19.6)	1.8% (1.0 to 2.9)	11.8% (4.2 to 24.0)	190.9 (109.4 to 324.6)	-20.5% (-27.7 to -9.7)	0.6% (0.4 to 1.1)	22.0% (11.5 to 38.0)
Ischemic heart disease	6.1 (2.4 to 12.0)	-32.8% (-37.6 to -25.3)	6.5% (2.5 to 12.5)	0.1% (-4.5 to 9.5)	85.2 (32.0 to 174.9)	-32.5% (-37.9 to -24.8)	5.2% (1.9 to 10.4)	-2.6% (-7.0 to 5.5)
Ischemic stroke	2.1 (0.4 to 5.2)	-35.2% (-41.1 to -24.4)	5.4% (1.2 to 13.1)	4.0% (-1.0 to 16.1)	31.7 (6.5 to 79.7)	-30.4% (-36.4 to -20.7)	4.4% (0.9 to 11.2)	1.8% (-4.0 to 11.5)
Type 2 diabetes mellitus	1.6 (0.8 to 2.6)	2.6% (-5.9 to 11.7)	9.4% (4.8 to 15.2)	-2.9% (-6.4 to 2.4)	57.5 (28.6 to 98.4)	17.2% (9.1 to 25.5)	7.7% (3.9 to 13.0)	-4.2% (-7.8 to 0.5)
Colon and rectum cancer	0.7 (0.2 to 1.3)	-13.6% (-20.1 to -4.3)	6.5% (2.0 to 11.9)	-0.8% (-5.2 to 7.9)	12.0 (3.6 to 22.6)	-15.4% (-22.1 to -5.7)	5.1% (1.4 to 9.4)	-1.6% (-6.6 to 7.5)
Breast cancer	0.2 (0.1 to 0.3)	-11.0% (-18.8 to -0.9)	1.2% (0.6 to 2.1)	-0.5% (-5.8 to 8.2)	4.6 (2.3 to 8.0)	-11.2% (-19.3 to -0.6)	1.0% (0.5 to 1.7)	-1.6% (-7.4 to 7.6)

Abbreviations: DALYs = disability-adjusted life years; PAF = population attributable fraction.

in 2019 were 11.1 (95% UI 5.7 to 19.5) per 100,000 people and 198.4 (95% UI 108.2 to 360.3) per 100,000 people, respectively (Table 1). Between 1990 and 2019, there was a decrease of -25.9% (95% UI -30.9 to -17.0) for age-standardized rate of low-PA-related deaths and a decrease of -18.3% (95% UI -25.2 to -5.5) for age-standardized rate of low-PA-related DALYs (Table 1).

By sex, in 2019, the age-standardized rates of low-PA-related deaths and DALYs were similar between males and females (Table 1).

Across all age groups, the rates of low-PA-related deaths and DALYs tended to rise with increasing age in both sexes (Fig. S1). However, due to declining size of the global population with increasing age, the numbers of low-PA-related deaths and DALYs peaked at the age group of 80–84 years in both sexes (Fig. S1).

Across the 21 GBD regions, the highest 2019 age-standardized rates of low-PA-related deaths [34.8 (95% UI 20.4 to 54.4) per 100,000 people] and DALYs [671.9 (95% UI 389.1 to 1089.5) per 100,000 people] were both seen in North Africa and Middle East (Table S1). While the lowest age-standardized rates of low-PA-related deaths and DALYs were observed in Southern Latin America [3.2 (95% UI 1.6 to 6.3) per 100,000 people] and Eastern Sub-Saharan Africa [61.3 (95% UI 27.9 to 132.7) per 100,000 people], respectively (Table S1). Between 1990 and 2019, the largest percentage increase in age-standardized rates of low-PA-related deaths and DALYs was seen in Southern Sub-Saharan Africa [35.3% (95% UI 22.1 to 51.0)] and Oceania [33.1% (95% UI 11.4 to 61.7)], respectively (Table S1). In contrast, high-income Asia Pacific had the largest percentage decreases in age-standardized rates of low-PA-related deaths [-57.8% (95% UI -64.6 to -46.6)] and DALYs [-45.0% (95% UI -54.1 to -28.4)] (Table S1).

In 2019, the age-standardized rates of low-PA-related deaths and DALYs varied widely across all countries and territories (Fig. 1 and Fig. S2). The highest age-standardized rates of low-PA-related deaths and DALYs were seen in Qatar [64.5 (95% UI 41.3 to 91.2) per 100,000 people] and Sudan [1176.2 (95% UI 725.6 to 1775.0) per 100,000 people], respectively (Fig. 1, Fig. S2, and Table S1). While Argentina was the country with the lowest age-standardized rates of low-PA-related deaths [1.9 (95% UI 0.9 to 4.3) per 100,000 people] and DALYs [34.0 (95% UI 16.1 to 74.9) per 100,000 people]. Between 1990 and 2019, Uzbekistan had the largest percentage increase in age-standardized rates of low-PA-related deaths [159.0% (95% UI 118.8 to 207.0)] and DALYs [146.6% (95% UI 98.5 to 195.9)], while Singapore had the largest percentage decrease in age-standardized rates of low-PA-related deaths [-62.5% (95% UI -69.2 to -53.6)] and DALYs [-57.1% (95% UI -65.2 to -44.0)] (Fig. 2, Fig. S3, and Table S1).

Impact of low PA on each disease

Globally, ischemic heart disease was the leading cause of low-PA-related DALYs [96.4 (95% UI 33.5 to 210.8) per 100,000 people] in 2019, followed by type 2 diabetes mellitus [55.9 (95% UI 27.2 to 97.6) per 100,000 people], ischemic stroke [31.2 (95% UI 5.7 to 82.0) per 100,000 people], colon and rectum cancer [12.6 (95% UI 3.4 to 24.2) per 100,000 people], and breast cancer [2.4 (95% UI 1.2 to 4.2) per 100,000 people] (Table 1). Of all ischemic heart disease age-standardized DALYs worldwide, 4.3% (95% UI 1.5 to 9.3) was attributable to low PA; the corresponding proportions were 7.0% (95% UI 3.4 to 12.0) for type 2 diabetes mellitus, 3.9% (95%

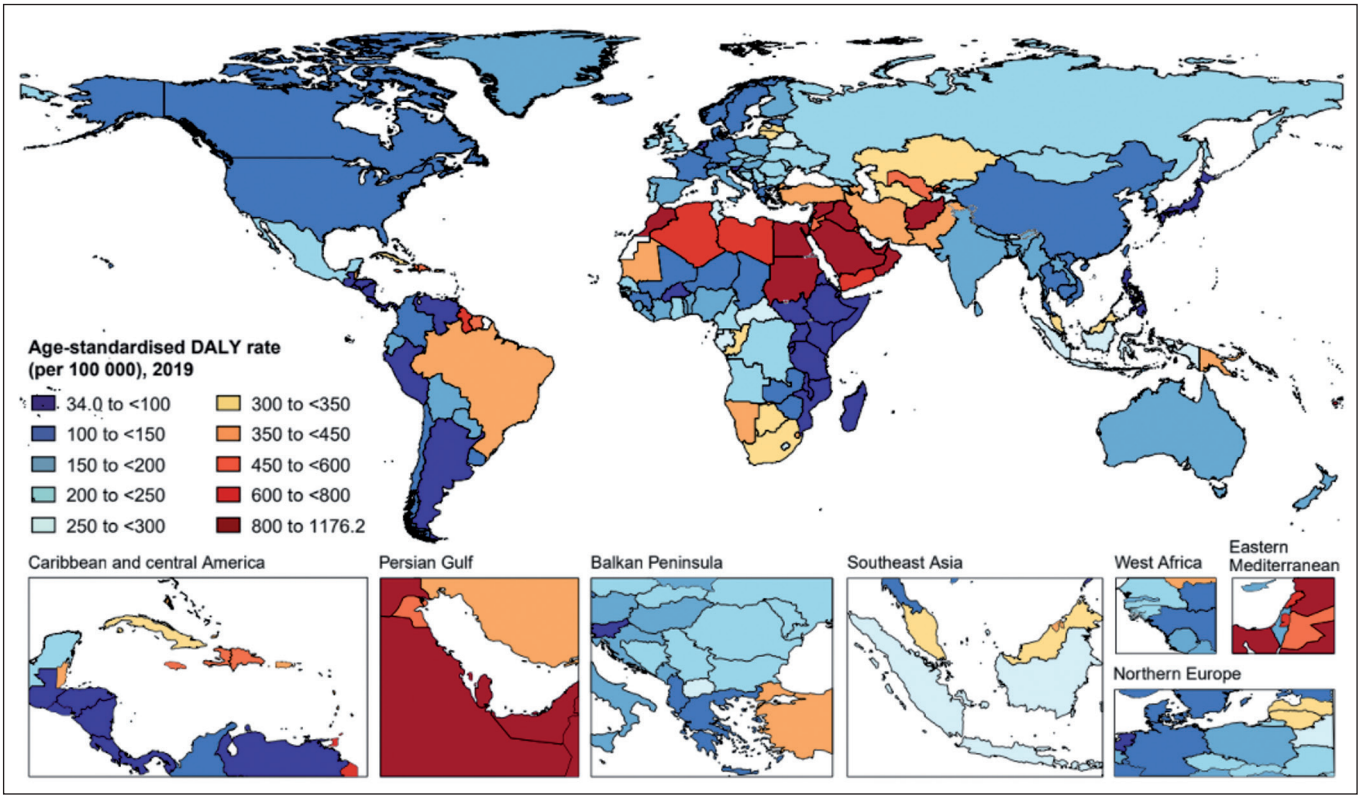


FIG. 1. Map of age-standardized DALY rate attributable to low physical activity for both sexes combined in 2019. DALY = disability-adjusted life year.

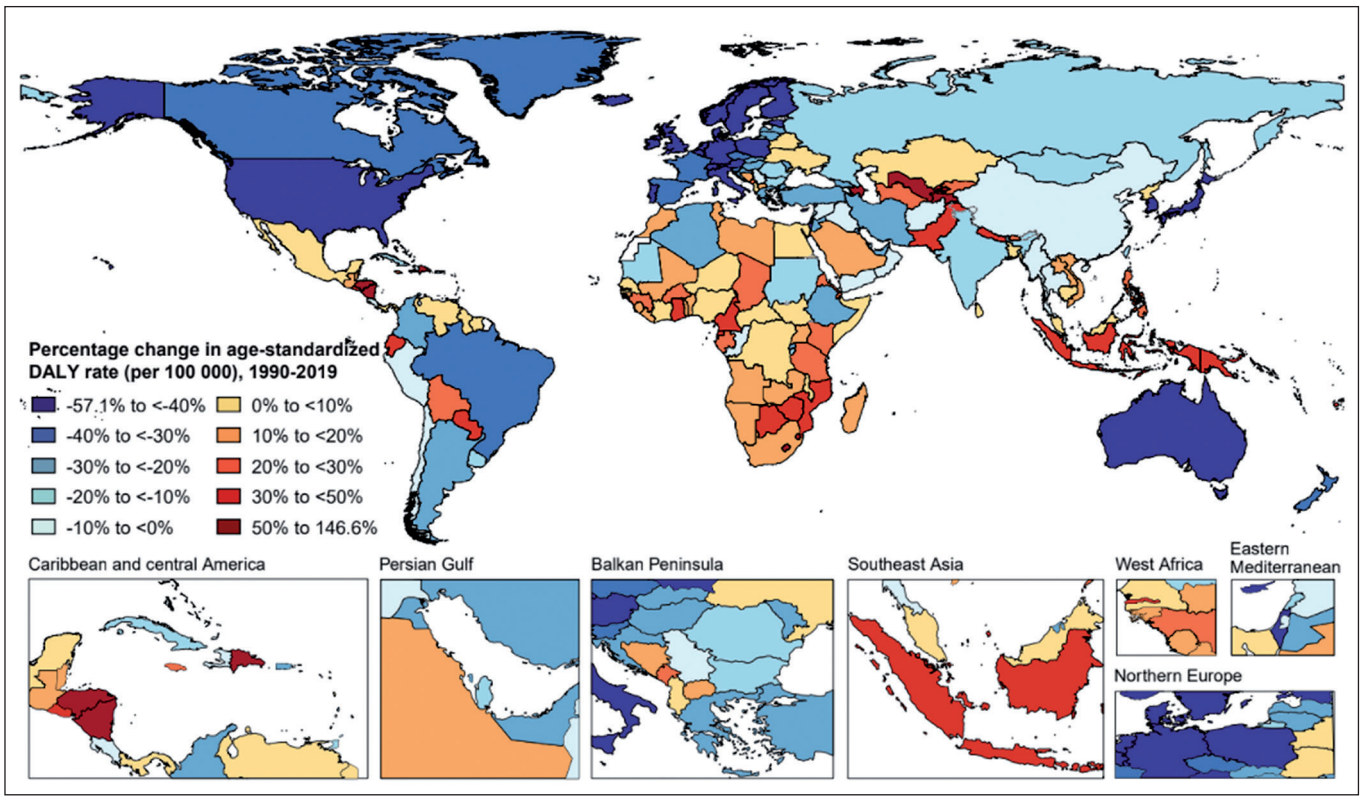


FIG. 2. Map of percentage change in age-standardized DALY rate attributable to low physical activity for both sexes combined, 1990–2019. DALY = disability-adjusted life year.

UI 0.7 to 10.4) for ischemic stroke, 4.3% (95% UI 1.1 to 8.3) for colon and rectum cancer, and 1.0% (95% UI 0.5 to 1.7) for breast cancer (Table 1).

The distribution of diseases that contributed to low-PA-related DALYs varied by GBD region (Fig. 3). Ischemic heart disease was the largest contributor to low-PA-related DALYs in most regions, particularly Central Asia, Eastern Europe, and North Africa and Middle East (Fig. 3). Type 2 diabetes mellitus accounted for the largest proportion of low-PA-related DALYs in Oceania, Latin America, Caribbean, Central and Southern Sub-Saharan Africa (Fig. 3). Moreover, colon and rectum cancer accounted for a relative higher proportion of low-PA-related DALYs in high-income Asia Pacific, Australasia, and Western Europe than in other GBD regions (Fig. 3).

Association between SDI and proportions of overall burden attributable to low PA

Of all age-standardized DALYs globally in 2019, 0.6% (95% UI 0.3 to 1.1) was attributable to low PA (Table 1). By SDI quintile, only countries in the high-SDI quintile had decreased proportions of age-standardized DALYs attributable to low PA during 1990–2019, while countries in other SDI quintiles had increased proportions in the same timeframe (Table S1). Fig. 4 depicts the changes in the attributable proportions across the 21 GBD regions by SDI from 1990 to 2019. Similarly, only the 4 regions with the highest SDI had decreased proportions of age-standardized DALYs attributable to low PA during 1990–2019, while other regions tended to have increased proportions (Fig. 4). Fig. 5 shows the association between SDI and the proportions of age-standardized DALYs attributable to low PA across 204 countries and territories in 2019. Across all countries and territories, as SDI increases, the proportions of age-standardized DALYs attributable to low PA tended to increase until SDI is about 0.77, but then decreases with higher SDI. Qatar, Bahrain, Saudi Arabia, and many other countries had much higher proportions of age-standardized DALYs attributable to low PA than expected based solely on SDI.

DISCUSSION

Strong evidence reveals that insufficient PA presents a major global public health issue. This study aimed to provide a comprehensive estimation of the worldwide epidemiology of low-PA-generated (less than 3000-4500 MET minutes per week) disease burden. The present findings suggest that since 1990, the contribution of low PA to deaths and DALYs have increased by 83.9% and 82.9%, respectively, reaching an alarming level of 0.83 million for deaths and 15.75 million for DALYs in 2019.

These findings confirm previous reports implicating low PA as a major risk factor for decreased life expectancy [4, 5] and the development of many adverse health conditions, including cardiovascular

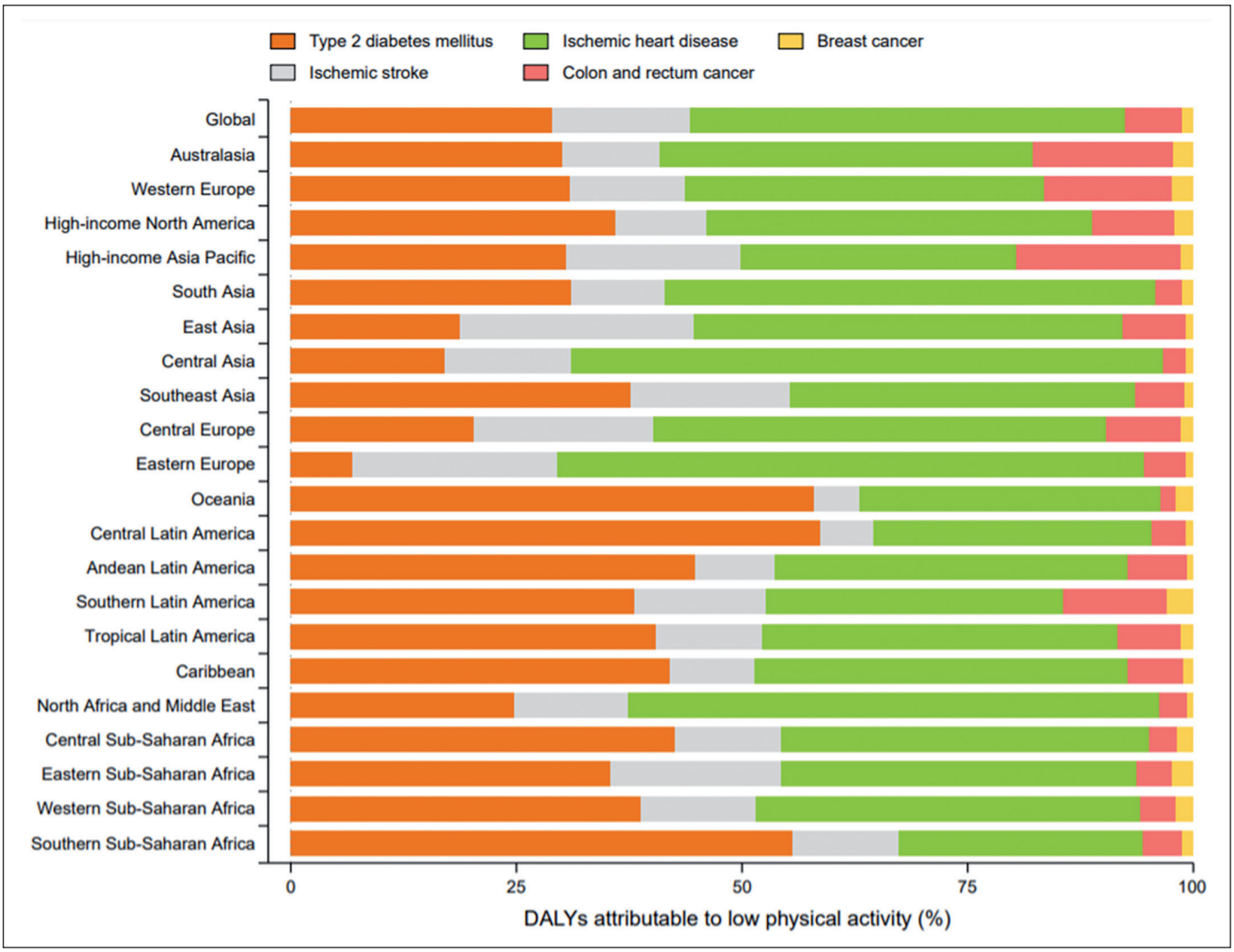


FIG. 3. Regional variation in DALYs attributable to low physical activity in 2019, by cause. DALYs = disability-adjusted life years.

disease (CVD) [17, 18], cancer [19], and diabetes [20]. Inversely, the beneficial impact of PA has been also confirmed with regard to the aforementioned diseases [21]. By improving major CVD risk factors (e.g., cardiorespiratory fitness) and other health outcomes, large studies have shown weekly aerobic activity of 150 min at moderate intensity can decrease CVD incidence (17%) and mortality (23%), along with reduced risk of developing ischemic heart disease (25%) [22]. A recent meta-analysis including a total of 68,416 breast cancer cases concluded being physically active reduces the risk of developing breast cancer by nearly 13% [23]. Similarly, previous large-scale follow-up observational studies reported an 18% to 33% lower risk of developing diabetes in physically active people [24, 25], with average a 6% lower risk of diabetes for each 500 kcal/week energy expenditure [26].

The exact mechanisms responsible for the reduced risk of mortality and developing diseases through an active lifestyle considered to be complex and multifactorial [27]. However, it is well established that compared to sedentary lifestyle, regular PA produces a kaleidoscope of beneficial biological impacts on pathways targeting specific endocrinologic, immunologic and metabolic processes [28]. Specifically, enhanced cardiac function, higher heart rate variability, healthier blood vessels, lower amounts of visceral fat, lower blood pressure, better lipid profiles (LDL and HDL subfractions), lower markers of systemic inflammation, and improved antioxidant, immunological and endocrinological systems have been previously reported in physically active populations [27].

Current public health goals focus on reducing disease burden by extending "healthspan", and providing extra years spent free of chronic conditions. The highest 2019 age-standardized rates of low-PA-related DALYs (per 100,000 people) seen in North Africa and Middle East (≈ 672), Oceania (≈ 512), Tropical Latin America and Caribbean (≈ 440), central Asia (≈ 317), and Southern Sub-Saharan Africa (≈300), as well as, alarming increases (1990-2019) in low-PA-related DALYs seen in most of Oceania (33.1%), central Asia (30.7%), Southern (25.7%) and Western (10.6%) Sub-Saharan Africa, and Southeast Asia (21%) countries indicates an urgent need for the

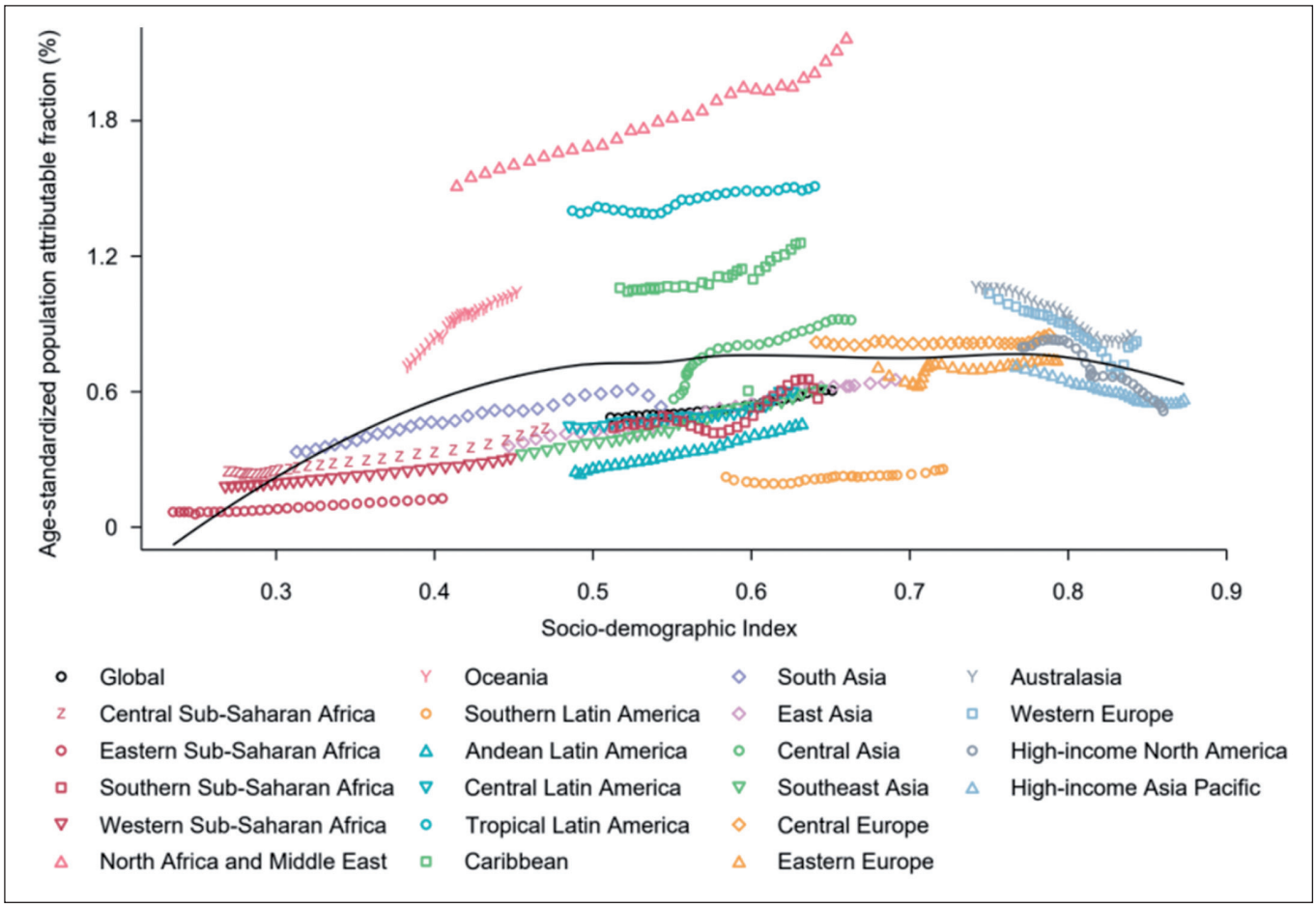


FIG. 4. Fraction of age-standardized DALYs from all causes attributable to low physical activity across 21 GBD regions by Socio-demographic Index for both sexes combined, 1990–2019. For each region, points from left to right depict estimates from each year from 1990 to 2019. DALYs = disability-adjusted life years; GBD = Global Burden of Disease, Injuries, and Risk Factors Study.

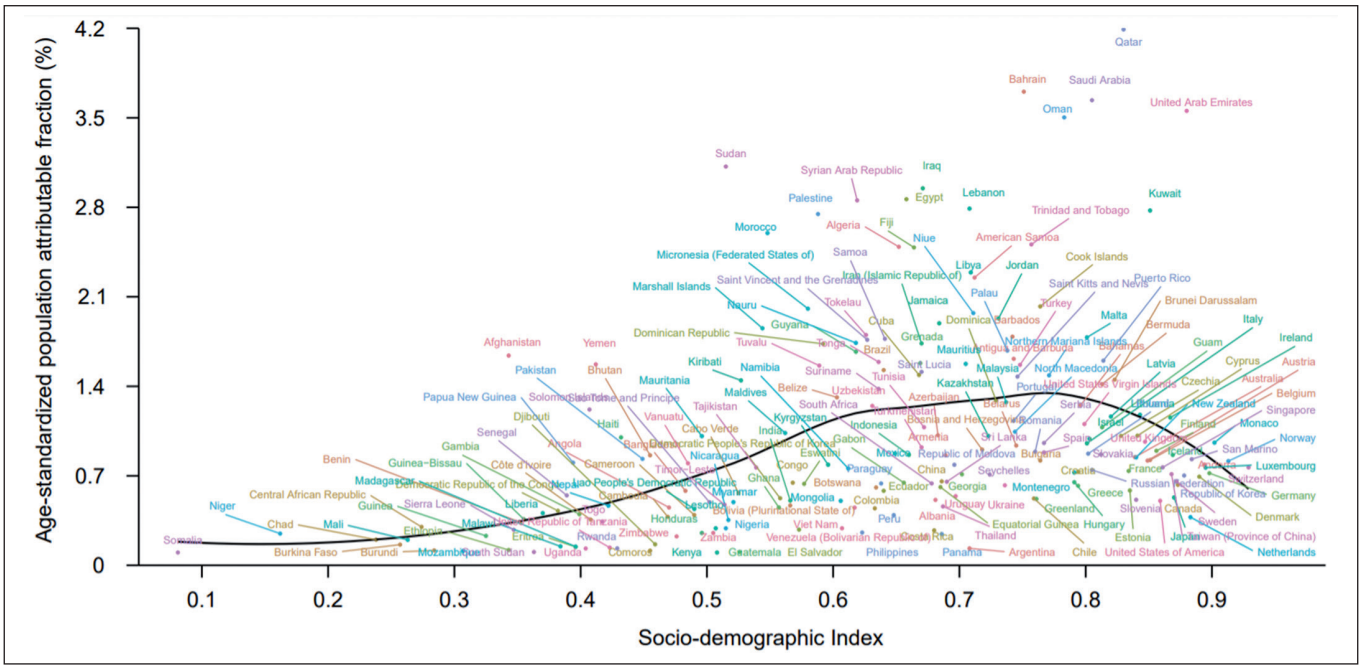


FIG. 5. Fraction of age-standardized DALYs from all causes attributable to low physical activity across 204 countries and territories by Socio-demographic Index for both sexes combined in 2019. DALYs = disability-adjusted life years.

development, implementation and fostering of an anti-low PA action plan in these regions. Previous reports estimate that decreasing inactivity by just 10% could prevent more than 533,000 deaths/year; this number is projected rise to over 1.3 million through a 25% reduction [6]. Therefore, disseminating appropriate PA recommendations especially in population subgroups that are most vulnerable to low-PA-related disease risk, becomes crucial.

Regarding the impact of age, the rates of low-PA-related deaths and DALYs tended to rise with increasing age in both sexes. This progressive higher impact of an inactive lifestyle on older aged adults can be explained by the gradual decline of physically active lifestyles and the gradual increase in the disease vulnerability [29]. Recent reports identify young- and middle-aged individuals as the most attractive targets for interventions to reduce the onset of noncommunicable diseases and extend healthspan [30, 31]. Therefore, to prevent DALYs in older populations, it may be advantageous to foster adherence to an active lifestyle in early age, when organs are not yet damaged.

The development status of regions and countries is one of the important factors of low-PA-generated disease burden. At the regional level, regions with the highest SDI largely decreased their proportions of age standardized DALYs attributable to low PA during 1990-2019, while other regions tended to have increased proportions in the same timeframe. This phenomenon suggests different transitions in PA and related disease spectrum across regions with various development status over the last decades. At the national level, a positive association was inversed from an SDI of about 0.77, where the age-standardized population attributable fraction (%) was highest and started to decrease. Therefore, it is recommended that a global anti-low PA action plan could be initially implemented in regions with an SDI of around 0.77.

While the results of our investigation provided a comprehensive estimation of the global disease burden attributable to low PA, it is important to point out certain limitations. First, PA data were mostly based on self-reported assessment methods (e.g., IPAQ, GPAQ questionnaires) known to be subject to certain biases [32]. However, given that PA data collected using objective methods (i.e., accelerometry) are mostly only available for high-income countries, utilizing these types of tools could make cross-country comparisons difficult. For more comparable results, a larger scale of PA data collected using objective methods could be warranted. Second, our analysis included only adult populations (aged ≥25 years) and it is well documented that PA levels can differ between different age groups [32, 33]. PA data in individuals younger than 25 years are needed to develop a more comprehensive understanding of low PA's overall impact on the global burden of disease. Third, PA data were not available for all countries and years. However, statistically robust and sound approaches have been applied in GBD 2019 in order to overcome data scarcity in some countries and deal with uncertainty.

CONCLUSIONS

Low PA is a an important risk factor of the considerable disease burden across the globe and seems to contribute to 0.6% of all age standardized DALYs globally in 2019. The extent of disease burden attributable to low PA varies substantially by age and across countries and is strongly associated with development status. Therefore, effective and targeted initiatives to promote PA within different age groups and countries are urgently needed. Importantly, taking into-consideration the contribution of multiple risk factors to disease burden, strategies to reduce global disease burden should not be only limited to promoting PA, but should also consider other risk factors identified in previous GBD studies [7, 11].

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Competing interests

The authors declare that they have no competing interests.

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SUPPLEMENTARY MATERIALS

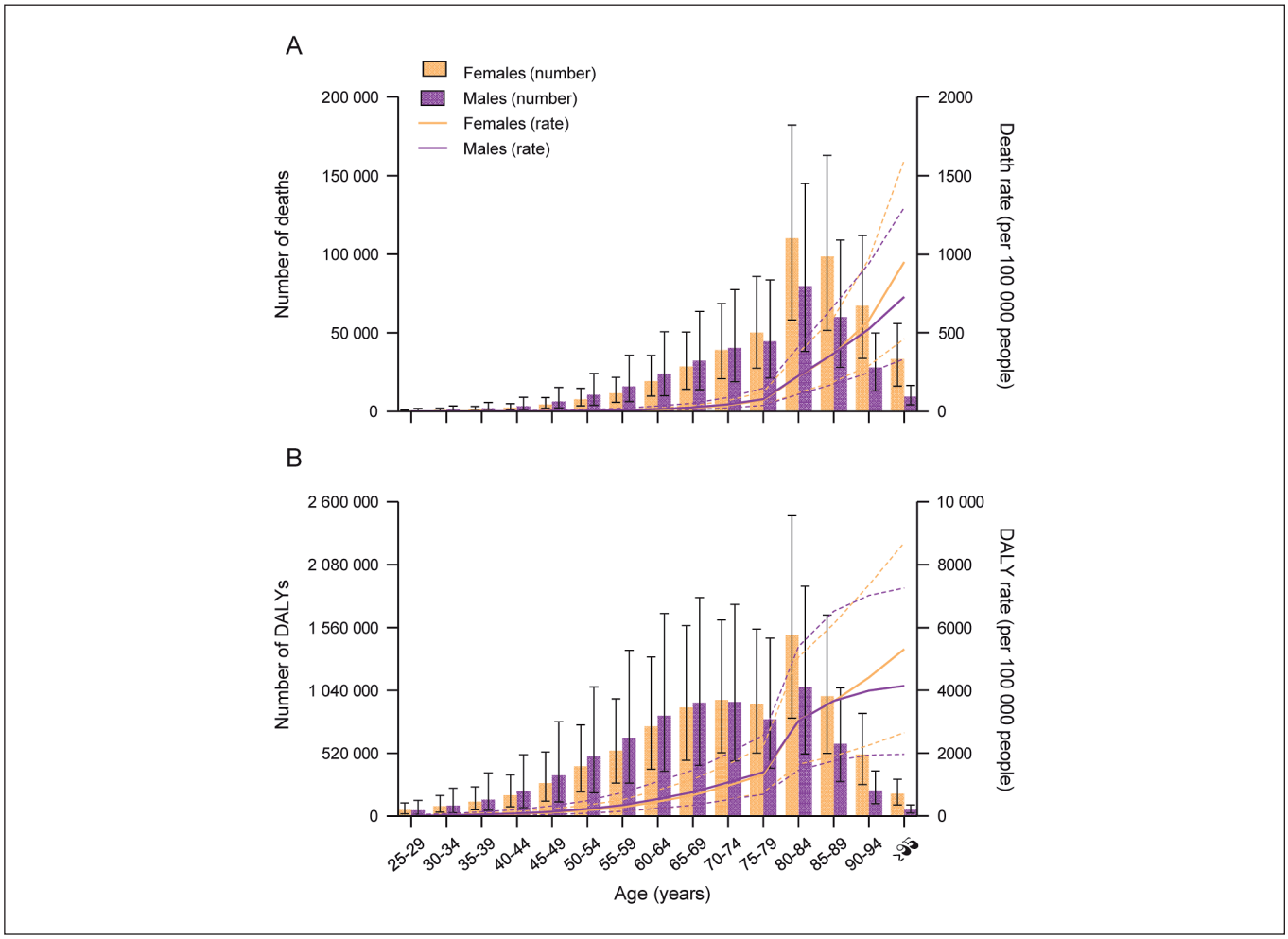


FIG. S1. Age-specific numbers and rates of deaths and DALYs attributable to low physical activity by sex, in 2019. (A) Deaths. (B) DALYs. Error bars indicate the 95% uncertainty interval. DALYs, disability-adjusted life years.

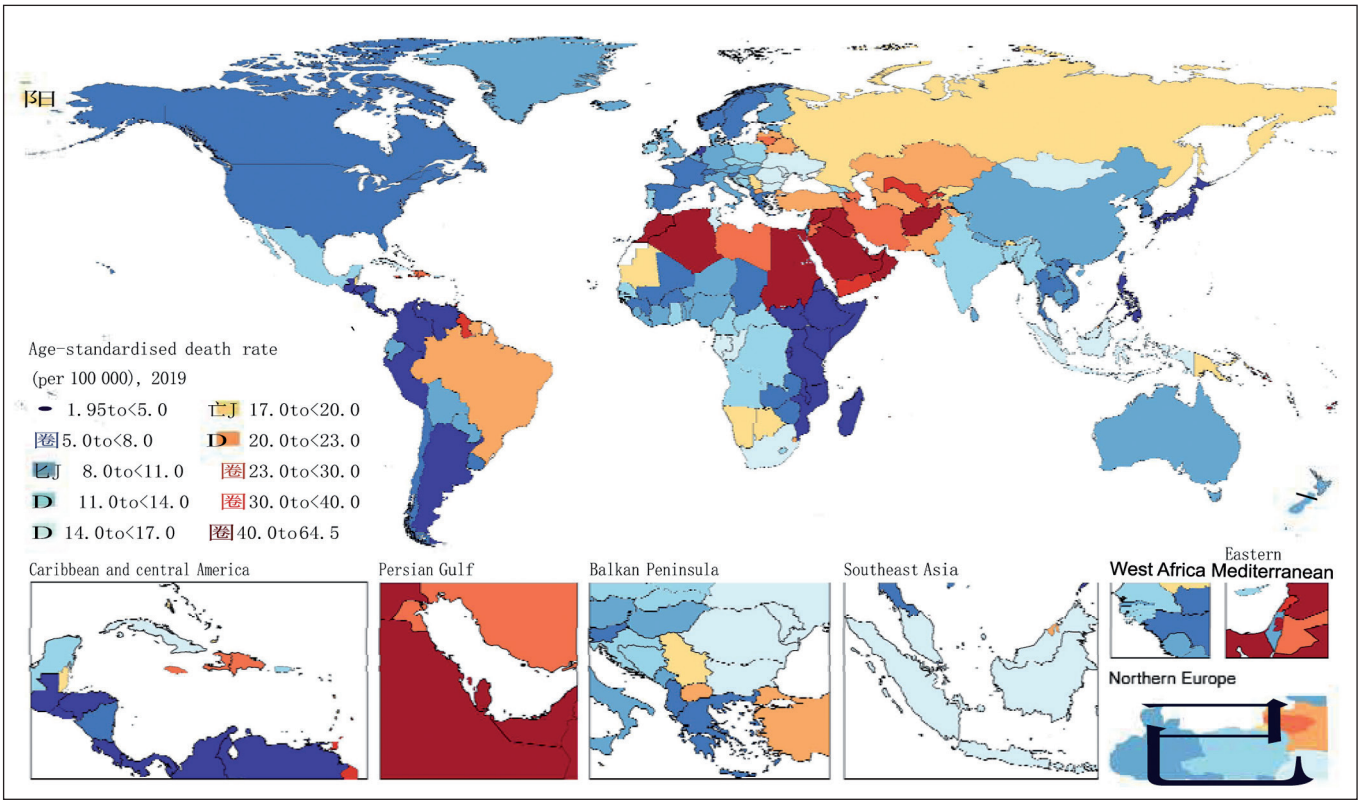


FIG. S2. Map of age-standardized death rate attributable to low physical activity for both sexes combined in 2019.

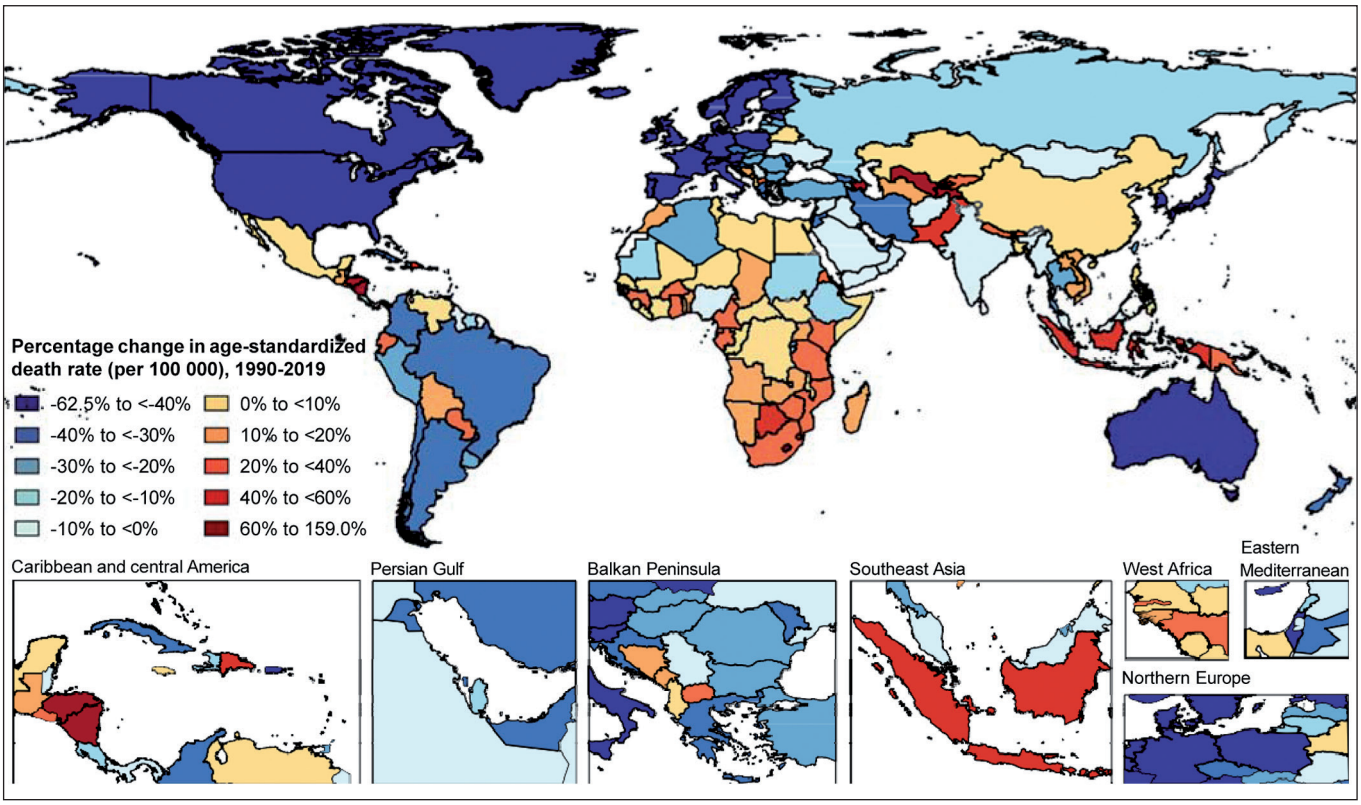


FIG. S3. Map of percentage change in age-standardized death rate attributable to low physical activity for both sexes combined, 1990–2019.

TABLE S1. Age-standardised Deaths and DALYs attributable to low physical activity for both sexes combined in 2019 and percentage change from 1990 to 2019, by SDI quintile and location.

1	2	3	4	5	6	7	8	9
	Deaths				DALYs			
	2019 age-standardised rates per 100 000 people	Percentage change in age- standardised rates, 1990–2019	2019 age-standardised PAF	Percentage change in age- standardised PAF, 1990–2019	2019 age-standardised rates per 100 000 people	Percentage change in age- standardised rates, 1990–2019	2019 age-standardised PAF	Percentage change in age- standardised PAF, 1990–2019
Global	11.1 (5.7 to 19.5)	-25.9% (-30.9 to -17.0)	1.51% (0.78 to 2.63)	12.2% (5.4 to 25.0)	198.4 (108.2 to 360.3)	-18.3% (-25.2 to -5.5)	0.60% (0.33 to 1.08)	24.5% (14.0 to 44.0)
SDI quintile								
Low-SDI quintile	10.1 (5.3 to 18.8)	-2.5% (-12.1 to 9.0)	0.88% (0.46 to 1.59)	54.0% (38.2 to 71.4)	186.9 (96.3 to 352.2)	-1.6% (-11.2 to 10.1)	0.38% (0.20 to 0.70)	68.0% (49.9 to 89.8)
Low-middle-SDI quintile	12.9 (7.0 to 22.5)	0.8% (-8.0 to 11.4)	1.36% (0.75 to 2.39)	56.4% (44.2 to 73.5)	227.5 (126.3 to 413.9)	1.0% (-8.7 to 12.0)	0.58% (0.32 to 1.02)	66.5% (51.9 to 86.9)
Middle-SDI quintile	13.1 (6.7 to 23.5)	0.4% (-9.1 to 10.6)	1.78% (0.92 to 3.14)	51.0% (38.6 to 65.4)	226.4 (118.8 to 412.4)	1.4% (-8.2 to 13.3)	0.79% (0.41 to 1.46)	57.8% (44.3 to 74.2)
High-middle-SDI quintile	12.7 (6.6 to 21.9)	-27.7% (-33.4 to -19.9)	2.09% (1.09 to 3.67)	14.2% (6.2 to 25.9)	205.7 (113.5 to 369.8)	-24.5% (-31.0 to -13.6)	0.86% (0.47 to 1.53)	15.6% (7.0 to 31.0)
High-SDI quintile	7.1 (3.6 to 12.3)	-52.0% (-56.7 to -42.6)	1.59% (0.82 to 2.76)	-27.3% (-34.5 to -13.0)	149.0 (82.3 to 265.1)	-37.2% (-46.6 to -17.8)	0.70% (0.39 to 1.23)	-19.7% (-31.1 to 4.6)
Central Sub-Saharan Africa	11.7 (5.8 to 22.1)	4.1% (-14.4 to 26.8)	0.93% (0.47 to 1.74)	55.9% (36.7 to 74.9)	224.3 (110.4 to 447.2)	4.0% (-13.1 to 25.8)	0.44% (0.22 to 0.83)	76.2% (55.2 to 99.5)
Angola	11.6 (5.8 to 22.7)	17.6% (-10.4 to 57.8)	0.97% (0.48 to 1.82)	103.5% (62.8 to 155.7)	222.3 (110.3 to 430.6)	12.4% (-12.3 to 47.5)	0.45% (0.23 to 0.85)	124.3% (84.4 to 174.4)
Central African Republic	13.2 (6.3 to 26.0)	6.9% (-16.2 to 36.9)	0.63% (0.31 to 1.18)	20.4% (6.3 to 37.9)	264.8 (127.0 to 529.6)	6.8% (-15.7 to 35.0)	0.30% (0.14 to 0.57)	27.6% (11.9 to 46.0)
Congo	16.2 (8.2 to 29.6)	1.5% (-19.1 to 28.7)	1.29% (0.67 to 2.38)	62.0% (41.1 to 93.2)	311.2 (158.4 to 595.4)	-1.0% (-21.1 to 25.1)	0.65% (0.33 to 1.20)	69.6% (46.4 to 100.0)
Democratic Republic of the Congo	11.1 (5.4 to 21.1)	0.3% (-20.2 to 25.1)	0.91% (0.45 to 1.71)	46.7% (27.4 to 67.4)	213.6 (102.3 to 419.4)	1.6% (-17.9 to 25.8)	0.43% (0.21 to 0.79)	69.1% (46.0 to 95.4)
Equatorial Guinea	15.4 (8.0 to 27.0)	39.6% (-3.4 to 113.4)	1.33% (0.71 to 2.25)	154.0% (72.7 to 269.3)	289.0 (153.2 to 517.9)	30.7% (-8.0 to 93.6)	0.61% (0.33 to 1.05)	160.5% (82.5 to 263.0)
Gabon	15.0 (7.9 to 26.5)	21.6% (-1.2 to 50.7)	1.35% (0.70 to 2.34)	65.4% (42.0 to 97.9)	276.3 (141.9 to 511.1)	21.4% (-1.9 to 50.6)	0.65% (0.33 to 1.17)	76.9% (50.1 to 111.5)
Eastern Sub-Saharan Africa	3.4 (1.6 to 7.0)	4.2% (-14.9 to 22.7)	0.29% (0.14 to 0.60)	76.4% (44.2 to 104.8)	61.3 (27.9 to 132.7)	-0.1% (-16.3 to 15.2)	0.13% (0.06 to 0.27)	89.3% (57.9 to 118.6)
Burundi	3.4 (1.5 to 7.7)	-10.4% (-33.1 to 16.7)	0.27% (0.11 to 0.60)	56.8% (27.0 to 95.3)	61.5 (27.2 to 146.8)	-13.9% (-34.8 to 10.8)	0.12% (0.05 to 0.27)	63.6% (33.1 to 101.4)
Comoros	2.7 (1.1 to 6.6)	3.6% (-18.8 to 41.5)	0.27% (0.11 to 0.67)	60.8% (29.9 to 106.6)	46.9 (20.4 to 114.4)	1.2% (-19.4 to 47.6)	0.11% (0.05 to 0.28)	69.4% (38.2 to 144.4)
Djibouti	4.2 (1.8 to 9.1)	30.4% (1.8 to 68.1)	0.38% (0.17 to 0.80)	63.0% (33.2 to 107.4)	73.4 (32.4 to 163.8)	28.7% (2.5 to 65.9)	0.16% (0.07 to 0.35)	74.8% (45.1 to 114.3)
Eritrea	4.2 (1.8 to 9.1)	34.7% (-4.7 to 91.8)	0.31% (0.14 to 0.64)	145.9% (80.5 to 240.8)	75.0 (32.8 to 166.1)	22.8% (-7.7 to 64.8)	0.14% (0.07 to 0.32)	172.7% (110.2 to 256.2)
Ethiopia	2.8 (1.2 to 5.9)	-16.4% (-44.4 to 14.0)	0.28% (0.12 to 0.59)	100.5% (34.3 to 164.5)	49.0 (21.8 to 106.3)	-28.7% (-49.4 to -4.2)	0.12% (0.05 to 0.26)	86.6% (33.3 to 146.6)
Kenya	2.5 (1.1 to 5.7)	23.5% (5.7 to 47.7)	0.22% (0.10 to 0.49)	41.6% (22.9 to 64.9)	45.0 (19.9 to 100.5)	26.3% (9.2 to 45.6)	0.10% (0.04 to 0.22)	62.2% (41.3 to 85.7)
Madagascar	4.0 (1.6 to 9.2)	11.5% (-14.5 to 43.5)	0.33% (0.14 to 0.75)	51.6% (27.9 to 77.8)	70.0 (29.9 to 169.4)	11.0% (-12.7 to 39.9)	0.15% (0.06 to 0.35)	77.0% (51.0 to 106.0)
Malawi	4.1 (1.8 to 8.4)	6.1% (-15.2 to 33.9)	0.34% (0.16 to 0.69)	77.4% (44.9 to 119.8)	74.1 (33.8 to 153.8)	4.1% (-15.4 to 29.2)	0.15% (0.07 to 0.30)	104.1% (67.5 to 152.2)
Mozambique	4.1 (1.8 to 9.1)	34.1% (2.1 to 75.2)	0.26% (0.11 to 0.57)	59.5% (29.0 to 93.6)	75.6 (33.0 to 171.9)	37.0% (8.9 to 74.0)	0.11% (0.05 to 0.25)	90.4% (57.8 to 130.3)

TABLE S1. Continue.

1	2	3	4	5	6	7	8	9
Rwanda	3.2 (1.4 to 6.8)	-13.6% (-35.3 to 12.3)	0.32% (0.14 to 0.66)	84.9% (39.6 to 133.8)	54.7 (24.7 to 112.5)	-20.2% (-38.9 to 1.3)	0.13% (0.06 to 0.28)	85.4% (41.8 to 131.6)
Somalia	3.6 (1.6 to 8.4)	6.8% (-18.3 to 37.1)	0.22% (0.10 to 0.50)	48.4% (19.9 to 83.8)	67.1 (28.4 to 160.0)	4.1% (-19.5 to 34.0)	0.10% (0.04 to 0.24)	61.0% (31.9 to 93.0)
South Sudan	3.2 (1.4 to 7.0)	3.2% (-20.1 to 34.0)	0.27% (0.12 to 0.57)	43.2% (16.8 to 74.5)	58.0 (25.6 to 126.6)	4.8% (-18.0 to 34.1)	0.10% (0.05 to 0.22)	55.3% (26.8 to 91.8)
United Republic of Tanzania	3.6 (1.6 to 7.9)	22.9% (-1.7 to 51.2)	0.34% (0.15 to 0.74)	92.0% (56.0 to 134.4)	62.3 (27.6 to 135.1)	23.2% (0.7 to 48.7)	0.14% (0.06 to 0.30)	117.7% (81.2 to 158.6)
Uganda	3.4 (1.5 to 7.0)	14.7% (-7.5 to 45.1)	0.30% (0.14 to 0.62)	118.5% (77.9 to 172.4)	62.0 (28.3 to 129.2)	16.7% (-4.4 to 45.0)	0.13% (0.06 to 0.27)	154.9% (112.6 to 212.1)
Zambia	7.3 (3.4 to 14.5)	16.8% (-9.9 to 51.5)	0.55% (0.26 to 1.05)	72.1% (39.8 to 115.1)	136.5 (64.7 to 273.8)	14.0% (-11.3 to 44.7)	0.25% (0.12 to 0.50)	90.9% (55.3 to 138.3)
Southern Sub-Saharan Africa	15.8 (8.7 to 26.1)	35.3% (22.1 to 51.0)	1.30% (0.70 to 2.10)	28.6% (16.1 to 43.1)	300.3 (161.1 to 516.9)	25.7% (13.2 to 40.7)	0.57% (0.30 to 0.97)	29.4% (15.4 to 45.5)
Botswana	17.9 (9.0 to 32.9)	43.4% (9.4 to 94.9)	1.27% (0.66 to 2.33)	48.6% (24.2 to 80.0)	341.7 (170.9 to 653.7)	48.6% (12.7 to 99.6)	0.61% (0.31 to 1.13)	54.5% (26.9 to 90.8)
Lesotho	13.8 (6.6 to 25.8)	100.9% (52.5 to 168.3)	0.62% (0.30 to 1.12)	28.7% (6.5 to 57.8)	263.3 (123.2 to 513.5)	104.8% (55.6 to 172.2)	0.29% (0.13 to 0.56)	38.1% (13.5 to 69.5)
Namibia	18.7 (10.1 to 32.6)	13.0% (-8.3 to 38.8)	1.53% (0.83 to 2.62)	29.6% (12.9 to 51.7)	366.8 (199.6 to 655.5)	12.7% (-8.6 to 41.9)	0.76% (0.41 to 1.31)	30.4% (14.7 to 54.4)
South Africa	16.7 (9.3 to 26.5)	31.7% (18.4 to 47.5)	1.47% (0.80 to 2.35)	27.3% (14.8 to 42.2)	319.7 (173.2 to 540.5)	19.5% (6.4 to 35.3)	0.64% (0.34 to 1.08)	28.4% (13.2 to 46.6)
Eswatini	21.9 (11.2 to 39.7)	55.2% (15.7 to 106.0)	1.30% (0.68 to 2.24)	32.1% (11.8 to 57.3)	433.1 (216.4 to 799.8)	60.4% (21.8 to 114.2)	0.64% (0.32 to 1.15)	35.4% (13.3 to 61.4)
Zimbabwe	7.2 (3.2 to 15.2)	36.6% (7.0 to 74.3)	0.48% (0.22 to 1.01)	22.3% (2.0 to 52.4)	133.5 (60.8 to 277.4)	45.4% (16.9 to 79.9)	0.23% (0.10 to 0.46)	37.1% (13.8 to 72.5)
Western Sub-Saharan Africa	9.2 (4.5 to 17.5)	8.1% (-9.5 to 26.9)	0.77% (0.38 to 1.45)	51.3% (26.8 to 73.5)	165.0 (79.6 to 311.3)	10.6% (-8.1 to 30.3)	0.31% (0.15 to 0.57)	69.7% (42.3 to 97.9)
Benin	9.2 (4.4 to 18.5)	13.9% (-5.4 to 41.0)	0.78% (0.37 to 1.52)	55.2% (32.1 to 87.5)	172.5 (81.8 to 342.8)	19.4% (-3.5 to 48.8)	0.34% (0.16 to 0.64)	78.2% (49.0 to 117.8)
Burkina Faso	5.2 (2.4 to 11.2)	27.5% (5.8 to 56.6)	0.40% (0.18 to 0.83)	82.9% (53.5 to 125.4)	95.0 (43.0 to 204.5)	28.8% (6.8 to 59.7)	0.16% (0.07 to 0.34)	104.9% (70.1 to 149.6)
Cameroon	11.3 (5.7 to 21.5)	31.1% (6.2 to 65.5)	0.89% (0.44 to 1.67)	56.1% (33.1 to 88.2)	210.7 (103.5 to 402.0)	39.1% (11.0 to 75.8)	0.39% (0.19 to 0.74)	78.8% (50.7 to 115.6)
Cabo Verde	9.7 (4.8 to 19.4)	70.1% (37.0 to 136.6)	1.21% (0.59 to 2.41)	78.3% (44.3 to 149.5)	169.2 (81.9 to 325.4)	71.1% (38.9 to 125.3)	0.57% (0.27 to 1.10)	130.3% (86.7 to 201.7)
Chad	6.7 (3.0 to 14.0)	16.6% (-3.2 to 44.4)	0.48% (0.22 to 1.00)	44.7% (24.4 to 72.3)	125.0 (57.2 to 259.7)	21.8% (0.6 to 51.0)	0.20% (0.09 to 0.42)	65.8% (39.9 to 98.6)
Cote d'Ivoire	9.9 (4.7 to 19.5)	2.2% (-14.7 to 28.1)	0.81% (0.38 to 1.58)	40.5% (20.4 to 71.9)	184.9 (87.3 to 365.7)	7.0% (-13.4 to 35.9)	0.36% (0.17 to 0.71)	59.0% (33.9 to 99.7)
Gambia	10.2 (4.7 to 20.3)	32.4% (5.9 to 70.9)	0.87% (0.41 to 1.69)	61.5% (36.7 to 97.6)	179.7 (81.0 to 366.4)	36.3% (8.1 to 76.1)	0.40% (0.18 to 0.82)	91.6% (56.3 to 138.2)
Ghana	11.5 (5.7 to 22.1)	34.6% (9.7 to 69.1)	1.01% (0.49 to 1.92)	75.1% (50.1 to 108.6)	208.0 (102.1 to 392.9)	39.2% (11.7 to 77.4)	0.45% (0.22 to 0.85)	98.4% (65.6 to 143.0)
Guinea	7.5 (3.5 to 15.5)	24.0% (-1.3 to 56.5)	0.55% (0.26 to 1.09)	60.2% (36.6 to 91.6)	136.1 (63.0 to 281.8)	28.2% (2.7 to 61.6)	0.23% (0.11 to 0.46)	91.9% (64.6 to 128.0)
Guinea-Bissau	11.3 (5.2 to 23.0)	15.0% (-9.7 to 48.5)	0.76% (0.36 to 1.49)	70.6% (42.2 to 108.8)	214.1 (97.6 to 437.9)	13.5% (-10.1 to 47.4)	0.36% (0.17 to 0.72)	92.3% (61.5 to 132.8)
Liberia	10.4 (4.9 to 20.5)	4.8% (-15.9 to 39.0)	0.92% (0.45 to 1.77)	91.4% (63.7 to 131.4)	197.8 (94.6 to 375.0)	10.6% (-10.9 to 43.6)	0.41% (0.19 to 0.79)	151.6% (105.7 to 214.3)
Mali	6.8 (3.1 to 13.7)	7.2% (-12.5 to 31.8)	0.53% (0.24 to 1.07)	62.5% (33.5 to 97.0)	117.4 (53.4 to 237.6)	10.4% (-9.8 to 37.0)	0.20% (0.09 to 0.39)	82.8% (52.7 to 120.8)
Mauritania	19.8 (11.3 to 31.1)	-16.4% (-30.8 to 2.2)	2.20% (1.26 to 3.44)	41.9% (20.0 to 68.3)	368.9 (210.8 to 593.0)	-18.6% (-34.3 to 1.9)	1.01% (0.58 to 1.58)	44.1% (20.5 to 73.5)

TABLE S1. Continue.

1	2	3	4	5	6	7	8	9
Niger	8.0 (3.7 to 16.7)	3.8% (-16.3 to 30.4)	0.64% (0.29 to 1.27)	66.6% (36.5 to 105.4)	140.2 (64.0 to 286.1)	6.4% (-13.4 to 33.0)	0.25% (0.11 to 0.49)	99.8% (66.3 to 147.8)
Nigeria	8.8 (4.3 to 16.9)	-0.3% (-25.2 to 27.0)	0.77% (0.38 to 1.47)	44.0% (11.3 to 70.5)	154.1 (72.9 to 296.6)	0.3% (-23.9 to 28.1)	0.29% (0.14 to 0.56)	57.0% (23.5 to 92.1)
Sao Tome and Principe	9.9 (4.5 to 20.0)	41.0% (16.7 to 71.5)	1.00% (0.45 to 1.97)	76.3% (47.9 to 114.8)	172.7 (81.4 to 344.9)	43.2% (18.9 to 73.0)	0.49% (0.23 to 0.98)	121.2% (86.8 to 167.2)
Senegal	11.5 (5.8 to 21.5)	4.9% (-11.6 to 30.0)	1.13% (0.57 to 2.15)	54.4% (30.9 to 87.9)	227.9 (114.1 to 433.5)	8.0% (-11.6 to 35.5)	0.55% (0.27 to 1.01)	76.8% (45.8 to 119.3)
Sierra Leone	9.3 (4.2 to 19.1)	9.2% (-10.9 to 41.8)	0.71% (0.33 to 1.43)	54.7% (32.2 to 89.0)	163.2 (74.2 to 328.8)	13.6% (-8.7 to 48.6)	0.28% (0.13 to 0.55)	82.5% (52.7 to 125.9)
Togo	9.5 (4.4 to 19.3)	10.1% (-8.3 to 37.8)	0.80% (0.38 to 1.55)	41.1% (23.0 to 67.3)	169.0 (75.9 to 346.9)	14.0% (-5.5 to 43.6)	0.34% (0.16 to 0.68)	60.3% (38.4 to 93.4)
Andean Latin America	6.1 (2.7 to 12.0)	-2.5% (-22.5 to 38.6)	1.05% (0.49 to 2.00)	56.8% (29.6 to 114.0)	116.0 (53.7 to 223.2)	8.9% (-15.0 to 53.0)	0.45% (0.21 to 0.84)	86.5% (50.0 to 153.0)
Bolivia (Plurinational State of)	9.0 (3.9 to 18.8)	19.7% (-8.9 to 65.9)	1.00% (0.44 to 1.97)	77.7% (44.3 to 132.9)	157.5 (68.8 to 314.7)	20.3% (-8.9 to 65.5)	0.47% (0.21 to 0.91)	112.1% (69.2 to 179.1)
Ecuador	8.4 (3.9 to 15.9)	25.6% (-1.5 to 77.7)	1.28% (0.61 to 2.48)	53.8% (28.9 to 108.9)	155.5 (73.1 to 295.4)	34.2% (4.9 to 83.0)	0.58% (0.27 to 1.07)	79.3% (46.8 to 137.2)
Peru	4.5 (2.0 to 8.9)	-20.5% (-42.5 to 18.0)	0.98% (0.44 to 1.87)	49.2% (18.3 to 110.2)	88.8 (40.1 to 169.8)	-7.8% (-33.0 to 38.5)	0.39% (0.19 to 0.73)	74.9% (34.8 to 154.0)
Tropical Latin America	20.2 (13.3 to 28.3)	-37.5% (-44.8 to -23.3)	3.19% (2.11 to 4.47)	-0.4% (-12.2 to 22.2)	442.2 (282.8 to 640.5)	-30.6% (-38.8 to -15.5)	1.51% (0.98 to 2.18)	7.7% (-5.7 to 31.0)
Brazil	20.4 (13.5 to 28.6)	-38.4% (-45.5 to -24.2)	3.23% (2.13 to 4.50)	-0.7% (-12.4 to 21.7)	448.6 (286.9 to 645.8)	-31.1% (-39.4 to -16.1)	1.53% (0.99 to 2.20)	7.7% (-5.8 to 30.8)
Paraguay	9.5 (4.3 to 19.1)	31.8% (-3.6 to 90.8)	1.54% (0.70 to 2.99)	33.6% (7.5 to 87.0)	172.6 (74.0 to 346.3)	49.9% (8.5 to 110.8)	0.64% (0.28 to 1.25)	64.7% (27.3 to 123.0)
Central Latin America	7.7 (3.6 to 15.5)	-5.7% (-18.3 to 10.0)	1.24% (0.58 to 2.42)	30.1% (14.4 to 51.4)	164.4 (75.5 to 318.2)	-3.1% (-15.4 to 10.6)	0.60% (0.27 to 1.13)	33.7% (18.2 to 52.1)
Colombia	4.7 (1.9 to 10.2)	-32.6% (-48.1 to -10.6)	1.01% (0.42 to 2.13)	18.5% (-2.1 to 49.9)	103.5 (44.5 to 210.5)	-20.8% (-39.4 to 4.9)	0.45% (0.20 to 0.88)	23.5% (-3.1 to 61.2)
Costa Rica	3.0 (1.2 to 6.9)	-18.1% (-38.7 to 13.9)	0.62% (0.24 to 1.43)	3.4% (-16.8 to 35.8)	60.2 (25.4 to 128.7)	-6.5% (-28.1 to 25.4)	0.27% (0.12 to 0.58)	9.4% (-13.0 to 42.6)
El Salvador	4.2 (1.6 to 9.8)	35.7% (-7.2 to 102.0)	0.65% (0.26 to 1.49)	76.4% (26.8 to 151.9)	80.3 (32.1 to 176.9)	41.6% (-6.0 to 106.4)	0.28% (0.11 to 0.61)	108.5% (42.4 to 192.9)
Guatemala	2.0 (0.8 to 5.2)	17.3% (-18.5 to 97.5)	0.24% (0.10 to 0.62)	102.1% (39.6 to 227.6)	35.5 (15.3 to 90.2)	15.3% (-25.4 to 98.8)	0.10% (0.05 to 0.26)	104.5% (31.7 to 240.7)
Honduras	4.8 (1.7 to 11.7)	75.3% (36.9 to 132.7)	0.54% (0.19 to 1.32)	72.6% (35.6 to 127.6)	82.7 (32.2 to 188.4)	53.7% (18.6 to 96.5)	0.25% (0.10 to 0.58)	98.3% (56.8 to 151.1)
Mexico	11.4 (5.4 to 21.3)	1.6% (-12.7 to 19.7)	1.73% (0.83 to 3.28)	33.9% (19.4 to 52.6)	245.1 (113.7 to 461.3)	0.8% (-11.6 to 15.6)	0.87% (0.40 to 1.61)	34.1% (21.4 to 50.6)
Nicaragua	6.0 (2.2 to 14.1)	88.9% (37.1 to 147.1)	0.83% (0.31 to 1.99)	87.6% (36.4 to 144.7)	96.0 (38.2 to 217.5)	63.1% (20.0 to 107.1)	0.35% (0.14 to 0.78)	122.8% (63.5 to 179.2)
Panama	3.0 (1.2 to 6.7)	-6.1% (-32.8 to 39.6)	0.63% (0.25 to 1.39)	20.1% (-9.1 to 72.6)	56.9 (23.5 to 117.5)	5.3% (-26.4 to 50.3)	0.24% (0.10 to 0.49)	26.8% (-9.1 to 75.7)
Venezuela (Bolivarian Republic of)	4.6 (1.7 to 11.3)	1.6% (-22.7 to 37.9)	0.68% (0.26 to 1.61)	18.4% (-4.1 to 48.5)	84.9 (34.1 to 198.7)	3.0% (-20.6 to 35.9)	0.29% (0.12 to 0.66)	18.3% (-3.6 to 45.5)
Southern Latin America	3.2 (1.6 to 6.3)	-26.1% (-42.3 to 5.5)	0.53% (0.26 to 1.04)	1.0% (-21.2 to 46.0)	62.8 (32.7 to 121.3)	-11.9% (-35.6 to 29.8)	0.26% (0.13 to 0.49)	15.6% (-15.2 to 71.5)
Argentina	1.9 (0.9 to 4.3)	-30.9% (-47.9 to 7.1)	0.30% (0.14 to 0.67)	-11.7% (-33.4 to 36.8)	34.0 (16.1 to 74.9)	-25.4% (-45.4 to 13.5)	0.13% (0.06 to 0.29)	-5.0% (-30.6 to 46.1)
Chile	5.2 (2.6 to 10.1)	-30.6% (-46.5 to 5.0)	1.07% (0.53 to 2.02)	13.8% (-12.3 to 72.7)	112.1 (57.4 to 205.4)	-9.5% (-33.3 to 39.6)	0.52% (0.27 to 0.93)	29.9% (-3.4 to 100.6)
Uruguay	6.8 (2.8 to 13.5)	-25.3% (-40.4 to 2.9)	1.13% (0.48 to 2.24)	0.1% (-19.4 to 37.7)	132.4 (58.8 to 262.6)	-14.3% (-33.6 to 25.4)	0.54% (0.24 to 1.05)	8.8% (-15.5 to 60.2)

TABLE S1. Continue.

1	2	3	4	5	6	7	8	9
Caribbean	20.7 (11.6 to 33.0)	-17.6% (-29.0 to -2.9)	2.73% (1.54 to 4.27)	3.2% (-5.1 to 16.5)	438.9 (247.0 to 726.3)	-4.1% (-17.4 to 12.5)	1.26% (0.72 to 2.04)	18.8% (7.7 to 35.0)
Antigua and Barbuda	21.4 (12.5 to 32.9)	-0.6% (-14.8 to 18.9)	3.13% (1.83 to 4.70)	11.0% (-2.1 to 29.9)	415.0 (238.2 to 656.9)	5.3% (-10.4 to 26.0)	1.61% (0.92 to 2.54)	19.1% (3.2 to 40.7)
Bahamas	17.8 (10.1 to 28.3)	-19.8% (-32.9 to -2.2)	2.35% (1.35 to 3.64)	-5.8% (-14.1 to 6.8)	392.6 (223.3 to 653.0)	-8.9% (-23.6 to 10.2)	1.25% (0.72 to 2.03)	2.0% (-8.3 to 17.4)
Barbados	23.4 (14.3 to 34.5)	-19.9% (-32.9 to -3.6)	3.49% (2.21 to 5.04)	-7.3% (-17.1 to 8.0)	465.8 (282.6 to 713.9)	-9.4% (-23.5 to 7.9)	1.79% (1.10 to 2.70)	3.0% (-7.7 to 18.8)
Belize	18.4 (10.5 to 28.5)	-4.9% (-20.6 to 22.3)	2.64% (1.55 to 4.10)	3.6% (-9.9 to 27.6)	395.4 (224.1 to 653.2)	15.7% (-4.8 to 48.0)	1.31% (0.74 to 2.12)	27.9% (7.9 to 60.4)
Bermuda	14.4 (8.1 to 22.2)	-56.0% (-62.8 to -44.5)	3.24% (1.87 to 4.89)	-16.0% (-26.1 to 0.5)	272.6 (162.0 to 431.3)	-49.4% (-58.5 to -33.5)	1.42% (0.84 to 2.19)	-23.2% (-34.3 to -2.2)
Cuba	16.5 (8.6 to 26.6)	-31.5% (-43.2 to -13.5)	2.98% (1.58 to 4.83)	-12.0% (-22.2 to 5.5)	333.9 (182.7 to 564.1)	-19.9% (-34.0 to -0.1)	1.49% (0.83 to 2.39)	0.4% (-12.9 to 21.2)
Dominica	21.1 (11.8 to 33.4)	-11.7% (-26.0 to 10.5)	2.46% (1.43 to 3.73)	-2.5% (-14.4 to 17.3)	428.8 (239.4 to 710.6)	1.8% (-15.0 to 25.2)	1.29% (0.73 to 2.07)	5.2% (-8.4 to 25.5)
Dominican Republic	27.7 (14.6 to 46.7)	41.8% (13.9 to 79.2)	3.62% (1.98 to 5.74)	41.3% (28.3 to 59.0)	557.1 (285.3 to 968.6)	58.9% (26.2 to 99.7)	1.73% (0.94 to 2.82)	85.7% (65.3 to 111.5)
Grenada	24.2 (13.8 to 38.0)	-15.0% (-26.3 to 3.9)	2.94% (1.69 to 4.52)	7.9% (-5.1 to 30.8)	482.7 (259.2 to 801.5)	-5.1% (-19.2 to 15.8)	1.58% (0.89 to 2.61)	18.1% (2.0 to 43.2)
Guyana	35.1 (19.2 to 58.4)	-3.9% (-23.8 to 25.1)	3.11% (1.75 to 4.98)	26.3% (12.1 to 50.9)	729.6 (389.1 to 1273.9)	4.3% (-17.2 to 34.9)	1.67% (0.89 to 2.81)	34.6% (17.4 to 61.5)
Haiti	27.6 (13.9 to 48.2)	-10.8% (-29.1 to 12.4)	2.17% (1.10 to 3.67)	26.1% (11.5 to 47.8)	533.8 (272.6 to 999.2)	-8.6% (-25.9 to 13.8)	1.00% (0.51 to 1.76)	36.9% (20.5 to 59.6)
Jamaica	24.2 (14.5 to 36.4)	8.6% (-11.6 to 38.0)	3.80% (2.37 to 5.48)	14.2% (0.9 to 32.5)	507.5 (299.4 to 786.7)	23.6% (2.6 to 51.9)	1.89% (1.14 to 2.89)	30.1% (16.1 to 49.2)
Puerto Rico	13.7 (8.0 to 21.1)	-43.1% (-57.1 to -23.7)	2.99% (1.88 to 4.42)	-8.7% (-23.4 to 15.4)	354.5 (205.7 to 564.1)	-21.8% (-39.7 to 2.4)	1.60% (0.97 to 2.42)	5.6% (-14.3 to 34.3)
Saint Kitts and Nevis	24.7 (13.8 to 39.5)	-39.1% (-47.8 to -24.9)	2.77% (1.59 to 4.32)	-7.0% (-17.4 to 12.1)	479.4 (268.2 to 768.4)	-30.9% (-42.0 to -13.6)	1.48% (0.82 to 2.37)	-2.8% (-16.4 to 18.1)
Saint Lucia	19.9 (11.3 to 31.0)	-37.0% (-46.6 to -23.5)	2.81% (1.66 to 4.26)	-8.0% (-18.7 to 8.5)	434.7 (238.3 to 709.0)	-21.7% (-33.8 to -5.7)	1.51% (0.86 to 2.44)	0.5% (-12.0 to 17.6)
Saint Vincent and the Grenadines	28.8 (16.3 to 45.1)	-11.8% (-22.6 to 4.1)	3.43% (1.98 to 5.23)	3.0% (-7.4 to 19.8)	559.3 (310.4 to 908.2)	-1.2% (-14.8 to 16.7)	1.76% (0.99 to 2.85)	15.4% (2.3 to 35.4)
Suriname	20.1 (11.2 to 33.1)	-10.4% (-25.5 to 15.3)	2.59% (1.49 to 4.04)	9.1% (-4.2 to 34.5)	468.5 (261.0 to 781.7)	9.2% (-10.3 to 42.6)	1.38% (0.76 to 2.25)	33.6% (13.2 to 67.3)
Trinidad and Tobago	32.9 (18.7 to 50.8)	-26.3% (-43.2 to -3.9)	4.76% (2.94 to 6.96)	9.1% (-2.8 to 27.9)	733.6 (412.7 to 1184.9)	-17.3% (-34.6 to 6.2)	2.51% (1.48 to 3.82)	6.3% (-7.7 to 24.9)
United States Virgin Islands	18.3 (9.5 to 31.5)	-3.5% (-22.4 to 29.3)	2.35% (1.22 to 4.06)	3.3% (-13.5 to 36.6)	311.2 (167.9 to 552.9)	2.6% (-18.7 to 40.3)	1.10% (0.59 to 1.96)	15.8% (-6.2 to 55.8)
Central Europe	13.2 (6.8 to 23.8)	-31.1% (-38.7 to -21.3)	2.02% (1.02 to 3.66)	5.2% (-3.3 to 19.0)	204.0 (109.9 to 378.6)	-29.2% (-38.7 to -13.2)	0.85% (0.45 to 1.55)	4.0% (-7.8 to 25.6)
Albania	7.7 (3.3 to 16.0)	3.5% (-20.0 to 30.0)	1.34% (0.60 to 2.69)	49.3% (30.4 to 70.4)	116.8 (53.3 to 246.0)	4.8% (-16.8 to 30.0)	0.51% (0.24 to 1.03)	51.1% (30.1 to 75.8)
Bosnia and Herzegovina	13.4 (6.6 to 25.2)	12.4% (-9.9 to 52.3)	1.96% (0.96 to 3.65)	38.3% (16.9 to 75.9)	217.0 (111.6 to 416.8)	14.0% (-11.3 to 58.9)	0.90% (0.46 to 1.71)	44.2% (18.1 to 93.4)
Bulgaria	16.8 (8.1 to 32.3)	-20.3% (-35.5 to 1.5)	1.88% (0.91 to 3.62)	0.0% (-14.0 to 20.2)	240.8 (120.3 to 472.2)	-17.5% (-32.6 to 3.0)	0.82% (0.42 to 1.57)	2.1% (-10.4 to 19.2)
Croatia	11.0 (5.4 to 20.4)	-31.4% (-44.1 to -14.1)	1.87% (0.94 to 3.38)	8.0% (-4.1 to 27.8)	159.9 (85.9 to 293.6)	-28.8% (-42.1 to -7.8)	0.73% (0.39 to 1.36)	2.5% (-12.5 to 25.8)
Czechia	13.2 (6.7 to 24.2)	-38.6% (-51.8 to -21.3)	2.43% (1.24 to 4.39)	13.3% (-6.9 to 40.4)	213.8 (116.5 to 389.3)	-33.1% (-48.8 to -9.2)	1.01% (0.56 to 1.79)	4.1% (-17.4 to 36.3)
Hungary	10.4 (5.1 to 19.7)	-27.4% (-40.3 to -10.8)	1.55% (0.77 to 2.93)	17.8% (1.0 to 37.7)	159.2 (82.1 to 301.9)	-27.1% (-40.8 to -7.0)	0.65% (0.35 to 1.22)	12.0% (-6.7 to 36.5)

TABLE S1. Continue.

1	2	3	4	5	6	7	8	9
North Macedonia	20.3 (9.8 to 39.6)	22.0% (1.8 to 48.1)	2.19% (1.08 to 4.26)	36.1% (19.7 to 56.2)	289.7 (145.9 to 550.2)	15.2% (-4.4 to 41.4)	1.04% (0.54 to 1.99)	49.5% (30.3 to 74.0)
Montenegro	10.8 (5.1 to 20.8)	19.4% (3.1 to 42.2)	1.44% (0.69 to 2.71)	19.0% (7.1 to 36.1)	181.8 (92.7 to 338.3)	20.7% (4.7 to 41.5)	0.73% (0.38 to 1.36)	34.8% (21.4 to 52.5)
Poland	11.9 (6.1 to 20.8)	-46.0% (-54.6 to -34.0)	2.05% (1.05 to 3.66)	-11.3% (-21.3 to 6.0)	198.3 (106.4 to 342.5)	-44.4% (-54.0 to -28.7)	0.87% (0.47 to 1.53)	-15.2% (-27.3 to 8.7)
Romania	15.8 (7.8 to 29.0)	-23.0% (-35.8 to -7.4)	2.21% (1.09 to 3.99)	12.8% (-0.4 to 30.7)	231.1 (119.8 to 430.7)	-18.0% (-32.1 to -0.2)	0.89% (0.46 to 1.61)	18.3% (3.7 to 38.2)
Serbia	17.4 (8.4 to 33.1)	-1.0% (-16.7 to 20.2)	2.13% (1.05 to 4.02)	21.8% (9.6 to 38.0)	243.1 (123.4 to 456.7)	-5.7% (-21.9 to 15.3)	0.96% (0.49 to 1.77)	30.6% (16.0 to 51.1)
Slovakia	13.8 (6.4 to 26.3)	-26.7% (-39.9 to -9.4)	2.21% (1.05 to 4.12)	14.7% (2.4 to 33.8)	202.5 (102.1 to 384.7)	-29.9% (-43.1 to -11.5)	0.87% (0.44 to 1.65)	2.1% (-11.9 to 23.9)
Slovenia	5.5 (2.8 to 9.9)	-45.5% (-60.1 to -25.1)	1.24% (0.66 to 2.24)	-1.4% (-18.4 to 21.4)	97.9 (53.3 to 177.4)	-37.8% (-54.7 to -13.1)	0.51% (0.28 to 0.90)	-5.1% (-25.4 to 22.6)
Eastern Europe	17.3 (8.1 to 32.3)	-10.4% (-20.6 to 1.0)	2.06% (0.95 to 3.93)	6.9% (-3.5 to 18.2)	232.6 (108.2 to 473.8)	-11.4% (-21.4 to 0.0)	0.73% (0.34 to 1.47)	4.4% (-5.7 to 14.9)
Belarus	20.1 (8.9 to 38.8)	2.7% (-15.8 to 23.9)	2.56% (1.14 to 4.82)	18.6% (6.7 to 32.1)	265.7 (118.6 to 535.7)	3.3% (-16.2 to 25.8)	0.94% (0.42 to 1.85)	24.3% (11.1 to 37.8)
Estonia	10.2 (4.8 to 19.8)	-50.7% (-62.7 to -34.4)	1.75% (0.82 to 3.32)	-14.2% (-30.8 to 13.0)	134.8 (67.8 to 260.1)	-49.3% (-61.1 to -30.9)	0.59% (0.29 to 1.14)	-19.1% (-34.9 to 5.9)
Latvia	22.4 (11.1 to 39.0)	-24.1% (-35.0 to -8.3)	3.28% (1.66 to 5.55)	11.1% (-1.0 to 29.6)	302.1 (157.6 to 553.4)	-23.2% (-34.7 to -6.2)	1.16% (0.59 to 2.05)	10.5% (-2.3 to 30.4)
Lithuania	23.3 (11.8 to 40.0)	-20.0% (-32.4 to -3.5)	3.50% (1.78 to 5.99)	8.7% (-2.0 to 26.4)	301.4 (156.1 to 548.0)	-21.5% (-33.7 to -4.9)	1.18% (0.60 to 2.11)	5.1% (-5.2 to 21.6)
Republic of Moldova	16.5 (7.2 to 31.7)	-30.0% (-38.8 to -19.6)	2.22% (0.97 to 4.23)	4.4% (-5.2 to 16.5)	224.7 (103.7 to 446.2)	-24.5% (-33.6 to -12.5)	0.79% (0.37 to 1.54)	7.6% (-2.6 to 21.5)
Russian Federation	17.4 (8.3 to 32.1)	-12.9% (-24.8 to 2.6)	2.15% (1.04 to 3.98)	9.5% (-2.3 to 24.4)	231.5 (110.3 to 454.9)	-15.5% (-26.6 to 0.0)	0.75% (0.36 to 1.48)	3.9% (-7.3 to 18.1)
Ukraine	15.9 (6.2 to 33.3)	-0.9% (-21.8 to 19.7)	1.61% (0.63 to 3.40)	-1.7% (-20.9 to 15.3)	224.1 (91.3 to 482.6)	3.0% (-17.4 to 24.2)	0.63% (0.26 to 1.35)	2.2% (-15.8 to 18.5)
North Africa and Middle East	34.8 (20.4 to 54.4)	-15.1% (-23.0 to -5.6)	4.50% (2.64 to 6.89)	25.7% (15.9 to 38.8)	671.9 (389.1 to 1089.5)	-9.6% (-20.1 to 5.5)	2.16% (1.28 to 3.43)	43.3% (28.4 to 65.9)
Afghanistan	46.1 (23.8 to 76.4)	-3.3% (-24.0 to 21.1)	3.21% (1.78 to 5.21)	26.9% (12.1 to 48.0)	909.9 (466.2 to 1605.9)	-1.6% (-23.5 to 28.5)	1.64% (0.87 to 2.86)	53.3% (27.1 to 90.4)
Algeria	42.2 (24.7 to 63.8)	-28.7% (-41.6 to -12.1)	5.75% (3.39 to 8.63)	19.4% (6.9 to 36.8)	671.7 (396.1 to 1077.4)	-23.6% (-38.2 to -1.9)	2.49% (1.48 to 3.91)	26.1% (9.0 to 52.2)
Bahrain	47.9 (31.2 to 67.7)	-33.3% (-47.5 to -10.1)	6.55% (4.32 to 9.04)	13.0% (-4.5 to 44.3)	904.2 (563.5 to 1327.3)	-28.5% (-45.8 to -0.8)	3.70% (2.39 to 5.28)	11.9% (-10.7 to 49.6)
Egypt	51.8 (26.9 to 85.7)	1.3% (-19.6 to 25.8)	5.06% (2.75 to 8.02)	32.3% (17.0 to 53.1)	976.3 (498.5 to 1705.6)	9.1% (-14.1 to 38.8)	2.86% (1.55 to 4.77)	69.2% (47.7 to 100.7)
Iran (Islamic Republic of)	24.0 (13.1 to 38.6)	-30.4% (-36.7 to -19.9)	4.03% (2.22 to 6.43)	24.8% (12.8 to 43.7)	433.3 (243.2 to 722.0)	-26.0% (-35.4 to -6.4)	1.74% (0.97 to 2.87)	38.5% (21.2 to 73.7)
Iraq	49.9 (29.5 to 75.7)	-6.2% (-22.7 to 10.6)	6.09% (3.74 to 8.88)	23.6% (13.9 to 36.3)	929.8 (543.0 to 1460.1)	-6.3% (-24.7 to 13.8)	2.95% (1.77 to 4.53)	38.7% (22.7 to 57.9)
Jordan	24.4 (14.8 to 37.3)	-32.3% (-43.9 to -16.6)	4.26% (2.60 to 6.42)	11.4% (-0.4 to 30.0)	454.0 (265.9 to 726.3)	-26.2% (-38.6 to -9.3)	1.93% (1.13 to 3.01)	9.8% (-3.1 to 27.9)
Kuwait	23.3 (14.7 to 34.0)	-34.2% (-44.2 to -21.0)	5.34% (3.38 to 7.55)	2.3% (-6.2 to 13.8)	559.0 (349.8 to 838.3)	-22.3% (-34.4 to -7.1)	2.77% (1.74 to 4.02)	14.3% (1.3 to 31.5)
Lebanon	36.9 (20.0 to 57.7)	-19.5% (-34.1 to -4.0)	5.54% (2.98 to 8.61)	20.5% (0.8 to 39.1)	719.9 (400.7 to 1149.1)	-12.7% (-28.6 to 8.8)	2.79% (1.56 to 4.38)	33.4% (13.7 to 59.9)
Libya	29.7 (17.4 to 46.5)	1.4% (-19.1 to 29.4)	4.55% (2.68 to 6.89)	20.2% (9.5 to 34.0)	643.4 (375.0 to 1034.9)	14.6% (-7.9 to 45.9)	2.29% (1.35 to 3.58)	41.8% (25.0 to 64.1)
Morocco	44.8 (25.1 to 69.9)	11.6% (-7.5 to 32.0)	5.26% (3.02 to 8.05)	42.4% (27.6 to 64.0)	802.8 (451.3 to 1317.5)	13.6% (-6.8 to 38.9)	2.60% (1.48 to 4.20)	71.3% (49.7 to 106.8)

TABLE S1. Continue.

1	2	3	4	5	6	7	8	9
Palestine	44.2 (27.2 to 66.4)	-8.1% (-25.1 to 16.5)	5.55% (3.47 to 8.22)	23.9% (12.3 to 41.7)	785.7 (476.7 to 1226.3)	-6.0% (-24.6 to 20.8)	2.75% (1.70 to 4.28)	33.5% (14.3 to 59.1)
Oman	60.8 (37.1 to 89.5)	-0.7% (-20.7 to 26.5)	6.66% (4.03 to 9.88)	38.7% (19.5 to 70.0)	1008.5 (603.2 to 1536.2)	-5.9% (-27.0 to 25.2)	3.50% (2.12 to 5.32)	43.8% (19.2 to 81.5)
Qatar	64.5 (41.3 to 91.2)	-15.3% (-31.7 to 7.2)	7.36% (4.90 to 10.18)	11.6% (0.0 to 28.7)	1073.3 (689.2 to 1547.8)	-17.8% (-35.4 to 7.6)	4.19% (2.74 to 5.90)	19.3% (2.6 to 42.6)
Saudi Arabia	46.9 (30.8 to 66.5)	-1.3% (-22.9 to 30.2)	6.18% (4.05 to 8.77)	41.6% (23.9 to 71.4)	1041.2 (668.7 to 1500.2)	14.8% (-12.4 to 54.2)	3.64% (2.34 to 5.14)	67.6% (40.3 to 106.8)
Sudan	58.7 (37.1 to 86.6)	-12.2% (-26.0 to 6.4)	6.27% (4.12 to 8.77)	41.4% (28.6 to 58.0)	1176.2 (725.6 to 1775.0)	-10.7% (-27.5 to 12.5)	3.12% (1.97 to 4.59)	68.7% (44.4 to 101.4)
Syrian Arab Republic	51.6 (27.0 to 84.2)	-0.3% (-22.9 to 30.9)	5.92% (3.23 to 9.26)	18.4% (8.9 to 31.7)	874.7 (466.7 to 1476.5)	-4.9% (-27.3 to 27.2)	2.85% (1.52 to 4.70)	26.9% (11.0 to 47.8)
Tunisia	15.3 (6.4 to 30.7)	7.3% (-16.8 to 42.0)	2.52% (1.11 to 4.84)	44.2% (24.2 to 74.8)	260.7 (120.5 to 524.1)	16.7% (-10.1 to 55.0)	1.08% (0.51 to 2.12)	67.9% (40.1 to 109.2)
Turkey	20.2 (11.4 to 31.6)	-28.6% (-44.0 to -8.5)	3.58% (2.11 to 5.52)	20.8% (4.1 to 44.8)	372.0 (215.3 to 600.7)	-30.0% (-45.3 to -9.1)	1.57% (0.92 to 2.51)	25.0% (0.9 to 56.6)
United Arab Emirates	47.6 (29.9 to 69.0)	-34.0% (-46.3 to -19.4)	5.70% (3.78 to 8.12)	0.3% (-11.6 to 13.0)	1026.4 (647.2 to 1493.8)	-23.8% (-38.6 to -6.4)	3.55% (2.32 to 5.08)	4.4% (-7.5 to 19.0)
Yemen	39.4 (20.8 to 67.0)	-3.6% (-21.6 to 21.7)	3.68% (1.95 to 6.01)	32.6% (18.1 to 54.5)	695.5 (360.0 to 1225.3)	-5.2% (-25.0 to 22.1)	1.57% (0.81 to 2.71)	43.6% (22.8 to 73.5)
Central Asia	21.5 (9.8 to 41.4)	29.6% (18.2 to 42.0)	2.16% (0.98 to 4.13)	34.1% (24.6 to 45.6)	316.6 (147.1 to 622.4)	30.7% (16.6 to 48.2)	0.92% (0.42 to 1.82)	61.7% (44.7 to 82.1)
Armenia	15.4 (7.2 to 29.3)	-10.3% (-24.1 to 8.9)	2.12% (1.00 to 4.02)	17.1% (3.6 to 37.3)	221.5 (108.3 to 446.0)	-6.1% (-22.1 to 16.9)	0.86% (0.41 to 1.66)	34.3% (14.7 to 62.7)
Azerbaijan	26.6 (11.5 to 53.4)	91.9% (63.0 to 131.5)	2.42% (1.03 to 4.79)	80.8% (56.9 to 112.5)	354.0 (159.1 to 712.5)	65.1% (35.1 to 102.3)	1.02% (0.45 to 2.06)	117.6% (81.2 to 163.5)
Georgia	13.3 (6.2 to 26.2)	-37.8% (-48.5 to -21.5)	1.64% (0.76 to 3.25)	-16.2% (-26.3 to 2.0)	211.3 (102.6 to 419.7)	-26.7% (-40.9 to -4.0)	0.71% (0.34 to 1.43)	-2.7% (-17.7 to 23.8)
Kazakhstan	22.8 (10.7 to 41.8)	7.0% (-5.7 to 24.3)	2.48% (1.17 to 4.38)	21.7% (11.0 to 37.4)	327.9 (162.5 to 618.5)	4.4% (-9.4 to 24.9)	1.01% (0.50 to 1.87)	32.5% (17.0 to 54.6)
Kyrgyzstan	17.6 (7.4 to 34.8)	38.5% (4.6 to 69.2)	2.17% (0.90 to 4.32)	73.3% (34.7 to 106.6)	233.5 (99.9 to 486.1)	23.3% (-3.8 to 49.5)	0.79% (0.34 to 1.63)	81.1% (41.8 to 115.4)
Mongolia	15.2 (6.1 to 31.2)	-5.0% (-21.9 to 19.6)	1.27% (0.52 to 2.59)	23.1% (8.1 to 47.1)	201.8 (82.1 to 450.6)	-10.6% (-28.3 to 14.4)	0.50% (0.21 to 1.09)	35.4% (19.4 to 61.8)
Tajikistan	20.1 (8.3 to 43.7)	127.4% (88.7 to 180.6)	1.77% (0.73 to 3.69)	97.1% (72.5 to 132.4)	284.1 (120.8 to 617.9)	101.7% (66.6 to 149.9)	0.76% (0.33 to 1.60)	148.7% (113.2 to 191.8)
Turkmenistan	20.8 (9.1 to 41.0)	13.2% (-5.7 to 38.2)	2.29% (1.00 to 4.51)	40.8% (26.5 to 62.7)	320.1 (141.4 to 669.5)	21.9% (0.9 to 50.5)	0.92% (0.41 to 1.87)	64.5% (43.1 to 95.3)
Uzbekistan	37.3 (15.6 to 75.3)	159.0% (118.8 to 207.0)	2.72% (1.14 to 5.44)	76.9% (53.5 to 105.1)	499.4 (216.6 to 1027.7)	146.6% (98.5 to 195.9)	1.25% (0.54 to 2.54)	142.6% (100.3 to 186.3)
South Asia	12.3 (6.2 to 22.2)	-2.3% (-16.3 to 13.5)	1.34% (0.68 to 2.41)	64.5% (45.1 to 89.6)	205.8 (103.2 to 389.9)	-6.5% (-19.0 to 8.0)	0.53% (0.27 to 1.01)	59.7% (40.5 to 85.5)
Bangladesh	11.3 (5.4 to 21.1)	8.3% (-13.9 to 33.6)	1.59% (0.79 to 2.85)	129.0% (95.5 to 168.3)	177.4 (88.5 to 339.5)	5.2% (-14.9 to 28.7)	0.58% (0.29 to 1.12)	133.4% (99.4 to 173.9)
Bhutan	17.1 (9.0 to 29.2)	29.8% (-0.1 to 70.9)	2.09% (1.08 to 3.51)	121.1% (73.7 to 182.2)	283.1 (151.1 to 511.0)	25.3% (-2.2 to 62.5)	0.86% (0.45 to 1.50)	147.6% (100.1 to 208.9)
India	11.7 (5.8 to 21.0)	-6.2% (-22.1 to 11.4)	1.29% (0.66 to 2.37)	64.8% (42.4 to 94.4)	191.5 (96.0 to 368.2)	-12.6% (-26.6 to 3.7)	0.51% (0.25 to 0.96)	53.1% (31.3 to 80.7)
Nepal	9.9 (4.8 to 19.4)	36.9% (5.2 to 82.4)	1.04% (0.50 to 1.96)	119.7% (78.4 to 177.2)	167.8 (82.2 to 330.0)	31.9% (3.3 to 70.1)	0.47% (0.23 to 0.91)	157.0% (110.0 to 218.5)
Pakistan	20.9 (10.6 to 36.6)	40.8% (17.0 to 74.4)	1.82% (0.96 to 3.16)	68.0% (47.1 to 96.1)	399.8 (198.7 to 729.8)	45.2% (21.7 to 76.6)	0.83% (0.41 to 1.50)	85.8% (60.0 to 118.0)
Southeast Asia	10.2 (5.0 to 19.5)	15.4% (2.4 to 31.2)	1.26% (0.61 to 2.40)	63.2% (49.3 to 81.8)	192.6 (93.7 to 364.2)	21.0% (6.8 to 38.7)	0.61% (0.30 to 1.17)	88.5% (70.0 to 113.1)

TABLE S1. Continue.

1	2	3	4	5	6	7	8	9
Cambodia	8.3 (3.7 to 17.2)	10.2% (-11.0 to 32.2)	0.82% (0.36 to 1.66)	74.5% (44.8 to 109.8)	141.9 (66.3 to 293.3)	9.1% (-10.8 to 34.0)	0.38% (0.18 to 0.77)	103.7% (68.4 to 147.4)
Indonesia	16.1 (7.8 to 31.0)	51.3% (27.3 to 78.4)	1.69% (0.82 to 3.24)	92.8% (73.5 to 120.0)	293.3 (141.1 to 559.2)	47.6% (25.3 to 74.0)	0.86% (0.41 to 1.63)	127.4% (101.1 to 161.7)
Lao People's Democratic Republic	10.0 (4.3 to 21.5)	15.2% (-8.8 to 48.9)	0.97% (0.41 to 1.98)	108.1% (70.3 to 156.7)	173.6 (77.4 to 365.0)	10.7% (-11.2 to 41.2)	0.44% (0.20 to 0.92)	136.7% (96.3 to 190.7)
Malaysia	16.6 (7.9 to 29.5)	-3.0% (-20.9 to 19.5)	2.23% (1.08 to 3.92)	13.3% (0.5 to 31.1)	342.9 (169.3 to 620.7)	2.4% (-14.4 to 23.8)	1.28% (0.66 to 2.25)	25.3% (13.5 to 43.4)
Maldives	12.5 (6.0 to 23.4)	-40.9% (-52.9 to -24.9)	2.33% (1.10 to 4.17)	35.5% (15.1 to 64.4)	229.6 (110.6 to 432.8)	-40.6% (-52.2 to -22.1)	1.03% (0.50 to 1.92)	28.3% (5.5 to 63.8)
Mauritius	20.9 (10.8 to 35.6)	-7.5% (-32.2 to 50.8)	3.07% (1.66 to 4.93)	34.0% (3.3 to 107.8)	442.5 (225.5 to 774.7)	1.4% (-28.1 to 63.1)	1.58% (0.81 to 2.69)	31.0% (-3.6 to 106.6)
Myanmar	11.1 (5.2 to 22.3)	-0.5% (-19.1 to 24.0)	1.11% (0.50 to 2.19)	73.0% (45.5 to 110.7)	191.5 (92.8 to 372.3)	-4.9% (-23.8 to 21.3)	0.49% (0.23 to 0.97)	88.5% (54.4 to 133.7)
Philippines	4.8 (1.9 to 10.9)	8.9% (-11.5 to 31.8)	0.56% (0.23 to 1.28)	28.2% (12.5 to 48.1)	86.7 (36.5 to 194.3)	29.3% (5.7 to 58.8)	0.26% (0.11 to 0.58)	64.9% (41.4 to 94.5)
Sri Lanka	9.0 (3.9 to 18.5)	-3.1% (-27.6 to 48.2)	1.46% (0.65 to 2.85)	57.4% (26.7 to 122.1)	160.8 (72.3 to 320.7)	7.7% (-20.1 to 62.8)	0.65% (0.30 to 1.27)	68.2% (31.7 to 141.3)
Seychelles	10.1 (4.8 to 19.4)	-2.0% (-15.9 to 23.1)	1.25% (0.61 to 2.35)	15.7% (0.9 to 43.9)	211.1 (104.2 to 395.0)	13.5% (-7.7 to 52.2)	0.71% (0.36 to 1.30)	33.2% (10.1 to 76.5)
Thailand	5.4 (2.5 to 10.4)	-22.8% (-41.8 to 2.5)	1.01% (0.49 to 1.90)	22.7% (5.6 to 48.3)	111.8 (54.3 to 206.8)	-7.6% (-28.2 to 21.2)	0.46% (0.23 to 0.85)	35.7% (15.3 to 64.3)
Timor-Leste	10.6 (4.4 to 22.5)	40.3% (10.3 to 73.4)	1.09% (0.44 to 2.22)	93.5% (60.4 to 128.7)	172.2 (78.1 to 365.4)	36.5% (10.1 to 66.1)	0.47% (0.21 to 0.98)	141.5% (103.3 to 184.9)
Viet Nam	7.7 (3.4 to 16.9)	17.0% (-5.0 to 47.1)	1.01% (0.44 to 2.21)	52.6% (27.0 to 85.8)	124.1 (57.0 to 259.0)	19.1% (-3.7 to 49.5)	0.45% (0.21 to 0.96)	67.1% (41.2 to 99.6)
East Asia	10.1 (4.6 to 19.2)	6.6% (-17.6 to 34.5)	1.59% (0.72 to 3.01)	88.3% (50.0 to 125.6)	145.7 (70.1 to 277.7)	-0.7% (-20.6 to 22.1)	0.65% (0.31 to 1.25)	82.1% (49.3 to 116.7)
China	10.2 (4.6 to 19.4)	7.5% (-18.0 to 36.8)	1.61% (0.72 to 3.05)	91.2% (51.4 to 131.1)	146.1 (69.8 to 279.9)	-0.4% (-21.1 to 22.9)	0.66% (0.31 to 1.27)	84.1% (50.8 to 120.0)
Democratic People's Republic of Korea	9.6 (4.3 to 19.2)	8.3% (-12.7 to 36.9)	1.17% (0.52 to 2.33)	39.2% (16.9 to 69.3)	154.2 (71.5 to 322.2)	8.6% (-11.2 to 33.3)	0.52% (0.24 to 1.08)	56.9% (34.1 to 85.7)
Taiwan (Province of China)	7.6 (4.1 to 12.8)	-21.9% (-41.7 to 8.8)	1.59% (0.90 to 2.53)	20.2% (-3.7 to 59.3)	140.3 (76.5 to 248.7)	-12.4% (-31.0 to 18.5)	0.71% (0.39 to 1.23)	19.6% (-2.7 to 54.5)
Oceania	24.3 (12.3 to 43.7)	28.4% (7.9 to 55.2)	1.93% (1.00 to 3.32)	39.2% (24.2 to 55.3)	512.1 (255.7 to 933.3)	33.1% (11.4 to 61.7)	1.04% (0.52 to 1.84)	46.7% (30.4 to 64.6)
American Samoa	29.6 (16.7 to 47.2)	17.9% (1.6 to 40.1)	3.34% (1.95 to 5.23)	31.3% (18.6 to 46.4)	735.9 (412.4 to 1227.8)	32.6% (14.2 to 54.5)	2.25% (1.29 to 3.70)	42.8% (28.2 to 60.9)
Federated States of Micronesia	47.1 (26.1 to 79.4)	45.6% (10.7 to 93.4)	3.19% (1.78 to 5.18)	59.9% (34.5 to 91.3)	996.4 (516.2 to 1798.7)	49.0% (9.8 to 102.1)	2.01% (1.06 to 3.48)	73.0% (39.2 to 112.9)
Cook Islands	24.1 (13.6 to 38.5)	2.9% (-15.4 to 26.9)	3.38% (1.97 to 5.29)	57.6% (36.5 to 81.6)	545.3 (291.3 to 922.7)	15.0% (-4.6 to 41.8)	2.02% (1.14 to 3.29)	63.0% (41.3 to 87.6)
Nauru	43.8 (23.1 to 76.4)	30.4% (12.0 to 55.0)	2.89% (1.55 to 4.97)	38.9% (23.3 to 60.2)	902.4 (455.1 to 1664.3)	37.2% (15.7 to 65.4)	1.74% (0.88 to 3.11)	47.4% (29.2 to 71.5)
Niue	32.8 (18.2 to 55.8)	22.7% (0.5 to 54.4)	3.37% (1.89 to 5.54)	40.6% (25.1 to 61.0)	706.8 (378.7 to 1255.2)	37.6% (12.2 to 72.2)	1.97% (1.06 to 3.35)	53.8% (34.3 to 78.0)
Palau	32.6 (17.9 to 55.0)	27.7% (-2.5 to 68.3)	2.75% (1.54 to 4.50)	44.9% (27.1 to 71.4)	701.8 (368.6 to 1264.8)	37.0% (4.7 to 79.1)	1.68% (0.89 to 2.89)	56.5% (35.5 to 83.4)
Fiji	48.8 (26.0 to 82.1)	46.2% (13.2 to 94.6)	4.21% (2.39 to 6.76)	61.9% (38.4 to 92.9)	1004.4 (512.3 to 1761.5)	48.9% (12.8 to 96.8)	2.49% (1.32 to 4.20)	64.2% (40.5 to 92.0)
Guam	13.9 (6.6 to 25.5)	-27.2% (-42.5 to -9.2)	2.26% (1.10 to 4.09)	2.4% (-16.4 to 24.8)	292.0 (147.4 to 553.7)	-8.5% (-27.2 to 12.6)	1.08% (0.55 to 2.01)	-0.2% (-17.2 to 19.9)
Kiribati	39.1 (20.3 to 68.4)	28.4% (3.1 to 62.7)	2.27% (1.22 to 3.86)	61.4% (40.3 to 90.5)	868.4 (430.0 to 1609.7)	23.8% (-1.6 to 59.0)	1.45% (0.74 to 2.56)	66.3% (41.7 to 94.2)

TABLE S1. Continue.

1	2	3	4	5	6	7	8	9
Marshall Islands	37.4 (19.8 to 65.1)	24.5% (-0.4 to 54.6)	2.79% (1.50 to 4.66)	43.7% (27.4 to 65.1)	869.4 (439.2 to 1572.2)	36.8% (10.5 to 70.7)	1.85% (0.96 to 3.21)	55.7% (37.4 to 79.6)
Northern Mariana Islands	21.1 (11.6 to 35.3)	12.4% (-7.3 to 36.6)	2.50% (1.37 to 4.10)	32.6% (15.6 to 49.2)	456.0 (247.4 to 803.2)	23.1% (3.0 to 46.5)	1.49% (0.81 to 2.50)	38.8% (23.2 to 55.1)
Papua New Guinea	19.1 (9.4 to 35.0)	37.8% (12.2 to 71.0)	1.51% (0.75 to 2.72)	45.5% (27.0 to 66.7)	404.6 (194.0 to 772.9)	39.5% (14.1 to 72.2)	0.80% (0.38 to 1.47)	55.5% (35.0 to 78.2)
Samoa	29.6 (16.1 to 50.7)	14.0% (-8.7 to 43.0)	3.01% (1.68 to 4.98)	37.0% (22.2 to 57.5)	620.7 (332.6 to 1089.5)	22.1% (-3.3 to 55.0)	1.77% (0.98 to 3.00)	47.5% (30.8 to 69.9)
Solomon Islands	35.8 (17.1 to 68.0)	43.2% (12.2 to 85.9)	1.87% (0.89 to 3.57)	61.9% (38.0 to 99.9)	787.8 (367.1 to 1567.8)	43.2% (8.8 to 91.3)	1.22% (0.56 to 2.38)	68.6% (40.4 to 110.3)
Tokelau	27.8 (15.0 to 48.1)	22.5% (-3.4 to 55.7)	3.12% (1.68 to 5.10)	57.2% (36.4 to 82.9)	576.8 (297.2 to 1034.3)	26.3% (0.0 to 61.1)	1.80% (0.96 to 3.05)	62.3% (40.8 to 87.9)
Tonga	22.9 (12.6 to 38.4)	19.3% (-2.2 to 47.2)	2.78% (1.58 to 4.45)	32.4% (20.0 to 47.2)	488.7 (262.3 to 850.8)	22.9% (1.6 to 51.5)	1.59% (0.86 to 2.67)	38.7% (26.2 to 54.3)
Tuvalu	31.3 (16.4 to 56.6)	24.9% (-2.5 to 64.1)	2.70% (1.45 to 4.61)	67.8% (46.1 to 96.4)	632.2 (322.0 to 1198.2)	25.7% (-0.7 to 65.3)	1.56% (0.80 to 2.75)	85.3% (61.1 to 115.9)
Vanuatu	19.6 (8.7 to 40.2)	36.9% (8.8 to 81.9)	1.47% (0.67 to 2.81)	53.0% (30.7 to 87.1)	372.9 (169.3 to 777.9)	40.1% (8.9 to 86.5)	0.80% (0.37 to 1.60)	58.6% (33.8 to 95.3)
High-income Asia Pacific	4.3 (2.1 to 7.5)	-57.8% (-64.6 to -46.6)	1.28% (0.62 to 2.23)	-24.7% (-37.0 to -4.7)	90.5 (45.0 to 163.2)	-45.0% (-54.1 to -28.4)	0.56% (0.29 to 1.02)	-20.5% (-32.8 to 2.1)
Brunei Darussalam	21.0 (10.7 to 36.2)	-26.5% (-36.9 to -11.6)	2.41% (1.23 to 4.14)	4.5% (-7.7 to 20.8)	403.7 (202.6 to 720.8)	-23.6% (-34.0 to -9.3)	1.45% (0.73 to 2.58)	3.3% (-8.5 to 20.0)
Japan	3.9 (1.8 to 6.9)	-58.3% (-66.0 to -47.8)	1.20% (0.57 to 2.11)	-31.0% (-43.7 to -13.5)	84.0 (42.0 to 151.9)	-43.3% (-52.6 to -28.7)	0.53% (0.27 to 0.96)	-25.3% (-36.9 to -7.4)
Singapore	5.3 (2.4 to 9.7)	-62.5% (-69.2 to -53.6)	1.64% (0.74 to 3.00)	-16.8% (-31.8 to 3.0)	115.0 (56.7 to 210.2)	-57.1% (-65.2 to -44.0)	0.77% (0.38 to 1.40)	-27.3% (-40.3 to -5.8)
Republic of Korea	6.7 (3.5 to 11.5)	-59.7% (-67.4 to -43.4)	1.71% (0.90 to 2.94)	-4.4% (-23.3 to 34.6)	120.3 (61.2 to 213.0)	-54.6% (-64.8 to -33.9)	0.70% (0.36 to 1.24)	-14.6% (-33.6 to 22.8)
High-income North America	6.0 (2.7 to 12.2)	-55.3% (-63.3 to -44.2)	1.17% (0.52 to 2.35)	-42.5% (-52.8 to -28.3)	130.4 (64.3 to 247.6)	-43.1% (-54.6 to -22.0)	0.51% (0.25 to 1.00)	-35.4% (-48.3 to -11.7)
Canada	7.2 (3.5 to 12.7)	-44.3% (-51.8 to -30.6)	1.75% (0.86 to 3.08)	-17.1% (-28.1 to 3.8)	123.5 (64.9 to 222.7)	-36.1% (-46.8 to -16.3)	0.63% (0.33 to 1.11)	-21.2% (-34.5 to 2.9)
Greenland	9.6 (4.3 to 17.6)	-40.9% (-51.9 to -24.1)	1.19% (0.54 to 2.19)	-5.0% (-18.0 to 17.5)	164.9 (79.5 to 317.9)	-34.9% (-47.4 to -13.6)	0.52% (0.25 to 0.99)	-0.1% (-14.4 to 26.5)
United States of America	5.9 (2.6 to 12.1)	-56.6% (-65.5 to -45.3)	1.11% (0.49 to 2.29)	-45.0% (-56.5 to -30.9)	131.1 (64.6 to 251.3)	-43.8% (-56.1 to -22.3)	0.50% (0.25 to 0.99)	-36.7% (-50.2 to -12.9)
Western Europe	8.6 (4.5 to 14.2)	-50.1% (-55.1 to -41.3)	2.03% (1.08 to 3.38)	-20.0% (-28.1 to -5.9)	158.1 (88.5 to 268.6)	-41.1% (-49.8 to -24.2)	0.82% (0.46 to 1.39)	-20.5% (-31.3 to 1.9)
Andorra	7.9 (4.2 to 13.1)	-26.8% (-45.8 to 0.5)	1.90% (1.03 to 3.05)	-3.7% (-17.2 to 16.7)	149.2 (82.7 to 249.5)	-13.0% (-35.0 to 18.7)	0.79% (0.45 to 1.27)	2.1% (-15.1 to 27.6)
Austria	9.9 (5.0 to 16.8)	-45.5% (-55.3 to -33.4)	2.36% (1.17 to 3.99)	-8.4% (-25.4 to 12.2)	155.8 (82.8 to 271.0)	-40.4% (-49.9 to -24.4)	0.82% (0.43 to 1.41)	-16.9% (-29.8 to 4.8)
Belgium	8.7 (4.7 to 13.8)	-52.0% (-57.3 to -43.4)	1.93% (1.05 to 3.06)	-25.8% (-33.7 to -12.1)	165.5 (94.6 to 274.7)	-41.1% (-49.8 to -24.7)	0.82% (0.46 to 1.34)	-23.4% (-34.0 to -2.2)
Cyprus	13.0 (6.5 to 23.0)	-51.4% (-59.2 to -39.9)	2.51% (1.25 to 4.37)	-13.7% (-26.7 to 6.0)	199.3 (98.8 to 371.8)	-46.0% (-54.2 to -34.2)	1.01% (0.50 to 1.84)	-23.3% (-33.7 to -7.5)
Denmark	8.4 (4.3 to 14.2)	-53.7% (-62.3 to -36.2)	1.82% (0.92 to 3.03)	-26.3% (-40.2 to 1.4)	137.6 (74.3 to 235.7)	-49.1% (-60.3 to -23.4)	0.69% (0.38 to 1.19)	-29.5% (-44.7 to 5.8)
Finland	10.4 (4.4 to 18.9)	-43.8% (-50.8 to -31.2)	2.42% (1.01 to 4.36)	-5.2% (-16.9 to 15.4)	174.6 (85.9 to 315.0)	-40.4% (-49.8 to -16.9)	0.90% (0.43 to 1.63)	-16.6% (-29.9 to 16.2)
France	7.9 (4.6 to 12.0)	-46.0% (-52.1 to -36.6)	2.03% (1.18 to 3.09)	-12.8% (-22.6 to 2.1)	138.0 (82.5 to 218.1)	-37.6% (-45.8 to -23.6)	0.74% (0.44 to 1.17)	-16.3% (-26.8 to 2.0)
Germany	8.4 (3.8 to 15.7)	-49.1% (-55.2 to -38.6)	1.82% (0.83 to 3.41)	-20.2% (-29.7 to -3.4)	144.1 (71.2 to 273.9)	-40.8% (-50.0 to -23.3)	0.72% (0.35 to 1.34)	-21.1% (-33.3 to 2.7)

TABLE S1. Continue.

1	2	3	4	5	6	7	8	9
Greece	7.8 (3.3 to 15.3)	-31.9% (-42.9 to -15.3)	1.66% (0.70 to 3.20)	-5.7% (-21.2 to 16.9)	125.2 (57.3 to 254.6)	-21.8% (-35.4 to 1.4)	0.62% (0.28 to 1.27)	-5.4% (-21.9 to 21.9)
Iceland	8.2 (4.0 to 14.0)	-50.9% (-57.0 to -40.0)	2.35% (1.13 to 3.95)	-17.0% (-26.9 to 0.8)	149.8 (80.2 to 256.8)	-42.2% (-52.4 to -19.5)	0.86% (0.46 to 1.47)	-22.5% (-35.0 to 6.3)
Ireland	12.8 (7.2 to 19.6)	-56.9% (-61.7 to -49.3)	2.97% (1.66 to 4.53)	-20.3% (-29.2 to -6.7)	223.2 (131.6 to 348.1)	-51.8% (-59.6 to -36.4)	1.16% (0.68 to 1.80)	-31.6% (-42.4 to -9.4)
Israel	9.7 (5.5 to 15.3)	-49.3% (-58.7 to -29.4)	2.48% (1.42 to 3.90)	-16.9% (-32.0 to 15.6)	175.5 (102.7 to 286.1)	-42.2% (-55.3 to -16.1)	0.99% (0.57 to 1.58)	-21.3% (-39.1 to 13.6)
Italy	9.5 (5.2 to 15.1)	-50.1% (-55.5 to -44.0)	2.45% (1.35 to 3.87)	-17.4% (-26.3 to -7.4)	172.8 (99.4 to 283.7)	-42.9% (-50.3 to -31.1)	0.95% (0.55 to 1.56)	-20.1% (-30.1 to -3.8)
Luxembourg	7.2 (3.4 to 12.3)	-60.2% (-67.4 to -50.1)	1.84% (0.90 to 3.15)	-23.8% (-35.7 to -6.2)	142.1 (74.9 to 245.6)	-45.7% (-57.6 to -19.6)	0.76% (0.41 to 1.30)	-19.8% (-35.6 to 16.7)
Malta	17.7 (10.5 to 25.9)	-50.1% (-55.8 to -42.3)	4.42% (2.64 to 6.32)	-14.4% (-22.1 to -3.1)	337.2 (208.4 to 504.5)	-43.4% (-50.8 to -31.6)	1.78% (1.10 to 2.64)	-25.4% (-33.9 to -11.5)
Monaco	11.3 (6.0 to 18.3)	-35.3% (-48.4 to -14.2)	2.26% (1.24 to 3.59)	-23.4% (-34.2 to -6.0)	202.3 (113.8 to 326.3)	-23.9% (-41.0 to 3.9)	0.96% (0.55 to 1.53)	-15.3% (-29.1 to 9.7)
Netherlands	4.4 (2.0 to 8.8)	-46.0% (-56.0 to -29.7)	1.00% (0.44 to 1.98)	-21.2% (-35.8 to 2.9)	70.8 (32.5 to 136.6)	-42.7% (-55.2 to -21.6)	0.38% (0.18 to 0.72)	-26.8% (-42.4 to -0.9)
Norway	8.0 (4.2 to 13.4)	-53.6% (-60.2 to -39.3)	2.03% (1.05 to 3.38)	-23.3% (-34.3 to -0.1)	149.9 (85.2 to 249.9)	-47.8% (-58.2 to -24.3)	0.82% (0.45 to 1.35)	-28.0% (-42.1 to 4.0)
Portugal	11.4 (6.4 to 18.1)	-54.9% (-63.1 to -40.6)	2.59% (1.47 to 4.10)	-17.3% (-32.5 to 8.3)	221.5 (130.7 to 345.3)	-42.1% (-54.2 to -22.6)	1.13% (0.67 to 1.79)	-11.4% (-28.4 to 18.3)
San Marino	8.6 (4.2 to 14.9)	-28.5% (-50.3 to -2.2)	2.07% (1.13 to 3.29)	-11.3% (-21.2 to 3.5)	159.1 (86.2 to 274.6)	-13.5% (-37.0 to 16.6)	0.83% (0.48 to 1.35)	-3.3% (-19.2 to 17.9)
Spain	7.6 (4.1 to 12.5)	-51.0% (-58.8 to -38.3)	1.98% (1.05 to 3.20)	-18.0% (-31.4 to 4.0)	158.7 (88.1 to 265.4)	-37.3% (-48.7 to -19.0)	0.88% (0.49 to 1.46)	-12.1% (-26.7 to 13.0)
Sweden	7.3 (3.3 to 13.8)	-51.2% (-57.5 to -38.7)	1.85% (0.84 to 3.47)	-25.8% (-35.4 to -6.9)	118.1 (57.2 to 219.3)	-47.4% (-56.1 to -28.2)	0.66% (0.32 to 1.23)	-31.9% (-42.9 to -7.2)
Switzerland	7.8 (4.0 to 12.9)	-51.5% (-57.0 to -42.3)	2.22% (1.15 to 3.64)	-18.8% (-28.2 to -3.0)	134.4 (75.3 to 223.8)	-45.1% (-52.9 to -29.2)	0.77% (0.42 to 1.25)	-22.4% (-33.0 to -2.0)
United Kingdom	9.7 (5.3 to 16.0)	-54.6% (-59.5 to -45.1)	2.09% (1.13 to 3.43)	-30.1% (-37.6 to -15.4)	202.0 (115.8 to 337.4)	-42.7% (-53.1 to -18.9)	0.97% (0.55 to 1.59)	-25.9% (-38.3 to 4.9)
Australasia	9.3 (5.0 to 15.0)	-49.2% (-57.3 to -34.2)	2.34% (1.27 to 3.81)	-16.9% (-30.0 to 7.9)	166.6 (95.2 to 272.4)	-40.6% (-52.9 to -16.3)	0.85% (0.47 to 1.39)	-20.5% (-36.2 to 12.1)
Australia	9.1 (4.9 to 14.6)	-51.6% (-59.6 to -36.6)	2.33% (1.27 to 3.77)	-20.7% (-33.9 to 4.8)	165.3 (94.9 to 270.5)	-41.9% (-54.1 to -18.0)	0.85% (0.48 to 1.39)	-22.9% (-38.3 to 9.0)
New Zealand	10.4 (5.4 to 17.4)	-35.1% (-46.7 to -13.4)	2.41% (1.24 to 4.02)	5.5% (-12.7 to 39.9)	173.9 (94.3 to 294.2)	-33.2% (-46.8 to -5.9)	0.84% (0.45 to 1.42)	-7.7% (-26.2 to 29.8)

Abbreviations: DALYs = disability-adjusted life years; PAF = population attributable fraction; SDI = Socio-demographic Index

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The effect of training schedule and playing positions on training loads and game demands in professional handball players

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ABSTRACT: In this research, we aimed to (1) describe the differences in internal and external load between playing positions and (2) characterize the training demands of the days before competitive events for professional handball players. Fifteen players (5 wings, 2 centre backs, 4 backs, and 2 pivots) were equipped with a local positioning system device during training and 11 official matches. External (total distance, high-speed running, player load) and internal loads (rating of perceived exertion) were computed. Substantial differences were recorded between the external load variables depending on each playing position and depending on whether it was a training day (high-speed running: effect size (ES) $\geq$ 2.07; player load: ES $\geq$ 1.89) or a match (total distance: ES $\geq$ 1.27; high-speed running: ES $\geq$ 1.42; player load: ES $\geq$ 1.33). Differences in internal load were not substantial. The rating of perceived exertion, at this competitive level, does not seem to discriminate the differences registered in the external load, probably due to the degree of adaptation to the specific effort of these players. The large differences observed in external load variables should be used to tailor practices and better adjust the training demands in professional handball settings.

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INTRODUCTION

In-season load monitoring is relevant in high-performance team sports as this process gives critical information to the technical staff. This information allows coaches to adapt the training contents, helping players perform to the best of their abilities during games [1] with reduced injury risk [2]. Despite this relevance, no studies, to the best of our knowledge, have analysed the training demands in handball as in other team sports such as football [3].

Previous studies in handball suggest that many factors affect the playing demands during games. Thus, gender (women travelled higher total distance than men) [4, 5], playing level (amateur handball players accumulated a lower total distance) [6], or age (adolescent handball players showed lower levels of exercise intensity, in the second half of matches) [7] have been reported in different pieces of research. It is worth noting that many studies [5, 8] show that playing positions modulate the game demands considerably because tactical roles attributed to each playing position are very specific [9, 10].

Thus, the external [5, 8, 11, 12] and internal load game demands [13, 14]. For instance, pivots (PIV) travel lower total distances (3149 ± 639 m) [5], while wings perform the highest number of sprints [8] and cover the highest high-speed running (HSR) distances (1229 ± 129.4 m) [11]. Playing position also influences internal load substantially [13, 14]. Povoas et al. [15] found that back players and pivots had the highest average heart rate (HR) values and

total game time at intensities > 80% HRmax. Therefore, and considering these previous results, monitoring game demands is relevant. However, training sessions represent the most significant part of the weekly training load (at least in volume), and we should accurately monitor them. We hypothesize that training demands are influenced mainly by playing positions, and these differences could have substantial consequences in training load management [16] and could explain injury rates [2]. Understanding these variations may improve load management [16] and mitigate injury risks [2]. Optimizing training to prepare players for competition with specific tasks also seems essential [17].

It is also worth noting that physical profiles differ between playing positions [18, 19], also influencing training loads [20]. Thus, body dimensions are relevant as they can alter training load [21, 22]. These differences add disparity to the training response, making training individualization necessary [18, 19].

Another aspect to consider is the management of training loads to help players perform during games to the maximum of their abilities. Many studies have shown that periodization is crucial for performance [16] and injury prevention [2].

To be physically prepared for the match, players must train to develop specific physical skills (e.g., lower limb muscle power and ability to accelerate) in an optimal manner close to or superior to competitive demands [17]. The knowledge of such game demands can lead professionals to apply the approach "train as you play" [23]; however, despite its importance, there appears to be no study in handball that provides this information. We do not know, for example, whether games offer the highest load of the microcycle. It is paramount, then, to compare training and game demands. Training load management control is a crucial driver of performance in a team sport [16] and a strategic advantage for the different coaching staff [3].

The aims of this research are 1) to describe the internal and external training load differences between playing positions and 2) to characterize the training demands to compete for every training day. Therefore, we examined the differences in internal (RPE) and external (using inertial measurement units (IMUs)) loading concerning training days, playing positions, and competitive playing demands. Our findings should help coaches to design playing positions' specific training content related to game demands.

MATERIALS AND METHODS

Experimental approach to the problem

We conducted a cross-sectional, observational study to determine the differences between playing positions during games and practices of a team playing in the second division of the Spanish handball competition during the 2018–19 season. The reported results consider the average values of 11 competitive home games and 25 weeks of practice. There were usually four training sessions a week; the day before the competition (match day; MD) was MD-1, two days before the competition (MD-2), and so on until MD-5. The research data emerged thanks to the daily monitoring of the players conducted in training and competition; therefore, relevant approval of the ethics committee was not required [24]. The study was conducted

TABLE 1. Physical characteristics of the players (mean ± standard deviation).

Position	Mean (n)	Age (years)	Body mass (kg)	Height (cm)
Left wings (LW)	3	23.0 ± 0.0	78.5 ± 3.5	176.0 ± 0.0
Right wings (RW)	2	23.5 ± 0.7	73.0 ± 2.8	179.0 ± 1.4
Centre backs (CB)	3	24.0 ± 1.0	90.3 ± 9.3	190.3 ± 7.5
Left back (LB)	3	23.7 ± 0.6	93.0 ± 6.6	192.3 ± 3.5
Right back (RB)	2	23.0 ± 0.0	89.5 ± 16.3	194.5 ± 9.2
Pivot (PIV)	2	29.5 ± 4.9	100.5 ± 7.8	192.5 ± 3.5

TABLE 2. Description of the objectives, contents and orientation of the volume and intensity related to the training days.

MD	Aim	Conditional work	Static phase (%)	Full court game (%)	Volume	Intensity	Training session time (min)
MD -5	Individual development	Structural	80	20	***	**	87.9 ± 8.2
MD -4	Individual development	Structural	60	40	****	**	97.5 ± 15.7
MD -3	Tactical session	Structural	60	40	****	***	95.0 ± 11.4
MD -2	Match preparation	Optimising	50	50	***	***	90.1 ± 11.5
MD -1	Match preparation	Optimising	70	30	**	*****	86.4 ± 8.5

Note: MD: match day.

following the ethical principles for biomedical research with human beings, established in the Declaration of Helsinki of the World Medical Association (updated in 2013), and the club's managerial structure approved its implementation.

Subjects

Fifteen professional handball players participated in this study. Some of the players were internationals with their national teams as they were still in their formative stages. Players were grouped according to their usual playing position during the competition (Table 1).

Sessions and games monitoring

The study was carried out using the WIMU PRO system (RealTrack Systems SL, Almería, Spain). Each device, whose dimensions were 81 × 45 × 16 mm (height/width/depth) and which weighed 70 g, was fitted to the back of each player with an adjustable vest (Rasán, Valencia, Spain).

In training, the recording was uninterrupted. During games, playing time was only recorded when the players were on the court. The time spent between player rotation, team time outs (TTO) (a maximum of three per team), periods when the game was interrupted, and the disciplinary sanctions typical of handball, where players must leave the court for two minutes, were omitted.

Table 2 describes the different training days' main characteristics (objectives, volume, duration, intensity, static or dynamic training).

Data processing

The positioning data record was monitored in real time and subsequently analysed using the SPRO software version 946–949 (SPRO, RealTrack Systems, 2018). The system operates using triangulations

TABLE 3. Comparison of the mean value of each indicator related to training day and games. Direction of the arrow describe the magnitude of the standardized difference, horizontal arrow stand for an effect size between 0.6 and -0.6, down arrow for an effect size above 1.2, diagonal down arrow for an effect size between -0.6 and -1.2 and diagonal up for an effect size between 0.6 and 1.2.

		CB	LB	LW	PIV	RB	RW
Total distance (m)	**Game**	**4562.7 ± 928.4**	**4699.5 ± 974.2**	**4946.1 ± 1051.0**	**4084.8 ± 1263.83**	**3872.0 ± 623.3**	**5306.6 ± 1422.2**
	MD -1	↘ 3861.9 ± 627.6	→ 4347.5 ± 623.6	↓ 3826.0 ± 654.7	→ 3526.4 ± 623.9	→ 3888.2 ± 663.9	↓ 3882.3 ± 628.3
	MD -2	→ 4457.0 ± 1008.2	→ 4731.6 ± 871.8	↘ 4236.9 ± 747.2	→ 3665.6 ± 597.7	→ 4136.1 ± 881.8	↘ 4394.7 ± 897.5
	MD -3	→ 4650.1 ± 1012.7	→ 4744.1 ± 730.9	→ 4593.2 ± 928.4	→ 3913.3 ± 969.7	↗ 4413.1 ± 947.4	→ 4828.7 ± 1182.9
	MD -4	→ 5025.3 ± 1197.2	→ 5154.4 ± 1184.4	→ 4998.9 ± 1212.8	→ 4145.6 ± 819.5	↗ 4712.9 ± 1167.6	→ 5060.4 ± 1286.4
	MD -5	→ 4344.5 ± 656.2	→ 4476.6 ± 684.2	→ 4349.9 ± 870.2	→ 3678.3 ± 884.7	→ 4187.6 ± 729.1	→ 4492.8 ± 675.9
High speed (m)	**Game**	**208.9 ± 90.54**	**267.2 ± 119.0**	**549.7 ± 186.2**	**228.9 ± 139.9**	**179.9 ± 79.2**	**668.4 ± 307.5**
	MD -1	↘ 111.9 ± 84.8	↘ 138.8 ± 82.6	↓ 151.7 ± 91.8	↓ 84.2 ± 69.1	↘ 126.5 ± 84.9	↓ 212.8 ± 129.1
	MD -2	↘ 107.9 ± 80.7	↓ 130.6 ± 106.2	↓ 236.4 ± 134.8	↘ 107.5 ± 71.3	↘ 107.9 ± 118.8	↓ 273.1 ± 161.2
	MD -3	↘ 146.7 ± 127.2	↘ 142.8 ± 105.1	↘ 293.2 ± 193.1	↘ 106.9 ± 85.6	→ 145.8 ± 141.0	↘ 338.8 ± 219.8
	MD -4	→ 166.9 ± 113.6	↘ 142.3 ± 94.9	↘ 298.9 ± 171.2	↘ 121.9 ± 92.2	→ 146.2 ± 100.1	↘ 313.4 ± 192.0
	MD -5	↓ 82.7 ± 99.0	↓ 61.1 ± 82.6	↓ 167.5 ± 218.6	↘ 59.1 ± 63.5	↘ 74.2 ± 89.0	↓ 181.2 ± 232.4
RPE (AU)	**Game**	**6.7 ± 1.73**	**6.6 ± 1.9**	**7.0 ± 1.5**	**5.7 ± 2.3**	**6.1 ± 1.3**	**7.4 ± 1.3**
	MD -1	↘ 5.3 ± 0.8	→ 5.6 ± 0.9	↘ 5.8 ± 0.7	→ 5.6 ± 0.9	→ 6 ± 1.0	↓ 5.5 ± 0.9
	MD -2	→ 6.4 ± 1.1	→ 6.9 ± 1.1	→ 6.2 ± 1.4	↗ 6.6 ± 0.8	→ 6.6 ± 0.9	↘ 6.6 ± 1.1
	MD -3	→ 6.6 ± 1.3	↗ 7.3 ± 0.8	→ 6.9 ± 1.3	↗ 7.0 ± 0.9	↗ 6.9 ± 0.8	→ 7.0 ± 1.1
	MD -4	→ 6.8 ± 1.1	→ 7.2 ± 1.0	→ 6.8 ± 1.4	↗ 6.8 ± 0.9	→ 6.8 ± 1.2	→ 7.1 ± 1.4
	MD -5	→ 6.5 ± 1.4	→ 7.1 ± 1.1	→ 7.3 ± 1.2	↗ 6.7 ± 1.0	↗ 7.0 ± 0.8	→ 6.9 ± 1.4
PlayerLoad (AU)	**Game**	**69.7 ± 15.9**	**74.1 ± 17.6**	**82.5 ± 21.9**	**56.3 ± 18.9**	**60.1 ± 10.1**	**89.9 ± 30.2**
	MD -1	↘ 54.8 ± 9.1	↘ 61.1 ± 9.3	↓ 54.6 ± 8.8	↘ 44.4 ± 9.2	↘ 53.8 ± 9.7	↓ 58.6 ± 11.1
	MD -2	→ 63.6 ± 12.7	→ 65.9 ± 10.6	↘ 62.2 ± 11.7	→ 49.4 ± 9.8	→ 58.1 ± 11.8	↘ 66.2 ± 13.7
	MD -3	→ 67.7 ± 13.2	→ 68.5 ± 9.1	↘ 69.9 ± 14.3	→ 54.1 ± 13.5	→ 63.8 ± 13.3	→ 75.7 ± 15.9
	MD -4	→ 70.5 ± 14.7	→ 73.1 ± 16.4	→ 78.9 ± 22.3	→ 55.5 ± 13.1	→ 67.9 ± 16.5	→ 80.4 ± 20.1
	MD -5	→ 63.2 ± 8.3	↘ 64.8 ± 9.7	→ 71.4 ± 14.4	→ 50.2 ± 13.9	→ 61.0 ± 10.9	↘ 72.9 ± 11.4

Note: MD: Match day; CB: Centre Backs; LB: Left Backs; LW: Left Wings ; PIV: Pivots; RB: Right Backs; RW: Right Wings; RPE: Rating of perceived exertion ; AU: Arbitray Units.

between four antennas with patented ultra-wideband technology (18 Hz sampling frequency) placed 5 m away from each one of the corners of the court and at the height of 6 m. These units include several sensors that record at different sampling frequencies. The sampling frequency used for 3-axis accelerometer, gyroscope, and magnetometer was 100 Hz and 120 kPa for the barometer [25, 26].

Total distance (TD, in metres) and high-speed running (HSR, distance covered in metres above 18.1 kph) [5, 7] were extracted from the root data reported by the system using SPRO software. The player load (PL; arbitrary units, au) was calculated as the square root of the sum of the squared instantaneous rates of change in acceleration in each of the three planes divided by 100 in absolute [27].

Internal load (IL) data were obtained through the RPE-based method (arbitrary units, au) [28, 29] at 10–30 minutes following every handball training session and game.

The recording of all training sessions and games resulted in 1033 individual records for the external load and 1008 files for the internal load.

Statistical analysis

Data in the text and figures are presented as means with standard deviation (SD). All data were first log-transformed to avoid bias arising from non-uniformity errors. Standardized differences in the mean (Cohen's effect size) were calculated to compare external and internal load between and within the different playing positions during games and training sessions. Effect size comparisons were rated using the Hopkins scale: 0.2 (small), 0.6 (moderate), 1.2 (large), 2.0 (very large) [30]. The 90% confidence interval was also calculated for each effect size. Considering the high number of comparisons, the results were not analysed when the lower limit of the effect size was below 0.6. The percentage of game demands for each variable was also calculated following this formula:

Statistical analyses were performed using RStudio (v1.3) and the Esvis package (v0.3.1).

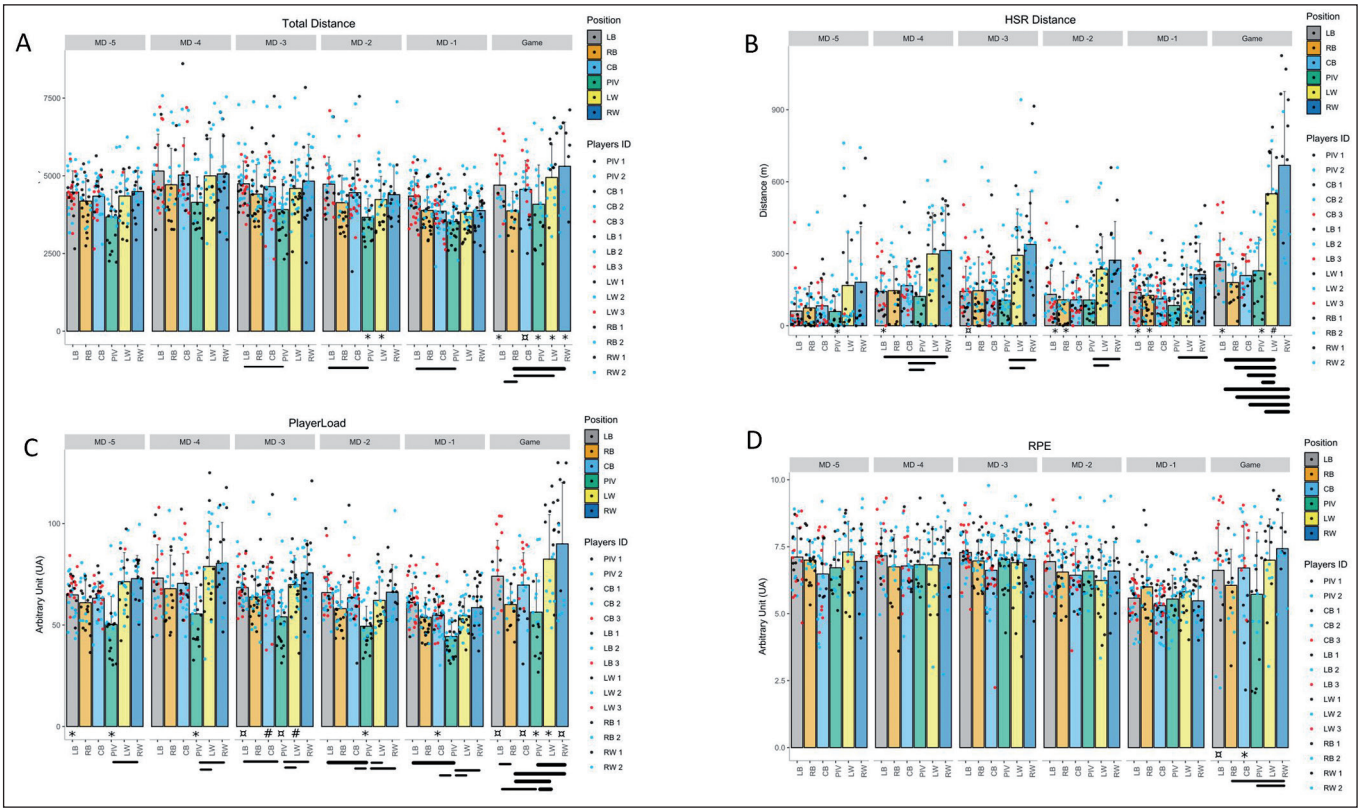


FIG. 1. Comparison between playing position related to game day and total distance (A), high-speed running distance (B), player load (C), and rate of perceived exertion (D). Bar graphs represent the mean and standard deviation for each playing position related to game day. Coloured dots stand for individual value within the playing position and game day. The thickness of the lines represents the magnitude of the difference (effect size): ▬ very large difference; — large difference; ── moderate difference. The magnitude of the difference of the within playing position is represented by ¤ when it is large very large, * when it is large and # when it is moderate. Only effect sizes with a lower limit above 0.6 are shown.

RESULTS

Table 3 summarizes each variable's mean value and standard deviation for playing positions and game day. Figure 1 shows total distance (TD), high-speed running distance (HSR), player load (PL), and rating of perceived exertion for each day of training, for each playing position, and for each player.

Game demands

During games, right backs (RB) travelled (4187.6 ± 729.1 m) largely to very largely less TD (ES range from 1.8 to 2) than the other playing positions (left backs (LB): 4476.6 ± 684.2 m, RB: 4187.6 ± 729.1 m, CB: 4344.4 ± 656.1 m, LW: 4349.8 ± 870.2 m, RW: 4492.8 ± 675.8 m) except when they were compared to PIV (PIV: 3678.2 ± 884.6 m). Wing players (RW: 668.4 ± 307.5 m, LW: 549.6 ± 186.2 m) cover very largely more HSR distance (ES range from 2.3 to 3.3) during games when compared to the other playing positions (LB: 267.2 ± 119 m, PIV: 228.9 ± 139.9 m, CB: 208.92 ± 90.5 m, RB: 179.9 ± 79.2 m). During games, RB (60.1 ± 1 au) and PIV 56.3 ± 2 au) reported up to very largely less value (for RB, ES vs. LW = 2.3, vs. RW = 2.1, vs. LB and for RB vs. LW ES = 2.3, vs. RW = 2.03) than the other playing positions (range from 69.7 ± 15 au for CB to 90 ± 30.2 au for RW). They were no substantial differences in the RPE.

Training sessions

Total distance

PIV travelled moderately to largely less distance (ES range from 1.2 to 1.6) in MD-5, MD-2, MD-1 (3678.3 ± 884.7 m, 3665.5 ± 597.6 m, 3526.4 ± 624.0 m) when compared to LB (4476.6 ± 684.2 m, 4731.6 ± 871.7 m, 4347.5 ± 623.6 m, respectively).

High-speed running

In MD-4, MD-3, and MD-2, the HSR distance travelled by PIV (MD-4: 392.8 ± 128.9 m, MD-3: 106.9 ± 85.6 m, MD-2: 107.5 ± 71.2 m) was largely to very largely lower (ES ranged from 1.3 to 2) than by wing players (MD-4, LW: 298.9 ± 171.2 m, RW: 313.4 ± 192 m, MD-3: LW: 293.2 ± 193.1 m, RW: 338.79 ± 219.8 m, MD-2: 236.4 ± 134.8 m, RW: 273.1 ± 161.2 m).

Player load

PIV showed the lowest PL value, up to largely less (ES ranged from 1.2 to 2.07) in all the training sessions and games (in MD-5: 50.2 ± 13.9 au, in MD-4: 55.5 ± 13.2 au, in MD-3: 54 ± 13.5 au, in MD-2: 49.4 ± 9.8 au, in MD-1: 44.4 ± 9.2 au). Wing players produced up to very largely higher PL (ES ranging from 1.5 to 1.8) demands in MD-5 (RW: 72.9 ± 11.4 au, LW: 71.4 ± 14.3 au), MD-4 (RW: 80.4 ± 20.1 au, LW: 78.8 ± 22.3 au), MD-3 (RW: 75.7 ± 15.9 au, LW: 69.9 ± 14.3 au).

LB showed the highest PL value in MD-1 (61.1 ± 9.3 au vs. 44.4 ± 9.1 au for PIV, LB vs. PIV, ES = 2.03).

Rating of perceived exertion

Like in matches, there were no substantial differences in the RPE, with values ranging from 5.72 ± 2.32 au for PIV to 7.43 ± 1.34 au for RW.

Games vs. training

Within playing position differences

PIV showed moderate to large within-playing-position differences during games in TD (4951.1 ± 1047.6 m vs. 3218.4 ± 779.7 m, ES = 1.97), HSR (343.6 ± 84.2 m and 114.2 ± 70.3 m, ES = 1.91), PL (68.7 ± 15.5 au vs. 44 ± 13.2 au, ES = 1.77). There were moderate to very large differences (ES 1.44 to 2.06) for LB during games in TD (4161 ± 657.5 m vs. 5400.3 ± 980.5 m), in PL (87.2 ± 15.8 au vs. 75.3 ± 10.9 au) and RPE (7.7 ± 1 au vs. 5.6 ± 1.1 au). There were large to very large within-playing-position differences in HSR distance travelled by LB (306.2 ± 355.1 m vs. 83.1 ± 162.3 m).

PIV also showed some individual differences (ES = 1.84) in the PL in MD-5 (62.8 ± 13.8 au vs. 43.8 ± 9.2 au), MD-4 (63.0 ± 10.2 au vs. 51 ± 13 au), MD-3 (62.6 ± 10.9 vs. 44.2 ± 8.4 au), MD-2 (55.9 ± 9 au vs. 43.5 ± 6 au).

Figure 2 shows the coefficient of variation for all the metrics in each playing position for the different training days. HSR distance showed a higher variation (77.3% to 87.9%). When considering playing position and training days, HSR distance in MD-5 had the highest percentage of variation (107% for PIV to 135% for LB, 123.5 ± 9.8%). Games were the sessions with the lower CV (33.9% for LW to 61.1%, 45.5 ± 8.8%) for HSR.

Figure 3 illustrates the difference between playing positions expressed in the percentage of variation related to the mean game demands in the different variables. LB and RB showed a moderately to largely higher percentage of mean game demands in MD-1 when compared to wing players in TD (LB: -7.5 ± 13.3%, RB: 0.41 ± 17.15%, LW: -22.6 ± 13.2%, RW: -26.8 ± 11.8%; ES from 1.14 to 1.81), in PL (LB: -17.4 ± 12.5%, RB: -10.5 ± 16%, LW: -33.8 ± 10.6%, RW: -34.9 ± 12.3% and ES from 1.38 to 1.71).

PIV showed up to largely higher percentage of mean game demands in RPE value in all training sessions (MD-5: 17.3 ± 17.6%, MD-4: 19.4 ± 16.1%, MD-3: 22.9 ± 16.8%, MD-2: 15.3 ± 14.2%, MD-1: -3 ± 15.5%, ES from 1.26 to 1.83) when compared to the other players (MD-1: from -15.6 ± 13.8% to -26.2 ± 12.5%, MD-2: range -11 ± 14% to 8.19 ± 13.9%, MD-3: 15 ± 13.3%, MD-4: -4.6 ± 18.5 to 11.4 ± 19.9%, MD-5: -3.3 ± 20% to 15.5 ± 12.6%).

RB followed the same pattern in MD-5, MD-3, MD-2, and MD-1 (ES from 1.14 to 1.68). RB (29.7 ± 47.17%) reached a moderately to large higher percentage of mean game demands in high-speed running compared to wing players (LW: -72.4 ± 16.7%, ES = 1.21, RW: -68.1 ± 19.3%, ES = 1.03) in MD-1.

There were large differences in the percentage of mean game demands between PIV in MD-2, MD-3, and MD-4 (respectively, -22.8 ± 10.7% vs. -0.8 ± 16.1%, ES = 1.6, -21.5 ± 14.9% vs. 11.1 ± 19.5%, ES = 1.85, -24.5 ± 5.3% vs 5.4 ± 23.5%, ES = 1.51).

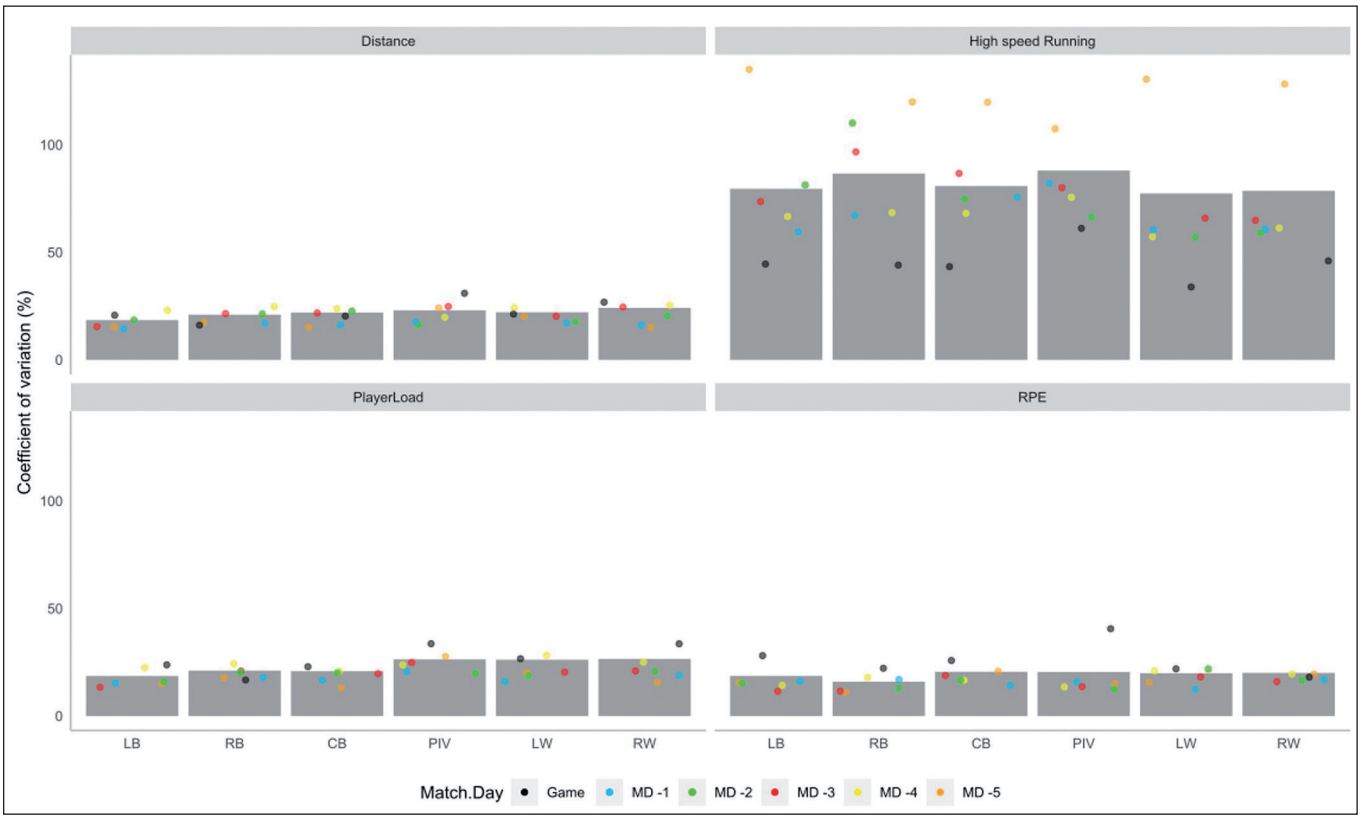


FIG. 2. Coefficient of variation for all the metrics in each playing position for the different training days.

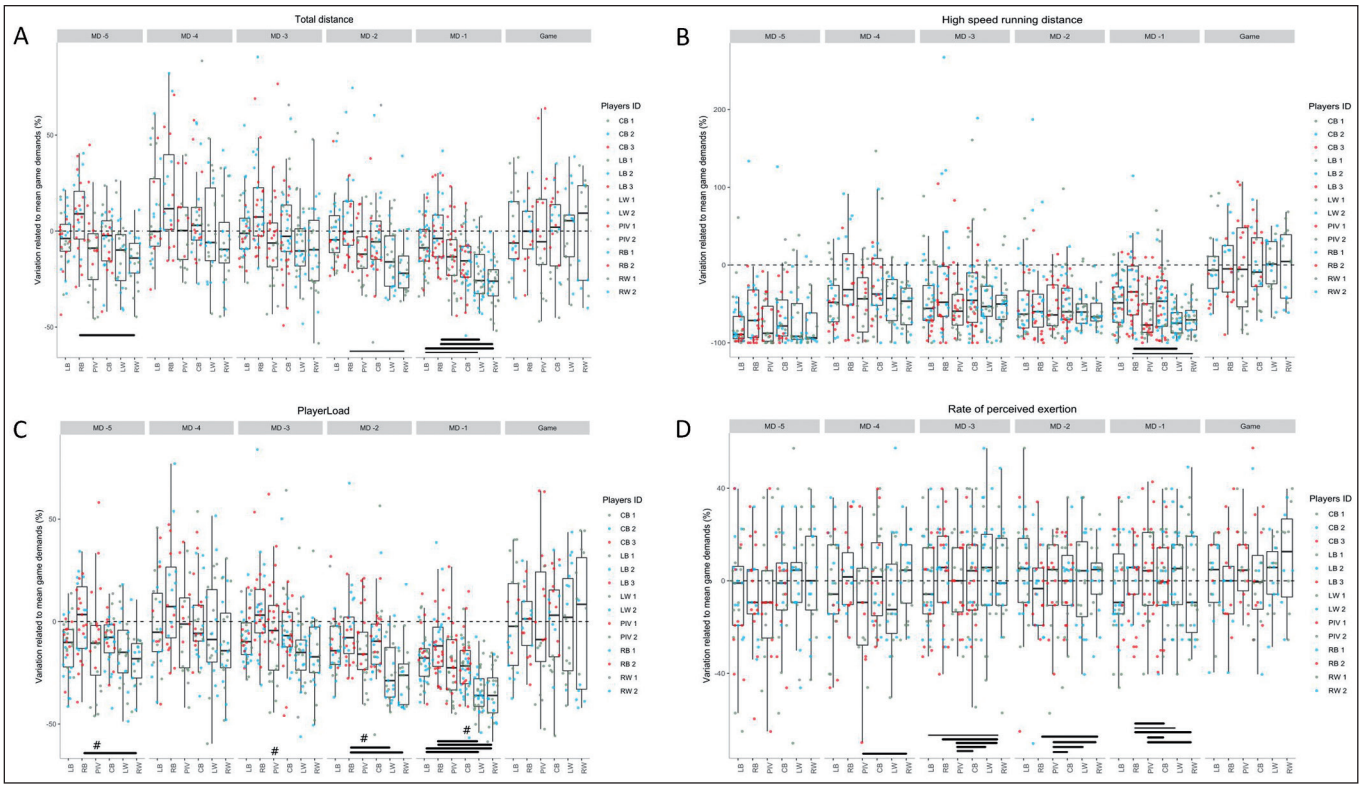


FIG. 3. Comparison of mean percentage of game demands between playing position related to game day in total distance (A), high-speed running distance (B), player load (C), and rate of perceived exertion (D). Bar graphs represent the mean and standard deviation percentage of mean game demands for each playing position related to game day. Coloured dots stand for individual value within the playing position and game day. The thickness of the lines represents the magnitude of the difference (effect size): ▬ very large difference; ▬ large difference; ▬ moderate difference.

DISCUSSION

To our knowledge, this is the first time a handball team has been monitored longitudinally during a season in practices and games with a combination of IMUs and RPE. The most significant differences between playing positions were noted on match days, showing that training does not replicate game demands. PL and HSR were the metrics with the most important differences. When the difference between playing positions was expressed as the percentage of variation related to the mean game demands, the most important differences were found in MD-1 and the RPE.

Match days

Regarding the external load in games, our results on match days are in line with previous studies. The wings (left (LW) and right (RW)) are, by far, the players who cover the most metres in HSR, both in training and in games. These results match those observed in earlier studies [5, 10, 12]. RW and LW were the players who covered the highest distance and RB the lowest. A similar effect has been found in previous studies [12].

Wings were also the players with the highest PL values compared to the other positions. These results differed from previous studies finding that CBs were the players with the highest PL value. Player rotation and team tactics could explain some of these differences because the nature of this playing time affects PL [31] substantially. In team handball, player rotations are unlimited and very easy to implement. As a result, many factors could explain this variation, such as players' performance level (the better they are, the longer they tend to play), the tactical choice of the coach, or game model requirements. PL has been developed as a measure of physical performance based on changes in acceleration to capture non-running-based work (e.g., jumping, changes of direction, acceleration, contact) [5].

PIV and RB had the lowest IL concerning the other positions. This result could be related to different players' rotation strategies. In many teams, RB are the players involved in the offensive/defensive systematic rotations for various reasons, such as a lack of defensive ability or fatigue management (RB need to be tall and left-handed and are essential for most teams). PIVs' performances are paramount for many teams, and the physical demands they must cope with are high [9]. As a result, many coaches tend to establish more rotations for the PIVs.

Training session

Total distance

PIV covered less distance than the other players during all training sessions (up to moderate to largely less than LB). The tactical and technical demands of the playing position likely play an important role. PIV players were a fixing point in the opponents' defence when backs played more around the defensive system. A vital part of handball training is devoted to the stabilized phase (Table 2), accounting for most ball possession in matches [32]. This result should be related to the main objective, the relative part of the session's static/full court phases, and the volume/intensity choice. It is expected that when training sessions are focused on static phases, PIVs do not accumulate many metres due to their defensive fixation function, performing more isometric or dynamic muscular actions. In turn, even if the training session is more dynamic (full-court situations), they tend to carry out the same function. Thus, they cover less distance and perform fewer running actions. These results are in line with those obtained in other studies where the PIV were the players who covered the lowest distance in official matches [5].

When expressed as a percentage of mean game demands, we can see that RB achieve a higher value than the other positions in many parts of training sessions. It is very likely that when there is a less stabilized phase in training (when coaches want their players to run more), the RB achieve a higher percentage as they run less than the other players in games. In training, all players tend to train simultaneously and perform the same tasks. These differences in RB (and to a lesser extent for LB) could be attributed to a higher rotation in playing time due to the demands on these positions according to the team's playing model [5].

High-speed running distance

Wings covered higher HSR distance in all training sessions than the other playing positions. These results confirm that training requirements are not always in line with game demands [5, 10, 12]. HSR distance is an essential metric for performance [33] and injury prevention [34]. Our findings support the idea of Karcher & Buchheit [9] that there is a need for specific sprint training and hamstring prevention work for wings. The HSR percentage of mean game demands suggests that training sessions do not replicate the competition load as the HSR distance is lower than the match demands in all training sessions for all players (Figure 3). This lack of specificity can lead to some issues in some players, especially wings (who cover the highest HSR distance, such as decreasing their performance [5, 12] and increasing their risk of injury [9]. HSR distances should be close to or above those required by the competition to allow players to cope with these demands [17].

Moreover, the coefficient of variation of HSR showed that this variable fluctuated a lot. Large differences were found in all playing positions depending on MD. This variation suggests that the technical and tactical objectives of the training largely influence the HSR content and that this variable is not always adequately managed [9]. Our results indicate that HSR distance is mainly subjected to tactical choices.

Player load

Our results showed a large variation in PL when comparing the different playing positions. This fact confirms that each player needs a training load as individualized as possible; the external load demands differ for each playing position [5, 6, 29]. At the same time, it was observed that MD-4 was the day that was closest in terms of PL to the competitive needs. As seen in Figure 2, MD-4 was the day when

the greatest volume of work was carried out both in terms of time and full court work and when the highest PL values could be accumulated.

PL is one of the most used variables to control the external load in training and competition in handball [5, 6, 29]. PIV were the players with the lower PL values in competition and the different training sessions. The specific demands of the position at a physical, technical, and tactical level may explain this result [5]. Most of the needs of these players are based on isometric strength work, as they were the players who were the most involved in contact actions and with few accelerations and lower high-velocity displacement [9, 22]. Wings showed the highest PL value in any training session, following the other external load variables (total distance and HSR). These differences between positions could be explained by the tactical demands of each position, their needs, and the game model used by the team [5].

Rate of perceived exertion

Our results suggest that players rated the session with similar intensities despite many differences in the external load (e.g., HSR distance). Surprisingly, the internal load did not reproduce the same pattern as the external loading. We could suggest two explanations for this offset. Firstly, the extensive experience of the players in handball and years working with the same methodologies in the same club (3.3 ± 2.2 years in the club) may have caused a specific adaptation [17]. Secondly, many players' characteristics influence internal load values, such as muscle mass, substrate concentrations [35], body size [22], or fitness level [36]. As a result, two players receive equivalent external loads, but the internal load could differ depending on individual characteristics. The player's physical characteristics and body dimensions are position-dependent [6, 18, 21]. Overall, these factors mainly explain the results.

Comparing the values obtained during training sessions and games, we see that the results are often higher after training. These differences indicate that training and rest time density is much higher during the week than on MD. There are likely more in-game breaks due to the refereeing, the opponent's game pace, and the player's rotation strategies.

The differences in the percentage of variation considering the mean game demands are probably caused by the discrepancies between training and game values. Game demands fluctuate greatly when compared to the training context.

Coefficient of variation

The coefficient of variation is related to periodization, as variations in training load are a key and widely studied factor in performance [37]. Many studies suggest that poor training-load management and flawed prescription constitute significant risk factors for injury [38]. Our results show that games are the moment with the highest fluctuations in most of the variables. This is logical, considering that teams do not have control over the opponent's executions. Most CVs are low and show a small magnitude (18 to 29%) except for HSR. HSR's CV showed values ranging from 57 to 135%. Large differences were found in all playing positions depending on MD. This variation suggests that the technical and tactical objectives of training largely influence HSR content and that this variable is not managed [9]. These results indicate that HSR distance is a by-product of tactical choices. Too much variation in the same training days illustrates, from our point of view, that coaches do not control this variable. It is also worth noting that HSR distance was much higher during games than during training sessions, as training content does not replicate HSR game demands.

Limitations

We could only study one professional team with a particular match and training model. The team's profile (only one match per week) also allowed us to have stable microcycles that may not be generalizable to other contexts (teams playing more than one match per week, national teams). Another limitation is that the analysis of defensive specialists was not considered. Some players have a particular role, playing only during the defensive phase, and are not included in the attack. The type of training provided by the coaching staff, and its intensity, also influence the training demands to a large extent and can be a limitation. Other parameters, such as different playing strategies [39], the opponent's level [40] and the use of a defensive specialist, may have revealed different results than ours.

Practical applications

Coaches must consider variables such as positional demands or the team's playing style to tailor training demands. Our results show that coaches should carefully evaluate several indicators to design the optimal training content. In our data, some values in the training sessions were above the game demands (total distance, RPE) and others under (HSR, PL). This scenario can be suboptimal to prepare players for the "worst case scenario" in competition.

It is worth noting that training demands differ largely between positions (wings and PIV vs. RB). Handball staff should use this information before designing microcycles to adjust training loads more precisely.

CONCLUSIONS

We observed that internal load does not show the same pattern even if there are substantial differences in external load variables between playing positions. Our results confirm the need to control the load and the complementarity of the two types of load variables. One of the most relevant findings was the substantial variation in HSR between positions, games, and training sessions. Coaches must give special attention to HSR because it is an essential variable for injury prevention (9) and performance (12).

Further research is needed in handball to study the parameters that influences the behaviour of internal and external loading variables to optimize training.

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Disclosure statement

The authors declare no potential conflicts of interest.

Conflict of interest declaration

The authors declare no potential conflict of interest.

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Effects of different maturity status on change of direction performance of youth tennis players

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ABSTRACT: The aim of this study was to examine the maturational status (i.e., peak height velocity [PHV]) differences in neuromuscular performance (i.e., vertical jump, linear sprint, change of direction (COD) using different tests, and change of direction deficit [CODD]) of young tennis players. One hundred and two tennis players (70 boys and 52 girls; age 13.9 ± 2.0 years, body mass 53.3 ± 12.7 kg, height 163.1 ± 11.9 cm) participated in the study and were divided into Pre-PHV (n = 26), Circa-PHV (n = 33) and Post-PHV (n = 43) groups. Testing included speed (5, 10, and 20 m), COD tests (i.e., modified 5-0-5, pro-agility and hexagon), and bilateral/unilateral countermovement jump (CMJ). Pre- and Circa-PHV players presented lower levels of performance in jumping ability (i.e., both bilateral and unilateral CMJs; $P < 0.001$; ES: 0.85 to 0.98), linear sprints (5 to 20 m; $P < 0.05$ to < 0.001; ES: 0.67 to 1.19) and COD ability tests (modified 5-0-5 test, pro-agility and hexagon) compared to the Post-PHV players. Moreover, Pre-PHV players presented lower CODD% ($p < 0.05$; ES: 0.68–0.72) than Post-PHV for both forehand and backhand sides, and Circa-PHV showed lower values in the CODD of the rolling situation to the forehand side ($p < 0.05$; ES: 0.58). Among the COD tests, the pro-agility test seems to be a simple, easy-to-implement and reliable test, which can provide interesting information about the COD with higher entry speeds. Moreover, specific training strategies related to the PHV and focused not only on the neuromuscular training and COD workouts, but also on maximizing motor skill proficiency, should be recommended.

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Change of direction deficit

INTRODUCTION

The design and implementation of athletes' training programmes should be related to the physical requirements as well as movement demands of the sport [1]. In this regard, tennis-specific research has explored the activity profile and physiological demands of tennis movement extensively [2–4], highlighting tennis as an intermittent sport that involves short bursts of intense activity (i.e., accelerations, decelerations, changes of direction (CODs), and strokes), during a variable period of time (i.e., to the best of 3 sets in junior levels, up to 5 sets in the Grand Slam tournaments) [5]. Previous research has shown that 80% of all tennis strokes are played covering less than 2.5 m, and fewer than 5% of strokes require more than 4.5 m between strokes [6], suggesting that accelerations, decelerations and CODs are of primary importance in tennis in comparison with maximum sprinting speed [7]. CODs, including deceleration followed immediately by reacceleration of the entire body or an individual body segment [4], occur at nearly every point in tennis and can be considered one of the most important physical skills needed to be a successful tennis player at any level.

Although every tennis point is different, and COD performance depends on a complex interaction of contributing movement variables such as acceleration, entry velocity, distance covered, and degree of change [8], its relevance is well established [9, 10]. However, perhaps due to this complexity, research into the tennis-specific COD is limited, with the earliest research describing players performing 1 to 4 four CODs per point [11]. More recently, and with the use of player tracking technology (i.e., Hawk-Eye), research reported an average of 5 CODs per point, with some variation depending on the participant's level and sex [4]. Thus, in a more complex analysis [12, 13], it was concluded that professional male and female tennis players performed around 2 CODs during a typical point, characterized by medium to high intensity, and involving basically lateral COD, supporting previous observations [6, 14], highlighting the

lateral nature of the tennis player's movement. As a result, in a competitive match, it is not uncommon for players to perform between 250 and 400 CODs [12].

The evolution of technical and tactical performance in tennis has been accompanied by a progressive increase in game speed [15], which in turn forces athletes to play closer to the margins of the court from an early age [4]. Thus, COD performance has been considered one of the most important physical qualities in the sport, with a recent study showing that COD speed was strongly related to tennis performance (i.e., ranking position) in a sample of 1434 youth tennis players (i.e., 11–17 years). However, tennis-specific information about COD testing and training is still scarce, with very few studies analysing this physical quality [16–18], as well as differences among levels, ages and sexes [19].

Testing the COD ability has received much attention in the last few years, with a wide variety of tests that measure COD ability [20] and employed in different intermittent sports, including tennis [10]. In general, protocols differ in terms of complexity and duration, and the selection of a COD test will depend on the athlete, sport and stage of development [21]. The '505 change of direction test', which requires players to sprint 5 m, turn 180°, and sprint a further 5 m, including a 5 m flying start [22], is probably the most popular test used in intermittent sports. Based on this test, and its comparison with linear sprints (e.g., 5 to 20 m), Nimphius et al. [23] introduced the concept of COD deficit (COD_{def}), representing the additional time or velocity that a COD requires when compared with a linear sprint over an equivalent distance (e.g. 10-m time vs. 505 time). More recently, a new standardization of the COD_{def} calculation was presented, based on the percentage difference between COD and linear sprint tests (i.e., CODD%) [24]. Researchers suggested that the use of CODD% may be advantageous for practitioners as it reports CODD in a comprehensive, uniform, and consistent manner.

Depending on the sport-specific needs, COD tests may require a low-velocity COD, such as the modified 505 test (i.e., using a stationary start); a high-velocity COD, such as the traditional 505; or a test such as the pro-agility test, which requires both a low-speed and high-speed COD that can be split [25]. In this regard, since CODs occur from various distance approaches in sport, it seems interesting to assess not only the COD_{def} following a static start (i.e., using the modified 505 test), but also the COD_{def} following a rolling start, characterized with higher entry speeds [25]. To the best of our knowledge, only one previous study has used the pro-agility test as a measurement tool in tennis players, reporting that the test was a reliable and valid test for use in competitive junior tennis players [26]. However, there is no information about the relationship between this test and linear sprint, other COD tests and jump performances in tennis players across different maturational statuses. By providing normative data, it enables practitioners to identify, monitor and develop players' performance through effective strategies for improving COD ability.

Therefore, the aim of this study was to examine the maturational status (i.e., peak height velocity [PHV]) differences in neuromuscular performance (i.e., vertical jump, linear sprint, COD using different tests, and change of direction deficit [CODD]) of young tennis players.

MATERIALS AND METHODS

Design

The current investigation is an observational and descriptive analysis to determine maturational status differences in measures of linear sprint, jumping performance, and COD ability in youth tennis players. Testing protocols were conducted over a 4-week period beginning at the end of February 2022, and sessions were undertaken between 12:00 pm and 5:00 pm, with the players being tested at their

TABLE 1. Descriptive characteristics of junior tennis players according to their maturational groups.

	Players (n = 102)	Maturational groups		
		Pre-PHV (n = 26)	Circa-PHV (n = 33)	Post-PHV (n = 43)
Chronological age (years)	13.9 ± 2.0	11.9 ± 1.2$^{\$\#\#\#}$	13.3 ± 1.1$^{\#\#\#}$	15.6 ± 1.6
Height (cm)	163.1 ± 11.9	150.8 ± 7.2$^{\$\$\#\#\#}$	162.1 ± 8.2$^{\#\#\#}$	171.3 ± 9.4
Body mass (kg)	53.3 ± 12.7	41.6 ± 7.9$^{\$\#\#\#}$	51.1 ± 9.2$^{\#\#}$	62.1 ± 11.0
APHV (years)	13.5 ± 1.1	13.8 ± 0.9	13.4 ± 1.2	13.4 ± 1.1
Maturity offset (years)$^{\&}$	0.4 ± 1.8	-1.9 ± 0.7$^{\$\$\#\#\#}$	-0.1 ± 0.6$^{\#\#\#}$	2.2 ± 1.0
Training volume (h · week^{-1})	10.3 ± 4.3	8.9 ± 4.2$^{\#}$	9.7 ± 4.1	11.4 ± 4.4

The values presented are means ± SD. Pre-PHV: pre peak height velocity group; Circa-PHV: around peak height velocity group; Post-PHV: post peak height velocity group; APHV: Estimated age at peak height velocity. $^{\&}$Estimation of years from predicted PHV. $^{\$}$significantly different from Circa-PHV group ($p < 0.05$). $^{\$\$}$significantly different from Circa-PHV group ($p < 0.001$). $^{\#}$significantly different from Post-PHV group ($p < 0.05$). $^{\#\#}$ significantly different from Post-PHV group ($p < 0.01$). $^{\#\#\#}$significantly different from Post-PHV group ($p < 0.001$).

respective tennis clubs. All tests were performed in the same order using the same testing devices, measurement protocols, and experienced evaluators. The testing took place on an outdoor synthetic court (temperature, 17.5–24 °C; relative humidity, 60–66.0%; Kestrel 4000 Pocket Weather Tracker, Nielsen Kellerman, Boothwyn, PA). Subjects were instructed to avoid all sources of caffeine for 24 h before testing and to have their habitual breakfast at least 3 h before the start of measurements.

Subjects

One-hundred and twenty-two junior tennis players (70 boys and 52 girls; age 13.9 ± 2.0 years, body mass 53.3 ± 12.7 kg, height 163.1 ± 11.9 cm, estimated age at peak height velocity (PHV) 13.5 ± 1.1 years) took part in this study (Table 1). The sample was composed of competitive players with similar competitive levels and technical abilities from eight different tennis clubs selected by the coaching staff. All players followed similar training schedules, including mixed participation (boys and girls training at the same time), and the organization of training groups based on the chronological ages (U13 and U15). The staff of the different clubs sent an electronic document with information about the number of injuries and the number of training hours. Thus, players included in the study completed 10.3 ± 4.4 h of combined tennis and physical training per week and had a minimum training background of 4.2 years. None of the players reported any history of chronic medical conditions during the previous 12 months. Before taking part in the study, the subjects and their parents/guardians were fully informed about the study protocol and provided their written informed consent. The Spanish Tennis Federation Ethics committee approved the procedures (RFET.EC_21.3) in accordance with the latest version of the Declaration of Helsinki.

Procedures

Maturity status

Body height was measured using a fixed stadiometer (± 0.1 cm; Holtain Ltd., Crosswell, UK), sitting height with a purpose-built table (± 0.1 cm; Holtain Ltd., Crosswell, UK), and body mass with a digital balance (± 0.1 kg; ADE Electronic Column Scales, Hamburg, Germany). Pubertal timing was estimated according to the biological maturation of each individual using a predictive equation previously described in the literature [27]. The age of peak linear growth (age at peak height velocity [APHV]) is an indicator of somatic maturity representing the time of maximum growth in stature during adolescence. Maturity offset (MO) was achieved in a non-invasive manner using the regression equation previously proposed [28]. Moreover, to account for the reported error, players were grouped into discrete bands based on their MO (pre-PHV [< -1], Circa-PHV [-0.5 to 0.5], post-PHV [> 1]), and players with a maturity offset from -1 to -0.5 (n = 10) and 0.5 to 1 (n = 20) were removed from the dataset when players were analysed by stage of maturation. Overall, 102 players (63 boys and 39 girls) were finally included in the study.

Countermovement jump (CMJ) test

A bilateral CMJ and unilateral (i.e. dominant [CMJD] and non-dominant [CMJND] side) CMJs were performed using an OptoJump photoelectric system (Microgate, Bolzano, Italy) and according to the protocol previously described [10]. During the jump, hands were held at the hips to minimize the influence of the upper body on jump performance. From a standing position with straight knees, players squatted down to ~90º and accelerated at maximal velocity in a vertical direction. Each player performed 3 maximal attempts interspersed with 45 s of passive recovery, and the highest jump was recorded and used for statistical analysis.

Sprint test

Time during a 20-m linear sprint (with 5 and 10 m split times) was measured by means of single beam photocell gates placed 1.0 m above the ground level (Witty System, Microgate, Bolzano, Italy). Each sprint was initiated 0.5 m behind the first photocell gate, which then started a digital timer. Players started the linear sprint test in a standing split position, with their preferred foot behind the starting line, followed by accelerating forward at maximal effort until they passed the last photocell gate placed at 20 m. Each player performed three maximal 20-m sprints with at least two min of passive recovery in between the trials, and the average performance was calculated.

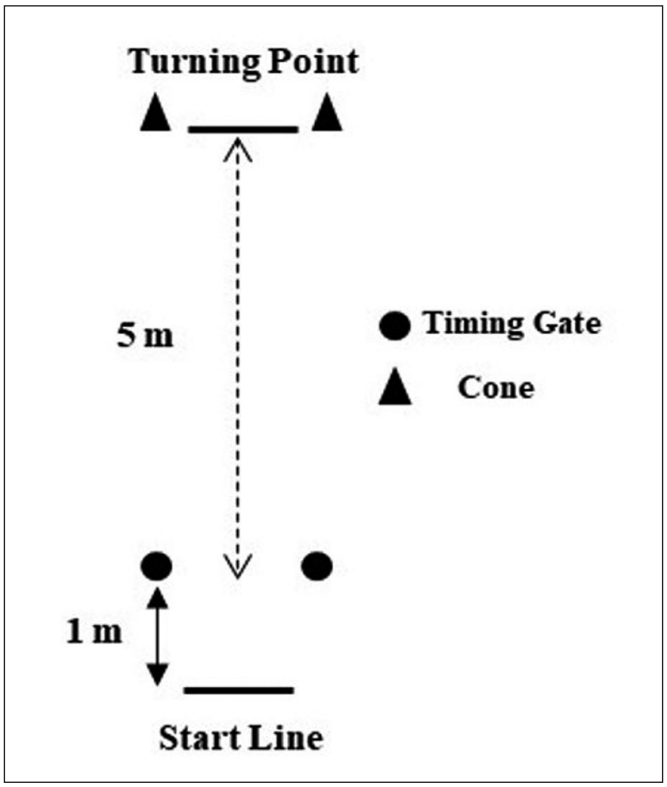


FIG. 1. Structure and dimensions of the modified 505 change of direction test.
Note: m = meters.

Modified 505 COD test

The abilities of the athletes to perform a single, rapid 180° change of direction over a 5 m distance was measured using a modified version (stationary start) of the 505 COD test [10] (Figure 1). Players started in a standing position with their preferred foot 0.5 m behind the starting line. They were asked to plant their preferred (i.e., considered as the dominant side) foot on executing the turn. Three trials were completed, and the best time was recorded (Witty System, Microgate, Bolzano, Italy). Two minutes of rest was allowed between trials [23]. The CODD% was calculated following the formula: CODD% t = ([*modified 505 time – 10-m sprint time*]/*10-m sprint time*)*100 [24].

Pro-Agility test

For the pro-agility test, players started from a line placed 0.5 m from the start line, facing perpendicular to the running direction. The test was conducted in the baseline of a tennis court, in order to simulate as much as possible a specific movement. The players were instructed to initiate the trials when they were ready (i.e., self-selected start), sprinted 5 m to the forehand side (i.e., right side for a right-handed player, and considered as the CODD% of the static situation), then 10 m to the backhand side (i.e., left side for a right-handed player, and considered as the CODD% of the rolling situation), and 5 m back to finish the test as they crossed the centreline (Figure 2) [25]. Three trials, interspersed with two min of passive recovery, were recorded for both the forehand and the backhand side, the order of which was randomized. The CODs within each test were conducted on alternative legs (i.e., for a right-handed player, when they ran to the forehand side, players used the right leg on the COD, and the left leg when they ran to the backhand) [9]. A researcher was positioned at each turning line, situated 60 cm after each photocell, and if the player changed direction before hitting the turning point, or performed the COD with the wrong foot, the trial was disregarded and repeated after a recovery period. Both the forehand and backhand side trials were recorded and used for further analysis [29]. Thus, the CODD% was calculated in both static and rolling situations, following the formula: *staticCODD% t* = ([*first 10 m of the pro-agility – 10-m time*]/*10-m sprint time*)*100; and *rollingCODD% t* = ([*first 10 m of the pro-agility – 10 to 20 m split time*]/*10 to 20 m split time*)*100.

Hexagon test

The hexagon test requires the player to stand facing forward in the middle of a hexagon measuring 60 cm per side and with 120-degree angles. With feet together and hips facing forward throughout the test sequence, subjects hopped forwards and backwards in a clockwise manner over each of the six sides of the hexagon, completing three sequences [30] (Figure 3). Each repetition was recorded using a mobile phone (iPhone XS; Apple Inc., Cupertino, CA, USA) running iOS 13.7 that was secured to a small tripod with a mount (GripTight Mount Pro, Joby, USA) and positioned 2 m from the hexagon. All trials were recorded at 240 Hz, and the time to complete three sequences was later analysed with video analysis software (Kinovea version 0.8.15, available for download at: http://www.kinovea.org). A penalty of 0.5 s was given each time the player touched a line, and a 1.0 s penalty was given if the player failed to follow the correct sequence [30]. A practice attempt was given prior to the three attempts used for analyses, with a two min rest between them. The fastest time of three attempts was used for analysis.

Statistical analysis

Descriptive statistics (mean and standard deviation) were calculated for each of the variables. The Kolmogorov–Smirnov test was applied to determine whether data sets were normally distributed.

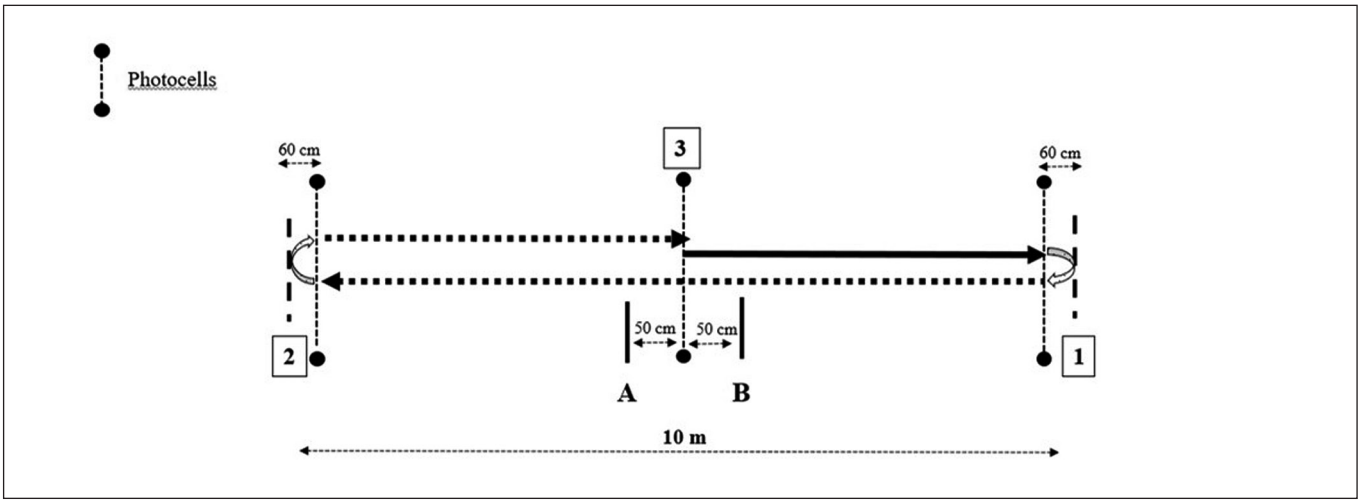


FIG. 2. Schematic representation of the pro-agility test.
Note: A: Starting line for a right-handed player moving to the forehand side; B: Starting line for a right-handed player moving to the backhand side; 1: Change of direction in the static situation; 2: Change of direction in the rolling situation; 3: Finish

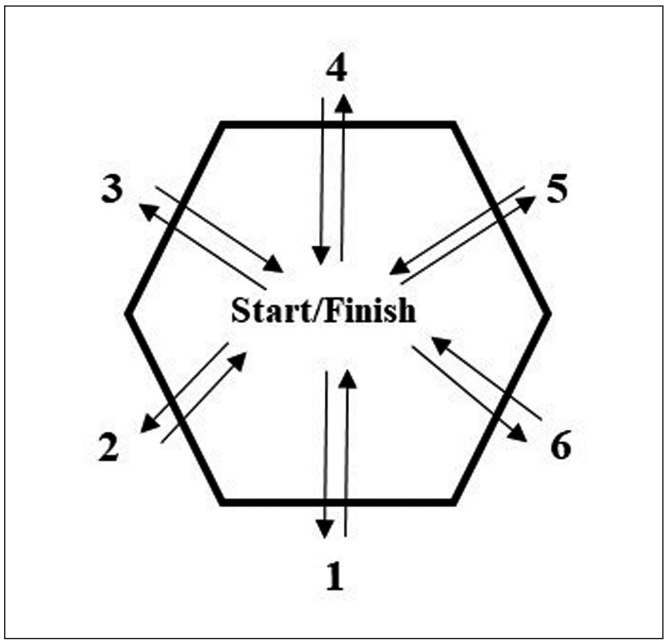


FIG. 3. Schematic representation of the hexagon test.

Within-session reliability of test measures were assessed using intraclass correlation coefficients (ICC) and the coefficient of variation (CV) with their corresponding 95% confidence intervals, respectively. We considered an ICC < 0.50 as poor, $0.50 \leq$ ICC < 0.75 as moderate, $0.75 \leq$ ICC < 0.90 as good, and ICC > 0.90 as excellent [31]. Absolute reliability was calculated using the standard error of measurements (SEM), which was calculated as SD $\times \sqrt{1}$ - ICC, where SD is the SD of all scores from the subjects [32]. The SEM was used to calculate the minimal detectable change (MDC) and was calculated as SEM $\times 1.96 \times \sqrt{2}$ to construct a 95% CI [32]. A paired t-test was used to assess the potential differences between sides during the pro-agility test, as well as between CODD% in the static and rolling situations. In order to investigate the differences caused by maturation, one-way independent-measures analyses of variance (ANOVAs) were performed, and the Bonferroni post-hoc test was used to aid in the interpretation of the results. Differences between genders were compared using an independent sample *t*-test. Effect sizes (ES) were calculated to estimate the magnitude of differences in the tested variables and interpreted using the following thresholds: $<$ 0.2, trivial; $\geq$ 0.2 to 0.49, small; $\geq$ 0.5 to 0.79, moderate; and $\geq$ 0.8, large [33]. Precise p-values were reported, and the significance level was set at p (probability of type I error) $< \alpha = 0.05$. All statistical analyses were performed using IBM SPSS Statistics 26.0 (SPSS, Inc., Chicago, IL.).

TABLE 2. Within-session reliability of test measurements.

	ICC (95% CI)	CV (%) (95% CI)	SEM	MDC
		Vertical jumping ability		
CMJ (cm)	0.985 (0.974–0.992)	3.45 (2.65–4.24)	0.76	2.11
CMJD (cm)	0.927 (0.843–0.963)	7.86 (6.08–9.65)	1.02	2.82
CMJND (cm)	0.962 (0.927–0.980)	6.84 (5.15–8.52)	0.76	2.11
		Linear sprinting ability		
5 m (s)	0.975 (0.948–0.988)	2.34 (1.70–2.98)	0.02	0.04
10 m (s)	0.990 (0.981–0.995)	1.36 (0.88–1.95)	0.02	0.04
20 m (s)	0.990 (0.982–0.995)	1.09 (0.75–1.42)	0.03	0.09
		Change-of-direction ability		
M505 (s)	0.925 (0.837–0.961)	2.23 (1.77–2.70)	0.10	0.28
CODD%	0.957 (0.871–0.986)	2.44 (1.62–3.25)	0.03	0.08
Hexagon (s)	0.824 (0.729–0.908)	4.34 (3.43–5.26)	0.35	0.97
Pro-Agility (s)	0.849 (0.775–0.898)	2.10 (1.58–2.63)	0.17	0.46
CODD%_S	0.874 (0.648–0.960)	3.65 (2.71–4.59)	0.05	0.15
CODD%_R	0.940 (0.822–0.980)	2.89 (2.12–3.65)	0.06	0.17

ICC = intraclass correlation coefficient; CV = coefficient of variation; CI = confident interval; SEM = standard error of measurement; MDC = minimal detectable change; D: dominant side; ND: non-dominant side; CMJ: countermovement jump; M505: modified change of direction test; CODD%: Percentage-based COD deficit; CODD%_S: percentage based CODD in the static situation; CODD%_R: percentage based CODD in the rolling situation.

TABLE 3. Differences between maturational groups on vertical jump, linear sprint and change of direction abilities.

	Maturational groups			One-way ANOVA	Effect size (90% IC)		
	Pre-PHV (n = 26)	Circa-PHV (n = 33)	Post-PHV (n = 43)	*P*-value	Pre-PHV vs. Circa-PHV	Circa PHV vs. Post-PHV	Pre-PHV vs. Post-PHV
Vertical jumping ability							
CMJ (cm)	25.0 ± 4.3$^{\$\$}$	24.6 ± 4.8$^{\$\$\$}$	30.4 ± 6.5	< 0.001	-0.09 (-0.53–0.34)	0.98 (0.58–1.38)	0.98 (0.54–1.41)
CMJ D (cm)	12.3 ± 3.2$^{\$\$}$	13.0 ± 2.9$^{\$\$\$}$	16.4 ± 3.9	< 0.001	-0.07 (-0.51–0.36)	0.98 (0.58–1.38)	0.89 (0.46–1.31)
CMJ ND (cm)	13.5 ± 3.2$^{\$\$}$	13.1 ± 3.0$^{\$\$\$}$	16.6 ± 4.1	< 0.001	-0.11 (-0.54–0.33)	0.96 (0.56–1.36)	0.85 (0.42–1.27)
Linear sprinting ability							
SP5 (s)	1.25 ± 0.1$^{\$\$}$	1.23 ± 0.1$^{\$\$}$	1.12 ± 0.2	< 0.01	-0.21 (-0.65–0.33)	-0.73 (-1.12– -0.34)	-0.85 (-1.27–0.42)
SP10 (s)	2.15 ± 0.14$^{\$\$}$	2.09 ± 0.13$^{\$\$}$	1.90 ± 0.33	< 0.001	-0.35 (-0.78–0.09)	-0.76 (-1.15– -0.37)	-0.93 (-1.36– -0.50)
SP20 (s)	3.79 ± 0.27$^{\$\$\$}$	3.67 ± 0.24$^{\$\$}$	3.29 ± 0.60	< 0.001	-0.48 (-0.92– -0.04)	-0.84 (-1.23– -0.44)	-1.08 (-1.52– -0.64)
Change-of-direction ability							
M505 (s)	3.07 ± 0.22$^{\$}$	3.03 ± 0.17$^{\$}$	2.78 ± 0.49	0.003	-0.21 (-0.65–0.23)	-0.68 (-1.06– -0.29)	-0.76 (-1.18– -0.33)
CODD%	42.94 ± 5.90	44.5 ± 6.1	45.52 ± 8.72	0.422	0.26 (-0.20–0.72)	0.24 (-0.21–0.68)	0.44 (0.00–0.89)
ProAgilityF (s)	6.69 ± 0.47$^{\$\$\$}$	6.59 ± 0.36$^{\$\$\$}$	6.21 ± 0.33	< 0.001	0.24 (-0.68–0.20)	-1.09 (-1.49– -0.68)	-1.10 (-1.62– -0.74)
CODD%$_{F_S}$	60.5 ± 6.6	62.6 ± 7.9	64.0 ± 9.9	0.326	0.28 (-0.18–0.75)	0.16 (-0.29–0.60)	0.41 (-0.03–0.86)
CODD%$_{F_R}$	100.3 ± 12.7$^{*\$}$	102.4 ± 11.9$^{*\$}$	113.7 ± 24.5*	0.011	0.17 (-0.29–0.63)	0.58 (0.13–1.03)	0.68 (0.23–1.14)
ProAgilityB (s)	6.62 ± 0.45$^{\$\$\$}$	6.62 ± 0.39$^{\$\$\$}$	6.18 ± 0.34	< 0.001	-0.00 (-0.43–0.44)	-1.20 (-1.61– -0.79)	-1.10 (-1.54– -0.67)
CODD%$_{B_S}$	61.3 ± 12.2	63.6 ± 8.1	64.2 ± 10.8	0.569	0.22 (-0.29–0.63)	0.07 (0.13–1.03)	0.25 (0.23–1.14)
CODD%$_{B_R}$	95.6 ± 25.9$^{*\$}$	101.7 ± 22.5*	111.6 ± 18.1*	0.020	0.25 (-0.21–0.72)	0.49 (0.04–0.93)	0.72 (0.27–1.17)
Hexagon (s)	10.74 ± 1.17$^{\dagger\$\$\$}$	10.18 ± 0.61$^{\$}$	9.70 ± 0.50	< 0.001	-0.60 (-1.05– -0.16)	-0.87 (-1.26– -0.48)	-1.16 (-1.60– -0.72)

he values presented are means ± SD. F- and P-values were obtained by One-Way ANOVA (3 maturational groups). Pre-PHV: pre peak height velocity group; Circa-PHV: around peak height velocity group; Post-PHV: post peak height velocity group; 90% IC: 90% interval confidence; D: dominant side; ND: nondominant side; CMJ: countermovement jump; SP5: 5-m linear sprint; SP10: 10-m linear sprint; SP20: 20-m linear sprint; M505: modified change of direction test.; CODD%: Percentage-based change of direction (COD) deficit; ProAgilityF: Pro-agility test to the forehand side; ProAgilityB: Pro-agility test to the backhand side; CODD%$_{F/B_S}$: percentage-based COD deficit in the static situation to the forehand/backhand; CODD%$_{F/B_R}$: percentage-based COD deficit in the rolling situation to the forehand/backhand. †Different from Circa-PHV group ($p < 0.05$). $^{\$}$Different from Post-PHV group ($p < 0.05$). $^{\$\$}$Different from Post-PHV group ($p < 0.01$). $^{\$\$\$}$Different from Post-PHV group ($p < 0.001$). * Different from CODD% in the static situation ($p < 0.001$).

RESULTS

The reliability data of the tests conducted in the present study are shown in Table 2. All tests showed acceptable between-trial reliability scores, with CV values between 1.1% and 7.9% and good to excellent ICC (0.824 to 0.990) (Table 2).

As shown in Table 1, the results showed that Pre-PHV players presented lower training volume values compared to Post-PHV ($p < 0.05$; ES: 0.58), with no differences compared to Circa-PHV players. In addition, Pre-PHV players also showed smaller body height ($p < 0.001$; ES: 1.5 and 2.4) and body mass ($p < 0.001$; ES: 1.1 and 2.1) values together with smaller MO ($p < 0.001$; ES: 2.8 and 4.7) compared to Circa-PHV and Post-PHV players, with no differences regarding APHV.

Table 3 shows the comparisons of the performance tests according to the maturational status. The between-group analysis revealed significant differences ($p < 0.001$ to 0.003) in all tests performed (i.e., jumps, linear sprinting, and COD). Post-hoc analyses revealed that compared to Post-PHV, Pre-PHV players were significantly slower ($p < 0.001$; ES: 0.76 to 1.19) in linear sprints (5 to 20 m) and all COD tests (M505, pro-agility and hexagon). Moreover, they showed significantly lower ($p < 0.001$; ES: 0.85 to 0.98) performance levels in all jumps (CMJ, CMJD, and CMJND). In addition, compared to Circa-PHV, Pre-PHV players also demonstrated moderately lower performances in the hexagon test ($p < 0.05$; ES: 0.6). Regarding the CODD% and CODD% in the static situation, no differences were found between groups. However, data showed significant differences in the CODD% of the rolling situation, with Pre-PHV players presenting lower CODD% ($p < 0.05$; ES: 0.68–0.72) than Post-PHV for both forehand and backhand sides.

When comparing Circa-PHV and Post-PHV players, the results also showed significantly lower values in all the variables analysed (Vertical jumping ability: $p < 0.001$; ES: 0.95 to 1.02; Linear sprinting ability: $p < 0.01$; ES: 0.73 to 0.85; COD ability: $p < 0.05$ to < 0.001; ES: 0.67 to 1.11), and CODD% in the rolling situation to the forehand side ($p < 0.05$; ES: 0.58). No differences were found in the CODD%, CODD% in the static situation, for both forehand or backhand sides, and CODD% in the rolling situation for the backhand side.

DISCUSSION

The aim of this study was to examine the maturational status (i.e., PHV) differences in neuromuscular performance (i.e., vertical jump, linear sprint, COD using different tests, and the percentage-based COD deficit (CODD%) in both static and rolling situations), of young tennis players. The results obtained showed that Pre- and Circa-PHV players presented lower levels of performance in jumping ability (i.e., both bilateral and unilateral CMJs), linear sprints (5 to 20 m), and COD ability tests (modified 5–0–5 test, pro-agility and hexagon) compared to the Post-PHV players. Regarding the CODD% and CODD% in the static situation, no differences were found between groups. However, data showed significant differences in the CODD% of the rolling situation, with Pre-PHV players presenting lower CODD% ($p < 0.05$; ES: 0.68–0.72) than Post-PHV for both forehand and backhand sides, and Circa-PHV showing lower values in the CODD% of the rolling situation to the forehand side ($p < 0.05$; ES: 0.58).

When comparing the maturational status differences in neuromuscular performance (i.e., vertical jump, linear sprint, COD using different tests, and their associated CODD%) of the tennis players analysed here, the results showed significant differences (ES ranging from 0.76 to 1.19) in all tests performed (i.e., jumps, linear sprinting, and COD), with Pre- and Circa-PHV players showing lower performance levels than their Post-PHV peers. Compared to Circa-PHV, Pre-PHV players showed no differences in any test, except in the hexagon test, with moderately lower performances (ES = 0.60).

As suggested in previous research, in sports in which the training environments are characterized by mixed participation (i.e., boys and girls training together), the use of an athlete's PHV instead of the chronological age seems to be a better measure to design athletic training programmes [34–36], as it is well known that maturation can influence many aspects of physical performance (i.e., speed, COD, and/or jumping ability) [37]. Pre-PHV players of the present study were significantly smaller (~ 7% to 12%) and presented lower body height (~ 18% to 30%) than Circa- and Post-PHV players, factors that can lead to differences in strength/power and therefore in physical tests. Interestingly, Pre- and Circa-PHV players of this study presented lower levels of jumping (~15–20%) and linear sprinting performance (~ 7–12%), compared to the Post-PHV. Regarding jumping ability, the results were in agreement with previous research conducted with similar tennis populations [19, 35], although the data related to linear sprinting showed no differences between Pre- and Circa-PHV players. This is contrary to previous research, including that on tennis populations [35, 38, 39], suggesting that the time around PHV could be a key point in the improvement in speed in young tennis players, which continues to increase, although not significantly, until Post-PHV stages. The lack of differences between Pre- and Circa-PHV groups here could be related to several factors. First, Circa-PHV subjects are taller and heavier than their Pre-PHV peers, so it seems that the possible benefits of a more advanced maturation are not clear for the Circa-PHV players. In this regard, since around the ages of PHV there is a disproportional growth and disruption of motor coordination in complex motor coordination tasks (i.e., "adolescent awkwardness") [39], we could speculate that these alterations (i.e., the regulation of the lower extremity joint stiffness [40]) may temporarily compromise the player's performance levels. Furthermore, when analysing training volumes, there were no differences between groups, which can be related to a bias directed towards a sport-specific activity at the expense of global motor skill training. Thus, the inclusion of training programmes that incorporate a variety of essential motor skills (i.e., locomotion, stabilization) seems to be an essential strategy from which youth athletes can maximize their motor skill proficiency and reduce the risk of sustaining acute and overuse injuries [36].

The regular assessment of physical and technical capacities considered crucial for sporting success is critical for developing tailored and effective training programmes [41]. For this reason, the implementation of practical tests able to provide valid and reliable measures is highly recommended. Results of the COD tests conducted in this study showed acceptable between-trial reliability scores and good to excellent ICC values (CV < 5%; ICC > 0.80). Since the tennis-specific literature related to the pro-agility test is scarce, its implementation in the tennis fitness batteries seems to be interesting. The present results showed that it is a highly reliable measurement, with similar scores to those of one of the most frequently used COD tests (i.e., 505 COD test). Values reported here are also in line with a previous study analysing a very similar test (i.e., the 20-yard shuttle test) in tennis players [18, 26], or studies analysing the pro-agility tests as a measure of COD ability and its utility in sports requiring multiple high degree directional changes, as a measure of repeated 180° COD ability [42, 43]. Furthermore, it should be highlighted that differences between Pre- and Circa-PHV compared to Post-PHV players were significant, with large ES, suggesting that this test is highly sensitive to discriminate between athletes from different maturational stage and a viable tool for talent identification. This hypothesis should be tested in future studies, as previous research has already shown that other specific tennis tests may be able to differentiate between players from different technical levels and ranking positions [18, 44].

In the last few years, and as a practical attempt of removing the confounding factor of large amounts of linear sprinting during the COD tests [20], the CODD has been introduced in the testing batteries of different sports, including tennis [10]. The present results showed that faster players in linear sprints and the M505 test did not present larger COD deficits, with CODD% scores obtained showing that players were 42–45% slower when performing the modified 505 test than when completing an equal distance during a linear sprint. Although this is in line with a recent study conducted with U13 and U15 male and female tennis players [10], the results are contrary to a very recent study conducted with a similar population, including different maturational groups, and showing that Circa-PHV and Post-PHV players who were the faster players in linear sprints presented higher CODD (11–14%) [35]. The differences may be related to the group configuration (i.e., age-grouped instead of biological) or to the CODD analysis (i.e., using percentages or seconds). Although faster tennis players will possibly have greater inertia and thus will need to apply higher breaking forces over longer ground contact times [45], the modified 505 test seems not enough to achieve considerable velocities.

Since tennis movement is mainly characterized by lateral movements, with 60–70% of all COD being > 105º [8], and players braked or decelerated at ≥ 3 ms^{-2} when entering medium and high intensity (i.e., > 2.5 $m.s^{-1}$) direction changes [12], it seems necessary to include high-velocity CODs in the regular testing of these athletes [20]. The inclusion of a rolling start (i.e., an increased entrance velocity), such as the one conducted during the pro-agility test, can help to determine how much time it "costs" an athlete to change direction [29]. The results of the present study showed that first, the CODD in the static situation obtained during the pro-agility test was significantly higher ($p < 0.001$; ES ranging from 2.0 to 3.0) than the CODD during the modified 505 test. To the best of our knowledge, there is no previous research analysing these measures, making comparisons difficult. Although no biomechanical analyses were conducted here, during a 180º COD players orientate their bodies in the direction of travel, while during the pro-agility test, players seem to enter and exit the COD with their bodies orientated down the court (i.e., toward the net) [46]. This can lead to a different entry speed and angle, altering therefore the "cost" of the COD. In this regard, recent research has highlighted several biomechanical differences among tasks with different COD angles [47], such as an increased ground contact time with increased angles during the COD. However, this is speculative, and more research is needed in this regard, including the measurement of ground reaction forces, as well as entry and exit speeds.

Regarding the CODD% in the rolling situation during the pro-agility test, the results showed that, compared with the CODD% in the static situation, an increased entrance velocity, caused by the distance run (i.e., 10 m), significantly exacerbated the CODD ($p < 0.001$; ES ranging from 2.0 to 3.0), meaning that players were more than 100% slower when performing the second part of the pro-agility test than when completing an equal distance during a linear sprint. Although this can be considered an effect of the test procedure (e.g., test position, including static/rolling situations), the results can illustrate the low capacity of these players to effectively decelerate and change direction with an increase in entry velocity [29]. In this regard, since the ability to decelerate efficiently is underpinned by eccentric strength capacity [48], it may indicate that youth athletes might benefit from focusing on deceleration training and increasing the eccentric strength to improve CODD. Moreover, and although the eccentric lower-limb load was not quantified, the accumulation of medium to high velocity COD during the competitive season can be considered a very interesting topic since intense CODs are associated with an increased lower limb load [47]. In this regard, the frequent lower limb joint loading of COD may represent a key risk factor for consideration in the management of hip and knee injuries, which are considered among the most common musculoskeletal complaints in tennis [49]. Future research should analyse the relationship between eccentric strength training and deceleration capabilities, including the CODD.

We recognize that this research had several limitations, include its cross-sectional design and the need to include larger samples with higher performance levels, which could help to avoid potential selection bias. A more detailed analysis of the training volume (i.e., strength, endurance, and/or other qualities) would also help to clarify whether performance differences are also mediated by training. Another limitation was the lack of strength/power related

measurements, which would definitely help to determine whether the differences found herein are mediated by differences in the strength levels or in the ability to change direction rapidly. However, we believe that the present design has high levels of ecological validity and may offer a starting point to suggest practical applications to tennis professionals.

CONCLUSIONS

In conclusion, the present research showed that maturity stage influenced physical performance in a large sample of young tennis players, with the results showing that Post-PHV players outperformed their Pre- and Circa-PHV peers in jumping ability, linear sprints, and COD ability tests. Moreover, Pre- and Circa-PHV players presented lower CODD% than Post-PHV players in the pro-agility test. From a practical perspective, it seems that the pro-agility test is a highly reliable test to measure the COD ability, including measures of CODD during static and rolling situations, which can be helpful in order to determine how much time it "costs" an athlete to change direction at high entry speeds. Moreover, coaches should be aware of the differences found in the physical performance and consider the practical implications that maturation can have in the long-term development of young tennis players. In this regard, since strength training leads to increases in lean body mass, which may also help improve the 'athleticism' of players, the combination of strength training (e.g. resisted sprints, horizontally directed power exercises, and eccentric strength training) and COD workouts (i.e., combining cognitive, physical, and technical aspects with tennis-specific movements in different angles of direction) may be beneficial to improve these qualities, especially to overcome the CODD, which appears to be consistent during all the PHV stages analysed here, and exacerbated in the Post-PHV group. Additional studies are warranted to determine the best training approaches and content (specific to each maturity stage) to meaningfully improve neuromuscular performance in young tennis players, including the CODD.

Author's Contribution

JFF, JCP, EBV have given substantial contributions to the study design/planning. JCP, RMG, JFF, EBV contributed in data collection/entry, data analysis/statistics and data interpretation. JFF, JCP, RMG, FC, EBV gave their contribution to preparation of manuscript and literature analysis/research. All authors have participated to drafting the manuscript. JCP, RMG, JFF, EBV edited and revised it critically. All authors contributed equally to the manuscript and read and approved the final version of the manuscript.

Conflicts of interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Ethical Approval

The Spanish Tennis Federation Ethics committee approved the procedures (RFET.EC_21.3) in accordance with the latest version of the Declaration of Helsinki.

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Acute effects of foam rolling and dynamic stretching on angle-specific change of direction ability, flexibility and reactive strength in male basketball players

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ABSTRACT: The purpose of our study was to determine the acute effects of dynamic stretching (DS), foam rolling (FR) and foam rolling combined with dynamic stretching (Combo) protocols on angle-specific change of direction (COD) ability, drop jump (DJ) performance and flexibility. Using a counterbalance crossover study design, eleven male basketball collegiate players (20.7 ± 0.6 years) were randomly assigned to one of the four protocols – control (CON), DS, FR, Combo – for each session, for a total of four sessions. A more aggressive foam cylinder with raised nodules, which is thought to be effective in stimulating the deep layer of muscle tissue, was used to observe for changes in their performance during sit and reach (SAR), DJ and COD tasks in 45 and 180 degrees. One-way repeated measures ANOVA was used to identify differences of each variable separately between interventions. The SAR after three interventions compared to the CON was significantly improved ($F_{(3,30)} = 5.903$, $P = 0.003$, $\eta^2 = 0.371$). In the 505 test, both limbs failed to show a significant improvement in COD deficit. The non-dominant limb showed a significant improvement of 6.4% after FR when performing the Y-shaped agility ($F_{(3,30)} = 4.962$, $P = 0.0065 < 0.05$, $\eta^2 = 0.332$). In the DJ, the reactive strength index and contact time changed significantly by 17.5% and -17.5% ($\eta^2 = 0.518$, $\eta^2 = 0.571$), respectively, immediately after FR. The current research suggested that FR may have an enhancing effect on COD speed in a 45° cutting task and neuromuscular function, while having the potential to improve non-dominant limb deficits in both COD tasks. In contrast, the Combo warm-up protocol did not produce a cumulative effect, suggesting the need for coaches to remain cautious about excessive warm-up duration.

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INTRODUCTION

Massage therapy for the relief of myofascial pain syndrome and muscle dysfunction can be traced back thousands of years [1, 2]. Self-myofascial release (SMR) is a form of manual massage. The foam roller as an SMR tool with its convenient, low-cost and easy-to-use features has been favoured by coaches and sports enthusiasts in recent years, widely used in training practice and scientific research fields [3]. Foam rolling (FR) can alter local blood flow volume and neuromuscular excitability, break up trigger points, improve muscle-tendon unit compliance, lower the pain perception threshold, and promote exercise-induced muscle damage (EIMD) recovery [4]. These physical and psychological changes acutely affect athletic performance [5].

Many researchers have evaluated the acute effects of FR or DS alone on flexibility by various methods [6–10]. Although moderators of the treatment (type of roller, rolling speed, duration and muscle) or dynamic movements used vary, most studies found strong improvement in joint range of motion (ROM) [6–9]. However, limited knowledge is available on the combined treatment of FR and DS (Combo), especially on the acute effects on ROM and performance [11]. A review by Anderson et al. [12] that included only four studies compared the effects of FR with combined treatment on ROM and performance-related variables. They concluded that the combination programme seemed to produce the greatest gains in jump power [13–15] and agility [14, 16] but had little effect on ROM [14, 16] compared with stretching alone. Similar performance enhancements were also observed in a quantitative review by Konrad et al. [11], but they concluded that FR followed by stretching led to a significant overall effect on ROM compared with the control group. The inconsistent findings and limited evidence of the Combo protocol led us to further investigate whether there existed a cumulative effect.

Changes in tissue properties and neuromuscular function after FR offer the potential for enhanced sports performance [17], particularly in basketball, which involves a lot of jumping and change of direction (COD) tasks with fast stretch-shortening cycles (SSC). The drop jump (DJ) test can be used to identify reactive strength as a tool to examine neuromuscular function [18]. In a laboratory study, Bradbury-Squires et al. found that FR effectively enhanced individuals' neuromuscular efficiency during a lunge [19]. In the field test, Wang et al. similarly found a significant increase in the reactive strength

index using vibration FR in the DJ test [20]. However, Richman et al. used the DJ and found no significant change in jump height in the Combo group compared to DS alone. Due to the lack of reported contact time, these findings leave researchers with difficulty in determining the detailed impact of treatment on neuromuscular function.

In exploring the acute effects of FR on agility, Peacock et al. used the pro agility test and found a significant decrease in completion time [14]. A similar effect was demonstrated in the Edgren 10 s side step test [21]; however, no significant changes were observed when assessed by Richman et al. [13] and Lopez-Samanes et al. [10] using the T test. The conflicting results in these agility tests may be attributed to differences in the number of directional changes, cutting angle, acceleration distance, entry velocity, etc. COD ability reflects the underlying ability of an individual to rapidly decelerate, change movement patterns, and re-accelerate processes [22]. It is a key component in basketball that can distinguish between players at different levels and positions. [23]. Therefore, COD should be assessed using an independent testing protocol rather than an agility test with multiple COD tasks [24]. Furthermore, recent studies have shown that in performing COD tasks, those below 90 degrees are velocity-oriented and those above 90 degrees are strength-oriented, suggesting specificity in the physical and biomechanical demands of athletes for COD tasks with different angle and entry speeds [25]. To better explain the conflicting results of the acute effects of FR on agility, our study was designed to observe athletic performance with a single, unilateral, angle-specific COD task at the same entry velocity. The aims of our current study were: 1) to investigate the acute effects of deep tissue foam rolling on specific angle COD ability, drop jump performance and flexibility in male basketball players; and 2) to explore the cumulative effects of deep tissue foam rolling combined with dynamic stretching on drop jump performance and flexibility.

MATERIALS AND METHODS

Although foam rolling as a pre-exercise method has been extensively applied by many coaches, the findings on its acute effects of performance variables are not consistent [5]. In this study, a more aggressive foam cylinder with raised nodules, which is thought to be effective in stimulating the deep layer of muscle tissue [26], was used to explore the effects on COD ability, reactive strength index and flexibility. A random crossover design was used to compare selected warm-up protocols (control, DS, FR, Combo). The intervention sequence for each player was randomly generated (https://www.randomizer.org) and concealed until interventions were assigned. To better control environmental and personal state variations, each participant performed four sessions with 48 h intervals at the same time of the day. The venue chosen was a gymnasium with a wooden floor at Hangzhou Normal University (temperature: 19.5 ± 0.9°C; humidity: 53 ± 2.2%; TH-007, SanLiang, Japan). The intervention protocol in the current experiment was modified from Peacock's study to maintain consistency of intervention doses as well as to facilitate comparative studies [14]. To our knowledge, no research exists that has used this particular type of foam roller to assess its effect on COD ability at different angles. Thus, the approach to this problem was to compare deep tissue foam rolling, dynamic stretch, and the combined protocol on Y-shaped agility, 505 test, drop jump and sit and reach test (SAR).

Subjects

To decrease expectancy effects, the participants in our research did not use foam rolling as a pre-exercise method. The subjects were collegiate male basketball player from the Sports Department of Hangzhou Normal University in the off-season (2 times/week, low to moderate intensity), with 11 players recruited (age: 20.7 ± 0.6 years; height: 181.8 ± 5.8 cm; body mass: 74.4 ± 9.4 kg; BMI: 22.4 ± 1.7 kg/m^2). The athletes were informed in advance of the injury risks and the purpose of the study, which was approved by the Institutional Review Board of Hangzhou Normal University. The authorized informed consent was signed voluntarily. In addition, subjects also needed to fill in the injury history questionnaire to confirm their eligibility before the experiment, and they were included in the experiment according to the standard after strict screening. Inclusion criteria: (a) aged between 18 and 24; (b) have been engaged in sports for at least three years; (c) keep daily physical activity. Exclusion criteria: (a) history of major lower limb injuries within the past three years; (b) participated in the latest regular stretching training programmes; (c) neuromusculoskeletal or cardiovascular disease in the past year that may potentially affect speed, strength, explosive power and other qualities; (d) during the test period, any injured participant would automatically quit the experiment process. A coach certified by the National Strength and Conditioning Association (NSCA) administered the entire experimental protocol to ensure proper exercise execution, providing the subjects with technical support and verbal encouragement.

Testing Procedures

For the familiarization visit, a well-trained assistant collected height, weight, BMI (InBody J30, Biospace, Seoul, Korea), leg length and a questionnaire with basic information of each player (Figure 1). The leg length was defined as the length of the anterior superior iliac spine of the right lower limb to the distal end of the medial malleolus [27]. Subjects were familiar with the standardized warm-up movements and testing protocols under the guidance of professional staff. Each participant randomly completed the control (CON), DS, FR and Combo protocols in four sessions at 48 h intervals. The test sequence for each session was SAR, drop jump, Y-shaped agility test and 505 agility test. Before the interventions and CON, players had a jog with 60–75% of maximal heart rate for 7 minutes (Polar H10, Polar Electro Oy). The maximum heart rate was estimated by the following equation: HR_{max} = 208-(0.7*age) [28]. During the experiment, athletes were asked to avoid caffeine intake and strenuous

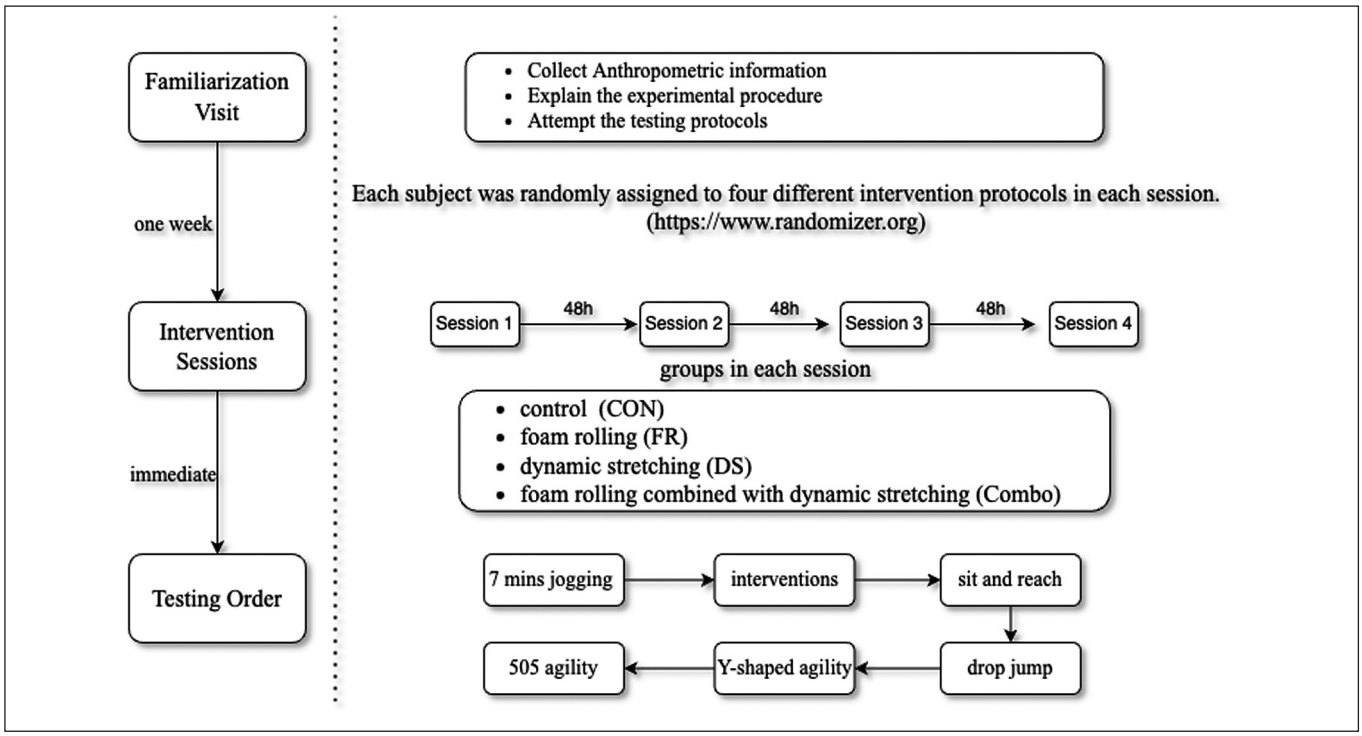


FIG. 1. Experiment flowchart.

exercise while maintaining a routine of physical activity and training. All tests are completed within 30 min to avoid attenuating the effects induced by the intervention [6, 29].

Intervention warm-up protocols

For self-myofascial release session, the foam roller selected in this experiment is a hollow roller (Joinfit, Suzhou Jiayou sports and leisure products Co., Ltd) with a convex surface, size 42 × 14 cm, material EVA outer layer +PVC inner tube. The FR protocol was adapted from Peacock et al. [14] including the legs (gastrocnemius, soleus), hamstrings (semitendinosus, semimembranosus, biceps femoris), quadriceps femoris, hips (gluteus maximus, gluteus medius, gluteus minimus), and back of the chest (erector spine, multifidus). The current study used a metronome to assist athletes to keep rolling uniformly at a speed of 6 seconds/back and forth. The continuous stimulation time of each unilateral muscle group was 30 seconds. There were 2 sets with an interval of 2 minutes.

The dynamic stretching programme is based on Peacock et al. [14] and incorporates parts of the F11+ warm-up programme [30], including mobility (body-weight squats, bilateral lunges, squat jumps) and flow manoeuvres (lunges and arm rotations during march, single leg Romania deadlift, high knees, back kicks during march, stride run). Each drill was performed for two sets of ten (meters/ repetitions), with 2-minute intervals. The professional staff supervised the entire process.

The combination warm-up programme (Combo) incorporates foam rolling followed by dynamic stretching. The details are as described above, with each part completing one set.

Sit and reach

The SAR is a valid and reliable (ICC = 0.92) test to appraise the flexibility of the posterior chain muscle groups [31]. Subjects were asked to remove their shoes and sit on the floor with their back against the wall; place both feet flat against the SAR box (ZW, Shanghai yilian, Inc, China) with the knees extended; slowly slide the module forward as far as possible with both fingertips and avoid jerky movements under supervision by an assistant. The SAR box uses the level of the feet as the zero mark. The score is recorded to the nearest centimetre on the reach indicator. Two attempts were measured with the mean used for analysis.

Drop jump

The reactive strength index (RSI) identifies the individual's ability to transition from eccentric contraction to concentric movement, as measured by the drop jump test in our study. The reliability and validity of the software (My Jump 2, iPhone 11, IOS 15.0 version) have been strictly verified and it has been promoted in field-based research and training practice recently due to its characteristics of high portability, simple operation and low cost [32]. RSI = flight time/contact time. Athletes stand on the 30 cm jump box with their

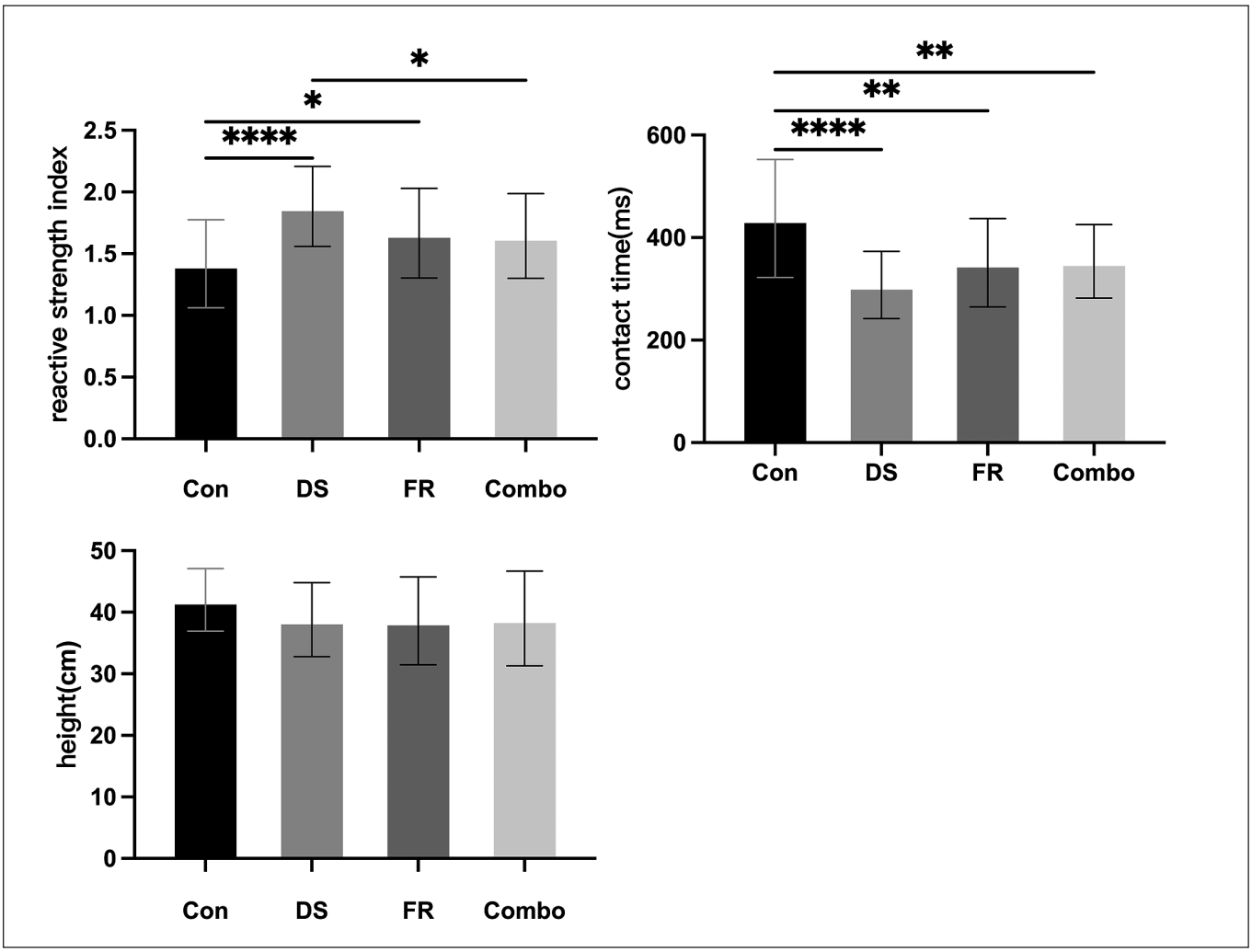


FIG. 2. The acute effects of different warm-up protocols on the drop jump performance.

hands on their hips to avoid an arm swing. The assistant reads out two instructions: (a) Jump with all your might; (b) Minimize the contact time. Three attempts were completed with 30 s recovery between jumps and the best RSI was recorded.

505 agility

As previously mentioned, because of its ability to differentiate unilateral turning ability, the 505 test was included in the present research. For the 505 test an established method was used, with a valid and reliable mobile app (COD Timer, iPhone 11, IOS 15.0 version) to record time [33]. A previous study showed that the change of direction deficit (CODD) in the 505 test is more effective in reflecting an athlete's ability to change direction [34]; thus the best CODD of two trials was used for the analysis for each leg with 2-minute intervals. Time was recorded to the nearest 0.001 seconds. If the subject changed direction before hitting the turning point, or turned off the incorrect foot, the trial would be disregarded and another trial completed.

Y-shaped agility

The current Y-shaped agility test modified from a previous study [35] added a 5 m acceleration zone to obtain a similar entry velocity in the COD task (Figure 2). The best of three trials with 2 minutes for each direction was recorded by a timing system (J14D-3R, Ziyu Electronic Technology, China). The change of direction speed (CODS) was used for analysis.

In our research, we define the dominant leg by the better performance in the control group for each angle-specific COD task.

Statistical Analyses

All data were analysed using IBM SPSS Statistics Version 21.0 (IBM Corporation, Armonk, NY, USA), and the main descriptive parameters were calculated. The Shapiro-Wilk test was used to verify variables for normality. To determine the statistical difference of differences among the CON, DS, FR and Combo groups, repeated-measures analyses of variance (ANOVAs) were conducted. Data that did not

meet Mauchly's sphericity test hypothesis were corrected using Greenhouse-Geisser correction. Multiple comparison analyses and graph drawing were examined using Bonferroni post hoc measures by GraphPad Prism 9. The alpha (α) level was set to $p \leq 0.05$ to determine significance.

RESULTS

For the SAR test, one-way repeated measure ANOVA was used to determine the acute effects of different stretching interventions as warm-up methods on the performance of athletes in the SAR test; According to the Shapiro-Wilk test, the data followed a normal distribution. Mauchly's sphericity assumption was satisfied ($P = 0.723 > 0.05$). Significant differences were found between the different warm-up protocols ($F_{(3,30)} = 5.903$, $P = 0.003$, $\eta^2 = 0.371$). Based on the results of Bonferroni's test, DS, FR and Combo protocols showed significant improvements in SAR compared to the CON (Cohen's d = -0.397, -0.335, -0.327 respectively), but there was no statistically significant difference between the interventions (See Table 1).

In the drop jump test, all parameters met Mauchly's sphericity assumption. The athletes showed significant differences in RSI, CT ($F_{(3,30)} = 10.738$, $p < 0.001$, $\eta^2 = 0.518$; $F_{(3,30)} = 13.286$, $p < 0.001$, $\eta^2 = 0.571$) after different intervention protocols according to Table 2, but not in height ($F_{(3,30)} = 2.353$, $p = 0.092 > 0.05$, $\eta^2 = 0.190$). The results of Bonferroni's multiple comparisons are shown in Figure 3 and Table 2.

For the Y-shaped agility test, there was no significant difference for the dominant leg in the time to complete the 45-degree change task between the baseline group and the groups after intervention, ($F_{(3,30)} = 1.300$, $P = 0.293 > 0.05$, $\eta^2 = 0.115$), while the difference in CODS for the non-dominant limb was statistically significant ($F_{(3,30)} = 4.962$, $P = 0.0065 < 0.05$, $\eta^2 = 0.332$). Bonferroni's multiple comparisons test was conducted to compare the acute effects of each protocol. The non-dominant limb took significantly

TABLE 1. The acute effects of different warm-up protocols on the sit and reach test

Intervention	N	Mean (SD)	95% CI	P value
CON	11	14.24(5.63)	10.46–18.02	-
DS	11	16.37(5.26)	12.83–19.90	0.004*
FR	11	16.04(5.40)	12.41–19.66	0.019*
Combo	11	15.99(5.11)	12.56–19.42	0.023*

Note: CON, control group; DS, dynamic stretching group; FR, foam rolling group; Combo, foam rolling combined dynamic stretching group; *, significant compared with the CON;

TABLE 2. The acute effects of different warm-up protocols on the drop jump performance

Indicators	Intervention	Mean	SD	95%CI	P value
RSI	CON	1.418	0.357	1.178–1.658	-
	DS	1.883	0.324	1.665–2.100	< 0.001*
	FR	1.666	0.363	1.423–1.910	0.030*
	Combo	1.644	0.342	1.414–1.873	0.040*[d]
CT (ms)	CON	437.5	115.3	360.0–514.9	-
	DS	307.5	65.63	263.4–351.6	< 0.001*
	FR	351.0	86.07	293.2–408.8	0.002*
	Combo	353.8	71.44	305.8–401.8	0.003*
Height(cm)	CON	42.02	5.073	38.61–45.42	-
	DS	38.80	6.010	34.76–42.83	0.231
	FR	38.62	7.123	33.84–43.41	0.178
	Combo	38.99	7.689	33.83–44.16	0.307

Note: RSI, reactive strength index;CT, contact time;CON, control group; DS, dynamic stretching group. FR, foam rolling group; Combo, foam rolling combined dynamic stretching group; *, significant compared with the CON; *[d], significant compared with the DS; p value, compared with CON

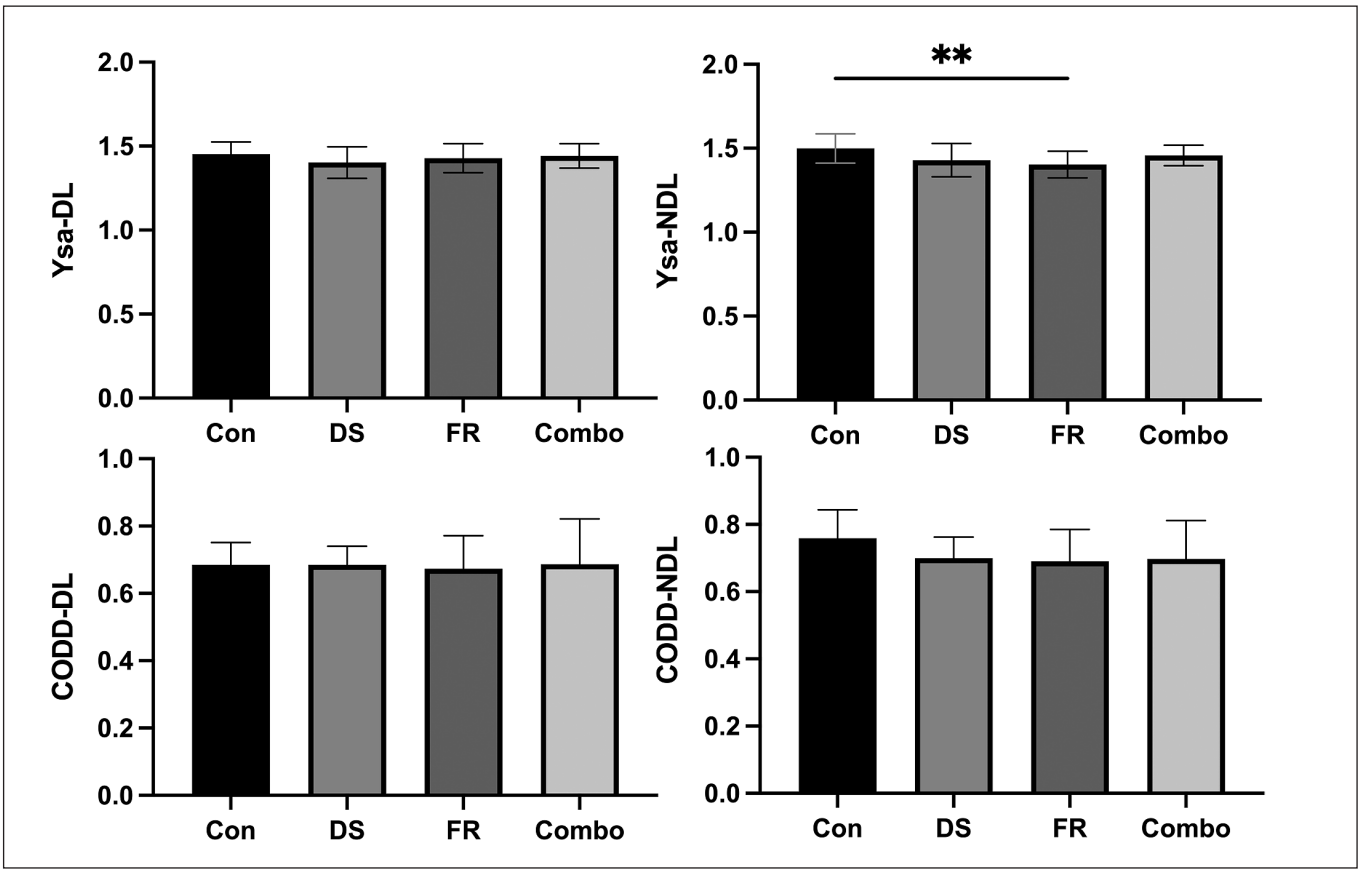


FIG. 3. The acute effects of different warm-up protocols on the specific angle change of direction ability.

TABLE 3. The acute effects of different warm-up protocols on 45°change of direction task

Indicators	Intervention	Mean	SD	95%CI	P value
ysa-DL(s)	CON	1.453	0.072	1.404–1.501	-
	DS	1.402	0.094	1.339–1.466	0.431
	FR	1.428	0.086	1.370–1.486	> 0.999
	Combo	1.442	0.072	1.393–1.490	> 0.999
ysa-NDL(s)	CON	1.499	0.087	1.441–1.558	-
	DS	1.429	0.098	1.363–1.459	0.071
	FR	1.403	0.080	1.349–1.457	0.006*
	Combo	1.457	0.061	1.416–1.498	0.709

Note: CON, control group; DS, dynamic stretching group; FR, foam rolling group; Combo, foam rolling combined dynamic stretching group; ysa, y-shaped agility; NL, dominant leg; NDL, non-dominant leg ; *, Statistical significance compared to control group; P value, compared with CON

TABLE 4. The acute effects of different warm-up protocols on 180°change of direction task

Indicators	Intervention	Mean	SD	95%CI	Cohen's d
CODD-DL	CON	0.686	0.066	0.6408–0.7301	-
	DS	0.685	0.055	0.6483–0.7221	0.003
	FR	0.673	0.099	0.6067–0.7396	0.131
	Combo	0.687	0.135	0.5967–0.7775	-0.017
CODD-NDL	CON	0.759	0.084	0.7028–0.8158	-
	DS	0.700	0.063	0.6577–0.7419	0.654
	FR	0.691	0.094	0.6273–0.7543	0.753
	Combo	0.697	0.115	0.6202–0.7743	0.682

Note: CON, control group; DS, dynamic stretching group; FR, foam rolling group; Combo, foam rolling combined dynamic stretching group; CODD, change of direction deficit; NL, dominant leg; NDL, non-dominant leg; Cohen's d, compared with CON

shorter time to complete the 45-degree COD after FR relative to the CON (Cohen's = 1.157) (Table 3).

For the 505 test, because of the significant result of Mauchly's test for sphericity ($p = 0.026$), Greenhouse-Geisser correction was used for statistical analysis of the CODD data for the dominant leg ($F_{(1.903, 19.03)} = 0.055$, $P = 0.941$, $\eta^2 = 0.005$). There was no significant difference in the CODD of non-dominant limbs ($F_{(3, 30)} = 1.527$, $P = 0.228$, $\eta^2 = 0.132$) among different intervention groups (Table 4 and Figure 4).

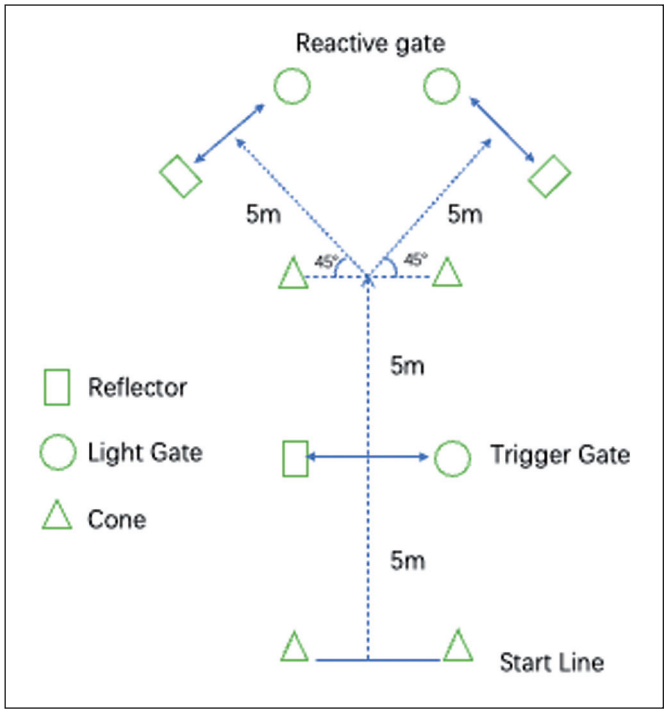


FIG. 4. The modified Y-shaped agility test.

DISCUSSION

After undergoing warm-up protocols of DS, FR and Combo, male college basketball players significantly improved their SAR by 15.0%, 12.6%, and 12.3% compared with CON. A number of previous studies have found significant acute effects of FR or DS alone on improving joint mobility in athletes [5, 6, 8, 15, 26], which is consistent with the results of the present study. Stretching and FR enhanced ROM appear to have similar mechanisms related to decreased soft-tissue stiffness, increased stretch tolerance and/or thixotropic effects [17]. Since the treatment time was essentially the same as the duration of treatments in this experiment, it seems to explain the almost identical increase in DS and FR compared to the CON group (Cohen's d = -0.397, -0.335 respectively). However, the Combo group was not significantly enhanced compared to DS or FR (Cohen's d = 0.070, 0.008 respectively). Although other studies of combined protocols used knee joint ROM [8], hip flexion ROM [26], and sit and reach [15] in assessing flexibility, the results were also consistent with the present study. Anderson et al. concluded that the Combo protocol did not have a superior effect compared to DS alone [12]. Intriguingly, even when the DS was replaced by static stretching in the combined protocol, it did not show a greater additional effect [11]. In addition, a saturation effect may be responsible for the lack of superior effect of the combined protocol, which suggests that stretching or FR beyond a certain time results in a loss of flexibility gains [36]. The Combo protocol of this study led to a significant increase in flexibility compared to CON (Cohen's d = -0.327), but did not show a cumulative effect, which may be related to the total duration of the intervention.

The results of the study showed that relative to the baseline group, the DS, FR, and Combo groups had improvements of the reactive strength index (RSI) by 32.8%, 17.5%, and 15.9% respectively,

with the first two protocols showing statistically significant improvements. In this study, the 30-cm drop jump was used to assess the changes in the lower extremity reactive strength after different intervention protocols. This ability not only correlates with the speed of the speed-oriented COD task [25], but also reflects the changes in the neuromuscular control function of the athletes [18]. Specifically, the contact times were significantly shorter after three warm-up protocol (-29.7%, -19.7%, -19.1% respectively), while the jump heights were essentially the same as before (-9.4%, -8.1%, -7.2% respectively). This suggests that the increase in lower limb reactive strength may be a result of increased neuromuscular excitability, which led to completion of the stretch-shortening cycle (SSC) in a shorter period of time, resulting in a shorter contact time. Local compression rolling of the foam roller may alter muscle and tendon surface tension and mechanical stress, which in turn activates proprioceptors and chemoreceptors, triggering neural tissue excitation and reinforcing feedback mechanisms [37]. In the study by Werstein et al. [38], they compared the changes in RSI after the intervention in the control, static stretching and dynamic stretching groups. The results showed that dynamic stretching significantly improved the athletes' RSI, which is consistent with our results. However, flight time was significantly improved while there was no significant difference in contact time, which is the opposite of the results of this study. This difference could be due to the different warm-up movements in the protocol. This study used four basic exercises, while the dynamic stretching in our experiment included squat jump, high knee, and running bounding to mobilize the organism more comprehensively. These forms of stretching actions may indirectly increase nervous system excitability [7]. FR may also increase the elastic potential energy of the musculotendinous unit during the eccentric phase at the completion of the SSC exercise by enhancing muscle compliance, leading to efficient performance during the concentric contraction phase [19].

Other studies [39] have suggested that foam rolling, when applied with pressure, decreases neuromuscular excitability and relaxes muscles, thus minimizing myofascial trigger point activity and pain. In a study by Godwin et al. [40], it was concluded that FR did not affect the performance of the drop jump. The control and experimental groups described in that experiment followed two protocols that used a basic warm-up, DS and a basic warm-up, FR, followed by DS, respectively. The two groups did not show significant differences in the results, probably because of the lack of a control group. Although our findings suggest that both DS and FR protocols led to a significant increase in RSI in athletes compared to the CON, the Combo group did not show a cumulative effect, which contradicts the results of a previous review [11]. After comparing the specific study protocols in this study with previous literature, it can be suggested that this may be due to fatigue of the athletes from the prolonged intervention protocol. Future studies need to further investigate the underlying physiological mechanisms of FR to enhance athletic performance and be alert to the detrimental effects of excessively prolonged warm-up activities on athletes' physical performance.

The acute effects of the Combo protocol on the unilateral limb COD of athletes at specific angles were examined for the first time in our study, and the results showed a significant reduction in the 45-degree CODS of the non-dominant limb after FR. In the task of changing direction from different angles, athletes have different requirements in all aspects of sports quality [41]. Generally speaking, the task of changing direction exceeding 90 degrees is often considered as strength orientation, which means that the eccentric muscle strength showed a significant and large correlation with COD speed performance [42]. In the execution of a 180-degree turning task, it is more necessary for athletes to overcome deceleration at high speed with great eccentric strength. However, Madoni et al. found that FR did not seem to affect muscle eccentric hamstrings peak torque and EMG [43]. The results showed that the CODD of the dominant limb decreased by 0.04%, 1.79%, -0.23% respectively compared with the CON (0.686 ± 0.020 s) after three warm-up programmes, while that of the non-dominant side (0.759 ± 0.025 s) decreased by 7.84%, 9.02%, 8.17% and the differences were not statistically significant. Additionally, the process of re-acceleration is similar to the acceleration process of sprint. Richman et al. found no significant change when observing the acute effect of self-myofascial release on 10-yard short sprint [13], which may be another factor influencing the results of this study. The other type of COD task is the smaller angle (below 90-degree) COD task, which is speed oriented [25]. This type of COD task requires athletes to have good sprinting ability to maintain maximum speed through the COD as much as possible. In this study, it was found that after DS, FR, and Combo protocols, athletes' CODS were shorter by 3.5%, 1.7%, 0.8% relative to the baseline (1.453 ± 0.072 s) for the dominant limb, and improved by 4.7%, 6.4%, and 2.8% for the non-dominant leg. Comparing the effects of FR on dominant and non-dominant limbs in different angular COD tasks, it was found that the enhancement effect was more pronounced in non-dominant limbs, suggesting that it may have a greater potential to improve lower limb asymmetry in the COD task. On the one hand, athletes are required to generate the maximum strength within 0.44–0.72 s of contact time in the turning step [24], while in the 45-degree cutting task, athletes' contact time is shorter than in the 180-degree task [44]. Therefore, the framework of directional changing ability sub-quality established by Young et al. includes reaction strength [45]. In the 30 cm drop jump test of the current study, the results revealed a significant enhancement for RSI of the DS and FR groups. It proved that compared with the Combo group, both the two former groups showed a more obvious improvement, whether in the dominant limb or non-dominant limb, velocity-oriented or strength-oriented task, which is consistent with our COD test results. On the other hand, after warm-up, CODD of the non-dominant limb in the FR group 180-degree task was increased more than that in the DS group, which may be caused by the fact that dynamic stretching can significantly improve the sprint ability [7]. When completing the

180-degree COD task, the stronger the sprint ability, the faster the speed and the greater the momentum, the longer the deceleration time to zero is required [44]. However, some studies have shown that FR does not significantly affect athletes' sprint ability, and may strengthen their reactive strength [6]. Therefore, the performance improvement after FR compared to DS may be more obvious when completing the 180-degree turning task. Unfortunately, at this stage of the study, it is not known why the difference in unilateral lower extremity CODS after FR in athletes exists.

Leaving aside the new findings, there are still some limitations in the current study. Firstly, the small sample size may limit the power of this study and increase the probability of false-positive results. The findings need to be interpreted with caution and a larger sample size study is expected to improve generalizability in the future. Due to the lack of experience with foam rolling and the use of a raised rigid rubber roller, some participants exhibited great discomfort, which would potentially enhance voluntary contraction and impact the true effect of the intervention. From this perspective, it suggested that the next stage needs to quantify pressure applied to the subject. Additionally, although reliable and valid software was used in this study to assess parameters related to the 505 and drop jump, more sophisticated instrumentation could be used in the future to capture more parameters (e.g., COD contact time, entry velocity) to help researchers better understand how treatment profoundly affects performance.

Practical applications

For college men's basketball players, warm-ups using DS, deep tissue FR and Combo protocols are effective in improving flexibility. However, the first two clearly maximize time efficiency. For small angle changes of direction drills or games involving fast SSC, pre-exercise FR is more recommended. Coaches need to be cautious in considering that the warm-up duration may not be too long.

CONCLUSIONS

For collegiate male basketball players, both deep tissue FR and Combo pre-exercise protocols were effective in improving flexibility. Deep tissue FR had a positive effect on the reactive strength required in exercises involving SSC, which may result from enhanced neuromuscular function. For 180°, strength-oriented COD tasks, the FR failed to show better potentiation. In contrast, for the 45°, velocity-oriented COD task, the non-dominant limb showed a greater enhancement after FR, and it remains unclear why its effect on the bilateral lower limbs differed. The possible positive effects of FR on lower extremity asymmetry presented in motor tasks need to be explored further in future studies. Of particular note, the Combo protocol in this study did not produce a cumulative effect for all variables, and the specific threshold of the saturation effect needs more attention.

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Conflict of interest declaration

The authors declare no conflict of interest.

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SUPPLEMENTAL MATERIALS

TABLE. Effect size (Cohen's d) for outcome variables in post hoc comparisons.

Testing		SAR	Drop jump			505 agility		Y-shaped agility	
Effect size		Cohen's d	Cohen's d (RSI)	Cohen's d (CT)	Cohen's d (H)	Cohen's d (DL)	Cohen's d (NDL)	Cohen's d (DL)	Cohen's d (NDL)
CON	DS	-0.397*	-1.340*	1.498*	0.491	0.003	0.654	0.615	0.843
	FR	-0.335*	-0.716*	0.997*	0.518	0.131	0.753	0.301	1.157*
	Combo	-0.327*	-0.650	0.964*	0.461	-0.017	0.682	0.132	0.506
DS	FR	0.062	0.624	-0.501	0.027	0.128	0.099	-0.314	0.315
	Combo	0.070	0.690*	-0.533	-0.030	-0.020	0.028	-0.483	-0.337
FR	Combo	0.008	0.066	-0.032	-0.057	-0.148	-0.177	-0.169	-0.652

Note: *, statistical significance.

TABLE. Subject characteristics (N = 11).

Parameters	Mean ± SD
Age	20.7 ± 0.6
Body mass (kg)	74.4 ± 9.4
Height (cm)	181.8 ± 5.8
BMI (kg/m^2)	22.4 ± 1.7
Leg length (cm)	95.4 ± 4.1

Table. Control group test results in specific angle change tasks.

player	505 test				y-shaped agility test			
	change of direction deficit				change of direction speed			
	left leg	right leg	DL	ASI (%)	left leg	right leg	DL	ASI (%)
#1	0.629	0.683	left	-8.6	1.477	1.528	left	-3.5
#2	0.746	0.804	left	-7.8	1.427	1.474	left	-3.3
#3	0.758	0.804	left	-6.1	1.477	1.472	right	-0.3
#4	0.762	0.758	right	-0.5	1.402	1.339	right	-4.7
#5	0.675	0.638	right	-5.8	1.435	1.477	left	-2.9
#6	0.695	0.633	right	9.8	1.430	1.456	left	-1.8
#7	0.667	0.908	left	-36.1	1.562	1.594	left	-2.0
#8	0.583	0.759	left	-30.2	1.461	1.428	right	-2.3
#9	0.762	0.763	left	0.0	1.441	1.421	right	-1.4
#10	0.867	0.733	right	-18.3	1.594	1.716	left	-7.7
#11	0.633	0.633	left	0.0	1.464	1.395	right	-4.9

Note: ASI = (DL-NDL)/DL*100%; ASI: asymmetry index; D: dominant leg; NDL:non-dominant leg.

Table. Temperature and humidity information for four sessions.

	Temperature (°C)	Humidity (%)
Control group	18.3	55
Dynamic stretching group	19.6	53
Foam rolling group	20.3	54
Foam rolling combined with dynamic stretching group	19.8	50
Mean ± SD	19.5 ± 0.9	53 ± 2.2

Note. SD: standard deviation.

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Recreational 3 × 3 basketball elicits higher heart rate, enjoyment, and physical activity intensities but lower blood lactate and perceived exertion compared to HIIT in active young adults

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ABSTRACT: This study aimed to assess and compare the physiological [percentage of maximal heart rate (%HR_{max}), blood lactate (BLa), creatine kinase (CK)], hormonal (testosterone, cortisol), psychological [rating of perceived exertion (RPE), enjoyment] and physical [percentage of moderate-to-vigorous physical activity (%MVPA) and vigorous activity (%VA)] responses of recreational 3 × 3 basketball (3 × 3BB) and high-intensity interval training (HIIT) in active young adults. Twelve apparently healthy male recreational basketball players (age: 23 ± 3 years; body mass: 82 ± 15 kg; stature: 188 ± 15 cm) completed a 3 × 3BB match and HIIT with similar duration. %HR_{max}, %MVPA and %VA were monitored during the protocols, while BLa, cortisol, and testosterone were measured before and after each protocol. CK was measured before the protocols and at 24 h, while RPE and enjoyment were assessed at the end of each protocol. 3 × 3BB elicited higher %HR_{max} ($p < 0.001$; $d = -1.6$, large), %MVPA ($p < 0.001$; $d = 2.7$, very large), %VA ($p = 0.030$; $d = 0.8$, moderate), enjoyment ($p = 0.014$; r-value = -0.500, large), and lower RPE ($p = 0.024$; r-value = -0.462, moderate) compared to the HIIT condition. Moreover, higher values of BLa were found in HIIT compared to 3 × 3BB at post-condition ($p = 0.020$; r-value = -0.601, large), while CK analysis showed only an increase within the HIIT condition ($p = 0.020$; r-value = -0.599, large). A time effect was found for both testosterone ($p < 0.001$, $\eta^2_p = 0.526$, moderate) and cortisol ($p = 0.005$, $\eta^2_p = 0.743$, strong), while no between-condition effect or interaction was found ($p > 0.05$). 3 × 3BB elicits higher %HR_{max}, enjoyment, and physical activity intensities but lower BLa and RPE compared to HIIT in active young adults and might be considered as a potentially suitable activity to increase participants' health status.

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INTRODUCTION

Possessing adequate physical activity levels is fundamental for young adults for the prevention of chronic diseases, which are among the most important causes of mortality worldwide [1]. However, more than 50% of young adults fail to meet the international physical activity guidelines [2]. Therefore, one of the main goals for sport and health scientists is to design and select suitable physical activities for young adults that could encourage their participation, and in turn produce positive effects on their health status.

In the last decade, the beneficial effects on fitness outcomes of short training methods such as high-intensity interval training (HIIT) have been widely studied [3, 4]. Typical HIIT sessions last ~10 min with a work-to-rest ratio ~1:1 (e.g. 30 s work and 30 s rest) and can stimulate similar or higher physiological adaptations compared to traditional aerobic training with longer duration such as running or cycling-based activities [4]. Moreover, HIIT programmes can be characterized by several activities including endurance, resistance training, sport, combat and brain activities in the attempt to be more appealing for young adults [5]. Overall, the use of these HIIT typologies was positively rated by young adults such as university students possibly due to their short duration and the selection of the activities that motivate their participation [5]. Consequently, HIIT activities have been suggested as one of the best methodologies to increase participants' adherence to training programmes and in turn increase their physical activity levels.

An alternative way to increase the physical activity level among young adults is the practice of team sports such as football, handball, or basketball [6]. Specifically, playing football small-sided games has shown a higher potential to involve and motivate sedentary people to engage in physical activity compared to other conventional training (e.g. running or cycling) [7]. Considering basketball, a previous investigation revealed that 3 months of basketball small-sided games (3v3) played on half and full court improved the overall fitness profile in untrained adult men (20–42 years) [8]. However, it should be considered that the training sessions lasted

~ 75 min with basketball small-sided games comprising 4 × 12 min games interspersed by 3-min breaks [8]. Potentially, the implementation of team sports activities with shorter durations like those implemented during HIIT modalities can be more appealing for individuals willing to be involved in regular physical activity. In fact, activities with long duration might decrease the adherence in regular physical activity programmes of young adults [9] since it has been shown that the perceived lack of time is one of the barriers for participation in regular exercise activities [10]. Therefore, minimizing the time dedicated to training although maintaining the physical and physiological response potentially leading to positive adaptations might be essential to increase the physical activity levels in young adults.

In this regard, recreational 3 × 3 basketball matches could be considered as a valuable tool to elicit adequate physiological responses and increase young adults' involvement in physical activities since they possess the advantages of being a regular team sport (e.g. ball involvement and teammate interactions) and having a short duration similar to typical HIIT typologies (10 min of live time). To the best of our knowledge, no previous study assessed whether recreational 3 × 3 basketball could produce similar physical and physiological responses to those elicited by HIIT modalities in young adults. This information seems essential since it might clarify whether 3 × 3 basketball can be considered as a valuable team sport activity to potentially elicit positive health-related adaptations. Therefore, the aim of this study is to compare the physiological, hormonal, psychological and physical responses of recreational 3 × 3 basketball and HIIT in young adults.

MATERIALS AND METHODS

Participants

Twelve apparently healthy, male, recreational basketball players (age: 23 ± 3 years; body mass: 82 ± 15 kg; stature: 188 ± 15 cm; %fat mass: 10.6 ± 6.3) were recruited to participate in this study. An a-priori analysis indicated that the present study is sufficiently powered using $\alpha = 0.05$, $\beta = 0.80$ and an effect size = 1.0 (G*Power, version 3.1.9.2; University of Dusseldorf; Germany) based on previous research investigating differences in enjoyment levels between HIIT and moderate intensity continuous exercise [11]. Participants completed the Physical Activity Readiness Questionnaire (PAR-Q) prior to participation to rule out contraindications to participation and a custom-made questionnaire in which they reported weekly physical activity levels in line with the recommendations provided by the World Health Organization [12]. Overall, the selected participants can be classified as "habitually active, physically fit and recreationally trained" based on the classification provided by Russel et al. [13]. The procedures, benefits, and risks involved in participation were explained to each player before participation and informed written consent was obtained from all players. The procedures received approval from the ethics committee of the Lithuanian Sports University [approval number: BNL-TRS(B)-2022–449].

Design

A descriptive within-subject design encompassing five experimental sessions was used to assess the acute physiological, hormonal, psychological, and physical responses in recreational 3 × 3 basketball and HIIT modalities. In the first session, participants' anthropometric characteristics (stature, body mass and %fat mass) and maximal heart rate (HR_{max}) were assessed. Furthermore, players were required to complete 4 min of both recreational 3 × 3 basketball and HIIT activities to familiarize themselves with the study procedures after receiving detailed explanations by the research staff members. Participants also familiarized themselves with all other procedures such as saliva and blood collections, and with the adopted scales.

Following familiarization, four experimental sessions were conducted over 9 days with participants divided into two groups (Figure 1). On day 1 and day 8, participants were randomly and equally divided into two groups performing either recreational 3 × 3 basketball or HIIT, while on day 2 and day 9 participants' conditions at 24 h were assessed (Figure 1). All experimental sessions were scheduled at the same time of the day (group 1: 8.30 am – 10.00 am; group 2: 10.00 am – 11.30 pm) to avoid issues due to circadian rhythms. Participants were also instructed not to perform any physical activity in the 48 h preceding the recreational 3 × 3 basketball or HIIT protocols and in the following 24 h, to maintain regular sleeping patterns and diet, and to avoid caffeine and alcohol prior to each experimental day. Moreover, before each experimental session, participants completed a questionnaire assessing their compliance with pre-test instructions.

Procedures

Recreational 3 × 3 basketball and HIIT protocols

The recreational 3 × 3 basketball matches were played following the official rules of 3 × 3 basketball (https://fiba3 × 3.com/en/rules.html) with a 10-min duration of live time (or match over when one of the two teams reached 21 points). The studied matches had an average duration of 10.2 min. Players were notified about the score, and a 12-s shot clock was used as in official competitions. It was played on the half court of an indoor regular-sized basketball court with a wooden floor and with the official ball for international 3 × 3 basketball competitions (size 6). Teams were generated by the research staff based on players' positions with no tactical indications provided. No substitutions were allowed during the match since teams were composed of 3 players and not 4 players as in official competitions.

The Gym HIIT was selected for the purpose of this study as the HIIT typology, since it has previously demonstrated its efficacy and feasibility of use in the university setting, with students rating this HIIT typology the most favourably [5]. Briefly, the Gym HIIT included a 12-min duration and a work-to-rest ratio of 30 s:30 s with a combination of various activities (i.e. push-ups, shuttle sprints, squat jumps, shuttle side-step, sit-ups and jumping jacks) (Table 1). Within the 30-s bout, participants were required to complete as many

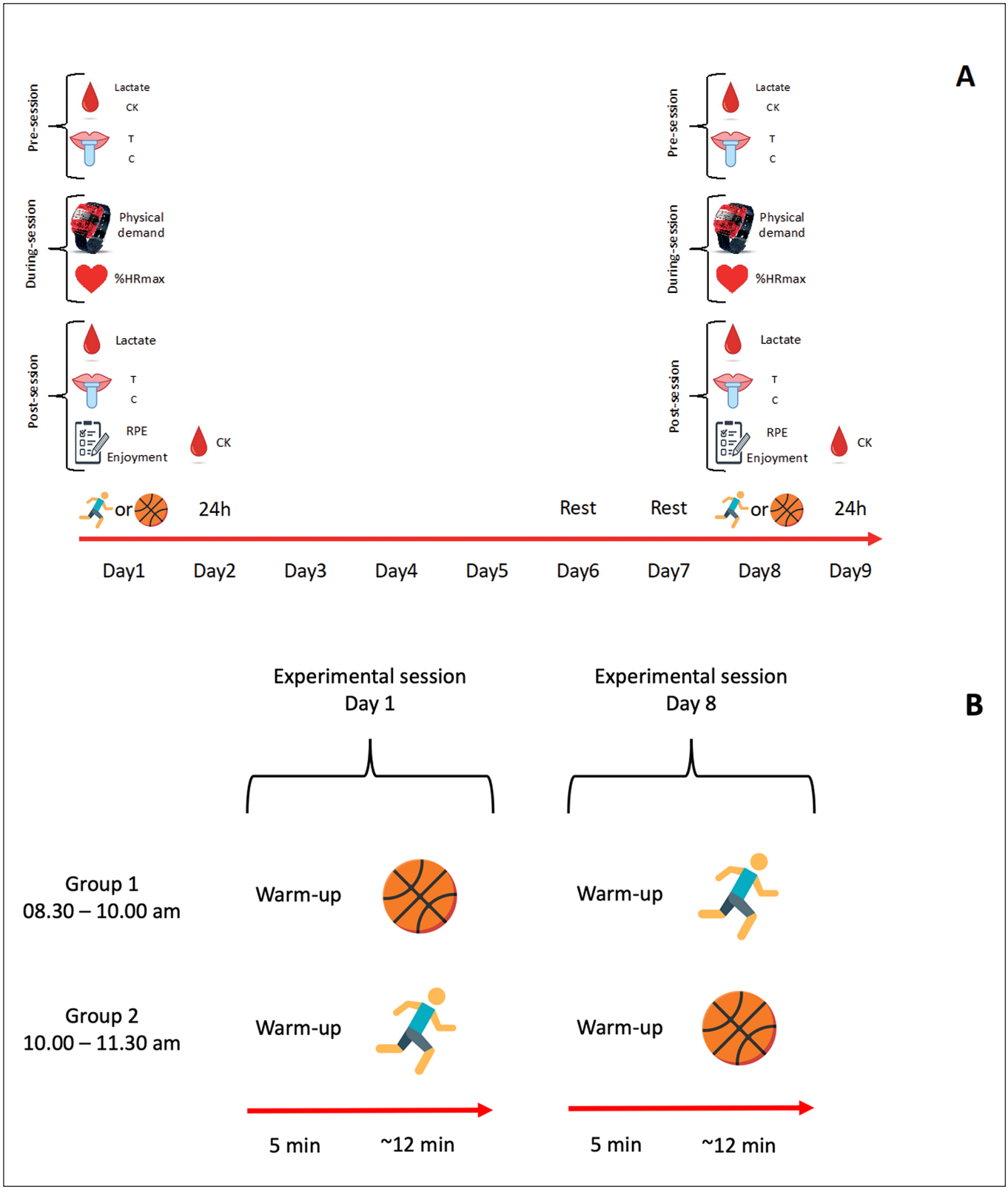


FIG. 1. **A** indicates the full study design. **B** indicates the organization in the experimental sessions on day 1 and day 8.
Note: = blood collection; CK = creatine kinase; = saliva collection; T = testosterone; C = cortisol; = monitoring physical activity intensities; = monitoring heart rate; $\%HR_{max}$ = percentage of maximal heart rate; = assessment of psychological demand; RPE = rating of perceived exertion; = high-intensity interval training; = recreational 3 × 3 basketball.

TABLE 1. Gym HIIT sequences and activities (total time 12 min).

Activities	Time	Sets
4 × Push-ups + 10 m Shuttle Sprint	30 s	4
Rest	30 s	
4 × Squat Jump + 10 m Shuttle Side-step	30 s	
Rest	30 s	
4 × Sit-Ups + 10 × Jumping Jacks	30 s	
Rest	30 s	

rounds of activities as possible (for instance, in the first bout they would repeat as many times as possible the 4 push-ups +10 m shuttle sprints). Both recreational 3 × 3 basketball and HIIT protocols were preceded by a 10-min standardized warm-up consisting of jogging and a series of mobility exercises and dynamic stretching followed by basketball-specific drills including dribbling and shooting.

Physiological and hormonal responses

Participants' HR_{max} was assessed in the first experimental session via the 30–15 Intermittent Fitness test specifically developed for basketball, [13] which has been largely used to assess basketball players' HR_{max} [14–16]. Briefly, the test consisted of 30-s shuttle runs performed across the regular-sized basketball court, interspersed by 15 s passive recovery periods. Players were asked to run back and forth on the court completing as many stages as possible following a pre-recorded beep with incremental speed. The test ended when players could no longer maintain the required speed and the heart rate registered at the final stage was considered as HR_{max}. During both recreational 3 × 3 basketball and HIIT, the $\%HR_{max}$ was measured using H10 Bluetooth heart-rate strap (Polar Electro Oy, Kempele, Finland) sampling at 1 s, which is considered one of the gold standards in assessing HR [17]. Each strap was connected via Bluetooth to each participant's smartphone using the app Polar Beat, which has been previously used [17]. At the end of each activity, data were transferred onto researchers' Polar cloud account, and successively downloaded on Excel spreadsheets for further analysis.

Moreover, blood lactate was measured as an objective internal response. Ear lobe blood samples were taken before (in resting condition) and 1 min and 5 min after the completion of each protocol, with the highest value indicated as the peak and used for further analysis. Blood samples were analysed using a Lactate Pro 2 CT-1730 analyser (Arkray Inc., Kyoto, Japan) [18].

Creatine kinase (CK) was measured to assess the muscle damage before and 24 h after each experimental session at the laboratories of the Lithuanian Sports University. About 5 mL of blood was drawn from the median cubital vein, with samples centrifuged immediately after, and analysed using a Spotchem EZ SP-4430 biochemical analyser (Menarini Diagnostics, Winnersh, Wokingham, UK) using soft reagent strips (Arkray Factory, Inc., Shiga, Japan). Plasma enzyme activity was reported as international units per litre ($IU \times L^{-1}$). The normal reference range for human plasma CK using this method is 56–244 $IU \times L^{-1}$ according to the manual provided with the analyser.

Saliva samples were used to measure testosterone and cortisol levels collected before and after recreational 3 × 3 basketball and HIIT protocols. Participants were instructed to not eat, brush their teeth, or consume any drink other than still water in the 90 min prior to saliva collection. Before saliva collection, each participant rinsed his mouth with distilled water, waited in a seated position for 30 s, and then removed all saliva from his mouth. Afterwards, they waited for ~15 min before the saliva specimen was collected into 15-mL ultrapure polypropylene SaliCap tubes through polypropylene straws (IBL International, Hamburg, Germany). Saliva samples was then stored at -20°C before determining testosterone and cortisol levels via an enzyme-linked immunoassay (IBL International, Hamburg, Germany) following the manufacturer's instructions. Samples were analysed in duplicate with an intra-assay coefficient of variation of 1.34% and 1.92% for testosterone and cortisol, respectively.

Perceptual and psychological responses

The rating of perceived exertion (RPE) was measured for each participant at the end of each protocol using the Category Ratio (0–10) RPE scale [19]. Furthermore, participants' enjoyment was assessed using the Exercise Enjoyment Scale (EES) [20]. Both scales were previously adopted with this population involved in activities with similar typology and intensity [9].

Physical responses

During each activity, participants' physical activity levels were assessed using 30 Hz accelerometers (GT3X model, Actigraphs, Pensacola, Florida, USA) attached to the right hip of the participants

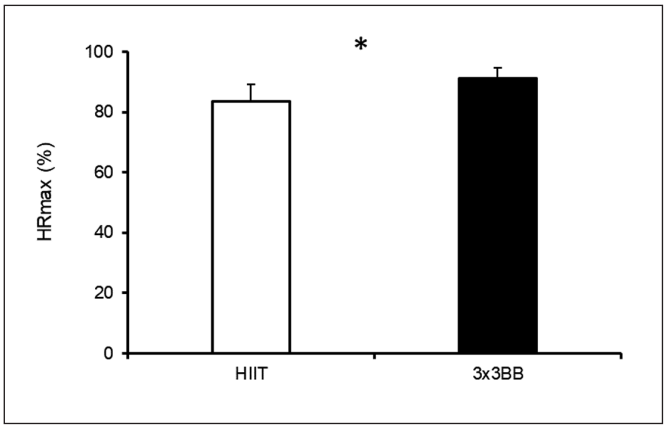


FIG. 2. Percentage of maximal heart rate ($\%HR_{max}$) during high-intensity interval training (HIIT) and recreational 3 × 3 basketball (3 × 3BB). Note: * = indicates $p < 0.001$.

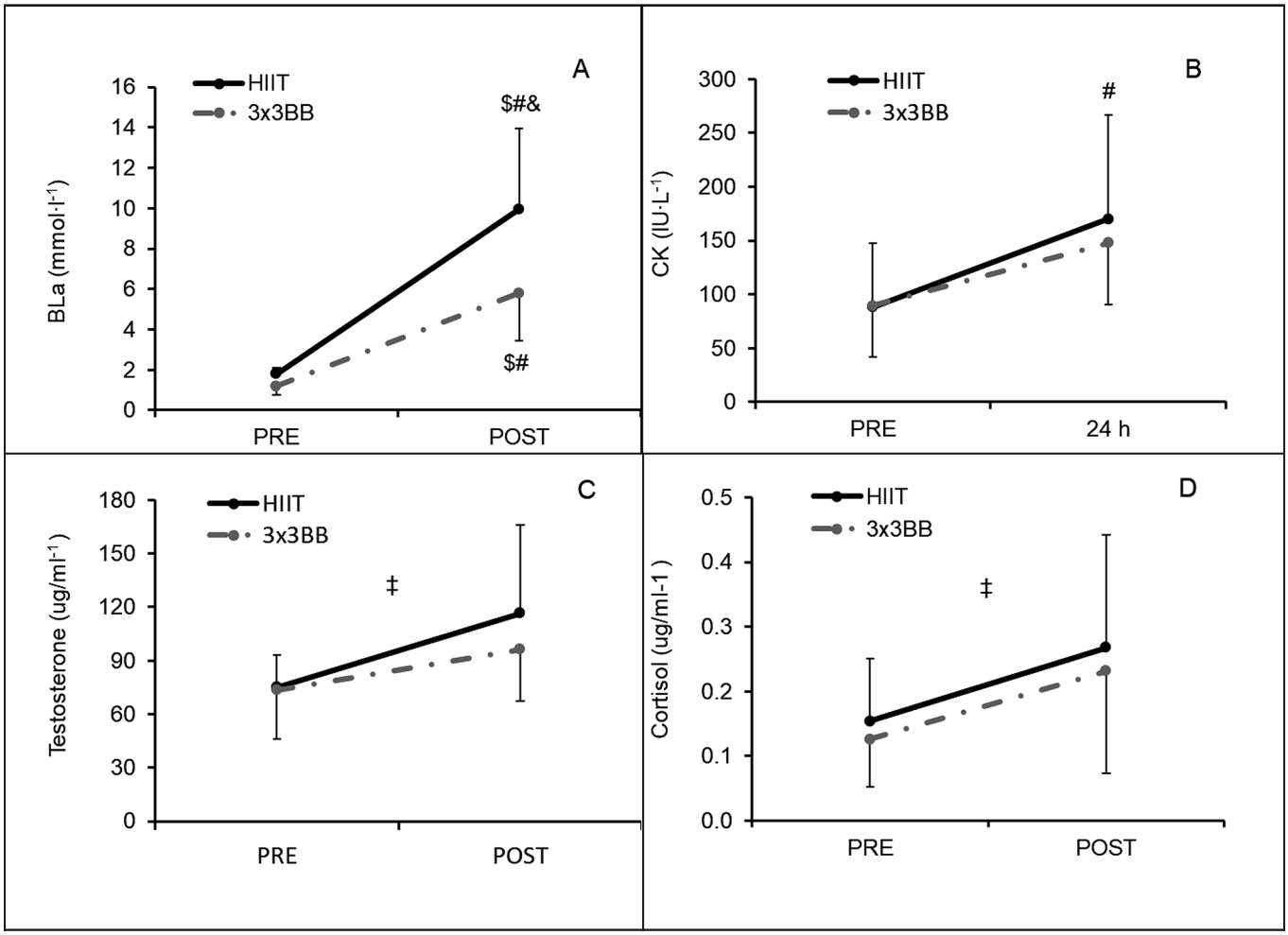


FIG. 3. Difference between high-intensity interval training (HIIT) and recreational 3 × 3 basketball (3 × 3BB) at different time points for: **A** – blood lactate (BLa); **B** – creatine kinase (CK); **C** – testosterone; **D** – cortisol. Note: non-parametric statistics was applied calculating median ± interquartile range (IQR) for BLa (HIIT-pre = 1.8 ± 0.2; HIIT-post = 10.0 ± 6.4; 3 × 3BB-pre = 1.2 ± 0.4; 3 × 3BB-post = 5.8 ± 3.1) and CK (HIIT-pre = 81.3 ± 32.3; HIIT-24h = 166.5 ± 96.6; 3 × 3BB-pre = 70.2 ± 60.2; 3 × 3BB-24h = 147.0 ± 71.7); # = indicates difference compared to HIIT-pre ($p < 0.05$); $ = indicates difference compared to 3 × 3BB-pre ($p < 0.05$); & = indicates difference compared to 3 × 3BB-post ($p = 0.020$); ‡ = indicates time effect for testosterone ($p < 0.001$) and cortisol ($p = 0.005$).

underneath clothing and secured with an elastic band. Using proprietary software (Actilife, version 6.13.4 for Windows), the time in minute spent at each physical activity intensity was calculated based on recommended vector magnitude cut points [21] and expressed in percentages. Specifically, the percentages of time spent in moderate-to-vigorous physical activity (MVPA) and vigorous activity intensities were determined similarly to previous studies in recreational team sports [22].

Statistical analysis

Mean and standard deviation (SD), median and inter-quartile range (IQR) and percentages (%) were calculated as descriptive statistics. Data normality for each continuous dependent variable was assessed using the Shapiro-Wilk test, which revealed non-normally distributed data for blood lactate and CK. Therefore, a paired-sample t-test was used to assess the differences between recreational 3 × 3 basketball and HIIT conditions in $\%HR_{max}$, %MVPA and %vigorous activity, while a 2 × 2 (time × condition) repeated measure ANOVA was used for testosterone and cortisol values. A non-parametric approach was used for the non-normally distributed variables and ordinal variables (i.e. RPE and enjoyment). Specifically, the Wilcoxon signed-rank test was used to assess the differences in RPE and enjoyment between recreational 3 × 3 basketball and HIIT conditions. Moreover, the Wilcoxon signed-rank test with Bonferroni correction was used to assess the between- and within-condition differences for blood lactate and CK. Cohen's d was used as an effect size measure for the paired t-test and values were interpreted according to Hopkins' benchmarks as follow: trivial ≤ 0.20; small = 0.2–0.59; moderate = 0.60–1.19;

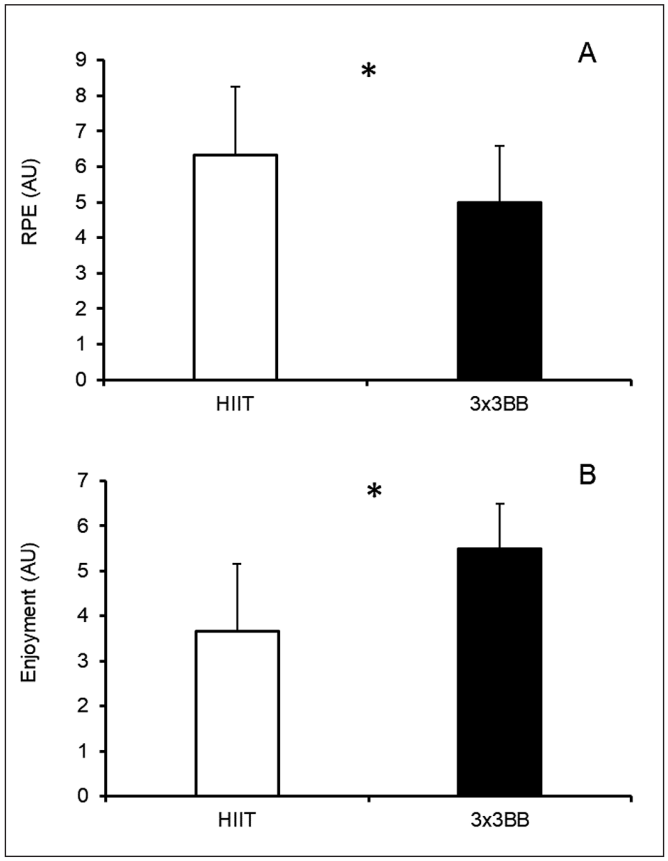


FIG. 4. Difference between high-intensity interval training (HIIT) and recreational 3 × 3 basketball (3 × 3BB) in: **A** – rating of perceived exertion (RPE); and **B** – enjoyment. Note: non-parametric statistics was applied calculating median ± interquartile range (IQR) for both RPE (HIIT = 6.5 ± 2.3; 3 × 3BB = 5.0 ± 1.5) and enjoyment (HIIT = 4.0 ± 3.0; 3 × 3BB = 6.0 ± 1.0); * = indicates $p < 0.05$.

large = 1.20–1.99; very large ≥ 2.0 [23]. Moreover, partial eta-squared (η^2_p) was used as a measure of effect size for the 2 × 2 repeated measure ANOVA and values were interpreted as no effect ($\eta^2_p < 0.04$), a minimum effect ($0.04 < \eta^2_p < 0.25$), a moderate effect ($0.25 < \eta^2_p < 0.64$) and a strong effect ($\eta^2_p > 0.64$) [24]. Finally, the r-value [Z/SQRT(N)] was adopted as an effect size measure for non-parametric statistics and interpreted according to Cohen's benchmarks considering 0.1, 0.3 and 0.5 as a small, medium and large effect size, respectively [25]. The α level was set at 0.05 and statistical analyses were performed using the software IBM SPSS for Windows (version: 28.0.1.0, IBM. Corp; Armonk, NY) and Jamovi for Windows (version: 2.3.5; Sydney, Australia; retrieved from https://www.jamovi.org).

RESULTS

Physiological and hormonal responses

The recreational 3 × 3 basketball condition elicited a higher $\%HR_{max}$ compared to HIIT ($p < 0.001$; mean difference (95%CI) = -7.6 (-10.7; -4.5); Cohen's d (95%CI) = -1.6 (-2.4; -0.7) – large) (Figure 2). Moreover, lactate analysis showed a significant difference across all the between and within comparisons ($p < 0.05$; r-values: large) except for the comparison between values before HIIT and recreational 3 × 3 basketball ($p = 0.222$; r-value: medium) (Figure 3). Furthermore, the CK analysis showed only a significant difference within the HIIT condition between pre- and 24 h time-points ($p = 0.020$; r-value = -0.599, large) (Figure 3). A time effect was found for both testosterone ($p < 0.001$, $\eta^2_p = 0.526$, moderate effect) and cortisol ($p = 0.005$, $\eta^2_p = 0.743$, strong effect), while no effect was found comparing the two conditions and their interaction ($p > 0.05$) (Figure 3).

Perceptual and psychological responses

Players perceived a higher RPE in the HIIT condition compared to the recreational 3 × 3 basketball condition ($p = 0.024$; r-value = -0.462, medium) (Figure 4). Conversely, players reported higher enjoyment for the recreational 3 × 3 basketball condition compared to the HIIT condition ($p = 0.014$; r-value = -0.500, large) (Figure 4).

TABLE 2. Differences in the physical activity intensities between recreational 3 × 3 basketball and HIIT

Physical activity intensities	Activities		Activity Comparison (3 × 3BB vs. HIIT)			
	HIIT	3 × 3BB	p	Mean difference (95% CI)	ES (95%CI)	Interpretation
MVPA (%)	75.6 ± 6.2	95.6 ± 1.9	< 0.001	20.0 (15.1; 24.9)	2.7 (1.4; 4.1)	Very Large
Vigorous activity (%)	61.4 ± 3.0	71.9 ± 15.2	0.030	10.5 (1.2; 19.9)	0.8 (0.1; 1.4)	Moderate

Data are presented as mean ± SD. Abbreviations: MVPA = moderate-to-vigorous physical activity; HIIT = high-intensity interval training; 3 × 3BB = recreational 3 × 3 basketball; 95% CI = 95% confidence interval; ES = effect size

Physical demand

Playing recreational 3 × 3 basketball elicited a higher physical activity intensity with very large and moderate differences in %MVPA ($p < 0.001$) and %vigorous activity ($p = 0.030$), respectively (Table 2).

DISCUSSION

The aim of this study was to assess whether recreational 3 × 3 basketball could provide physiological, hormonal, psychological, and physical responses comparable to an activity with similar duration recognized to elicit health benefits in young adults such as the Gym HIIT. The main results revealed that recreational 3 × 3 basketball elicited greater heart rate responses, enjoyment, and physical activity intensities but lower lactate, CK and RPE compared to HIIT in young adults. These results suggest that the use of 3 × 3 basketball as recreational activity could potentially produce health benefits in young adults.

Physiological and hormonal response

The exercise intensities reached during both recreational 3 × 3 basketball and HIIT might be classified as vigorous based on the classification of various organizations such as the American College of Sports Medicine (ACSM) [26], which identified a vigorous exercise intensity > 77%HR_{max} or ranging between 80% and 90% HR_{max} [27, 28]. Our results also showed that Gym HIIT elicited 83.6 ± 5.5% HR_{max}, which is in line with the previous investigation of Eather et al. [5] documenting an average of 82.2% HR_{max} during the Gym HIIT and HIIT modalities following the same structure. This intensity has been shown to induce positive adaptation in cardiorespiratory fitness and upper body muscular fitness [5]. Interestingly, recreational 3 × 3 basketball elicited a higher average %HR_{max} (91.2 ± 3.5) compared to the Gym HIIT. A possible reason for this result might be that no substitutions were allowed during the recreational 3 × 3 basketball matches, reducing the number of stoppage times compared to the HIIT activity, which had a fixed work-to-rest ratio of 1:1 (30 s work and 30 s rest). It should be considered that the cardiovascular intensities produced by recreational 3 × 3 basketball were also higher than those indicated during ~75 min of recreational 3 × 3 basketball activity composed of 4 × 12 min bouts with 3 min rest in between and played either on full (83.8 ± 6.0 %HR_{max}) or half court (84.5 ± 2.9 %HR_{max}), which was also shown to produce beneficial effects on participants' cardiorespiratory fitness, systolic blood pressure, and glucose tolerance [8]. Overall, these results highlight that health practitioners could consider the use of recreational 3 × 3 basketball as a potential activity able to increase the cardiovascular fitness in young adults similarly or even superiorly than the proposed HIIT modality.

Measuring blood lactate concentration can provide indications about the metabolic stress of training and the contribution of the anaerobic glycolytic pathway [29]. It is hard to make a comparison between the blood lactate concentrations documented in the HIIT typology proposed in this study and the HIIT adopted in previous studies due to different activity typologies and training regimes adopted. Nevertheless, it can be noted that the proposed HIIT typology induced a high metabolic response with average blood lactate concentration of ~10 mmol × L^{-1}, which is higher than HIIT including all-out cycling protocols [30] or jumping exercises with little or no rest [31] (~9 mmol × L^{-1}) and lower compared to other HIIT typologies including more strenuous activities such as Tabata training [9] or CrossFit sessions [32] (12–15 mmol × L^{-1}). In contrast, recreational 3 × 3 basketball elicited a remarkably lower blood lactate concentration of ~6 mmol × L^{-1}, which is in line with the values documented in elite male (6.33 ± 2.43 mmol × L^{-1}) and female (6.09 ± 2.24 mmol·L^{-1}) 3 × 3 basketball players participating in various European and world championships [33]. Overall, these results highlight the higher metabolic stress imposed by the HIIT activity compared to recreational 3 × 3 basketball. It is hard to define the mechanisms involved in this difference of lactate production, but it can be speculated that strength exercises (although with body weight) involving both upper and lower limbs performed during the HIIT induced higher muscular stress, producing an accumulation of protons and reactive oxygen species and consequently higher acidosis in the exercising muscles [34].

The suggested higher muscular stress during HIIT compared to recreational 3 × 3 basketball is also supported by the statistically significantly higher plasma CK values (although with a small effect) found in this study. To the best of the authors' knowledge, no previous investigation has assessed the plasma CK values following Gym HIIT and 3 × 3 basketball (both recreational and official competitions), making any possible comparison with previous literature difficult. Nevertheless, our outcomes documented that both activities produced lower CK values measured at 24 h (Gym HIIT: 169.9 ± 96.6 IU × L^{-1} and recreational 3 × 3 basketball: 147.7 ± 57.1 IU × L^{-1}) compared to other studies investigating longer activities such as a simulated basketball match (408.6 IU × L^{-1}) [35] and muscle damage induced exercises (~800 IU × L^{-1}) [36]. Furthermore, the changes in CK from pre- to post-activity measured at 24 h for the HIIT typology adopted in the current study (~80 IU × L^{-1}) were lower compared to HIIT adopting the same work-to-rest ratio and durations (30 s:30 s) but ending at voluntary exhaustion (~100 IU × L^{-1}) [37]. These outcomes suggest that the short (~12 min) activities proposed in this study did not induce a high level of muscle damage in active young adults, suggesting that limited recovery time might be used between these activities in this population. The slightly higher level of muscle damage found in the Gym HIIT modality might be due to the higher involvement of strength exercises compared to recreational 3 × 3 basketball, involving a higher number of muscle groups, also including the upper limbs (i.e. push-ups). These data should also be confirmed in a sedentary population, which might reach different muscle damage levels compared to the active participants involved in the current study.

To the best of our knowledge, this is the first study comparing the effect of playing recreational 3 × 3 basketball and performing a HIIT session on salivary testosterone and cortisol, which have been considered as sensitive biomarkers to monitor the anabolic and catabolic responses of HIIT [38] and basketball activities [14, 16]. Indeed, assessing the responses of testosterone and cortisol may be used to detect potential disorders before observing clinical symptoms (e.g., overtraining, anxiety, and depression) [38]. Our results indicated an effect of time for both investigated hormones, while no between-activity differences were evident. These results seem in line with those reported in a systematic review and meta-analysis focusing on hormonal responses of HIIT sessions, which highlighted an increase of both hormones following HIIT sessions (testosterone in the range 0–30 min and cortisol 0–60 min) [38]. When considering 3 × 3 basketball activities, no previous study has assessed the effect of playing official or recreational 3 × 3 basketball matches on salivary cortisol and testosterone levels. However, when considering the cortisol levels, it should be noted that our results are similar to those obtained in semi-professional basketball players involved in playing 3 × 3 small-sided games played with different tactical tasks and a different training regime, [39] which indicated an increase of cortisol following any proposed small-sided games. Differently, the increase in salivary testosterone levels found in our study are not supported by previous literature in 3 × 3 basketball small-sided games, which showed either an increase, a decrease or no changes in salivary testosterone levels based on the combination of various training tasks and regimes [39]. It should be noted that inconsistent results were also found in a recent systematic review assessing the changes in salivary testosterone levels measured before and after official basketball matches [40], suggesting that further studies are necessary on the mechanisms related to testosterone levels following basketball activities. Overall, our study indicated that both activities increased the level of cortisol and testosterone in active young adults, which can be considered as important information about the anabolic and catabolic process elicited by recreational 3 × 3 basketball and HIIT.

Perceptual and psychological responses

A higher RPE was found in HIIT compared to recreational 3 × 3 basketball. This result might be explained by the higher metabolic stress induced by the HIIT condition compared to the 3 × 3 basketball condition. However, this outcome is in contrast to the heart rate results, in which a higher %HR_{max} was observed in 3 × 3 basketball compared to HIIT activity. Furthermore, it should be noted that while the intensities elicited from both activities might be categorized as vigorous due to the high HR responses registered (> 77% HR_{max}), interestingly, RPE responses do not match the vigorous definition since average values of 5 AU and 6 AU were reported, for recreational 3 × 3 basketball and HIIT, respectively, which are more representative of a moderate intensity [28]. Despite the higher cardiovascular intensities found in recreational 3 × 3 basketball, the low RPE values might be related to the nature of the activity, characterized by teammate interactions, which in turn can promote positive psychological responses, as previously observed in other recreational basketball activities [41].

The investigated players also reported much higher enjoyment during 3 × 3 basketball compared to the HIIT activity. A possible reason for this result might be that since all players were previously or currently recreational basketball players, they would enjoy participating in basketball-specific activities more than gym-based activities. The higher enjoyment elicited by playing recreationally 3 × 3 basketball together with the lower RPE values documented in this study could indicate that recreational 3 × 3 basketball might improve the long-term exercise adherence, which seems fundamental to be physically active.[10]

Physical demand

Our findings showed that recreational 3 × 3 basketball elicited higher physical activity intensities measured via accelerometers compared to the HIIT condition with very large and moderate effect sizes reported for the percentage of time spent in the MVPA and vigorous activity, respectively. A possible explanation for this result could be the higher displacement likely attained during the recreational 3 × 3 basketball compared to the HIIT condition. Indeed, the adopted accelerometer, although considered one of the main tools to assess physical activity intensities in adults, [42] records accelerations while placed on participants' hip and might not have been able to fully detect the physical demand of the activities performed during the HIIT, which were also characterized by gym-based static activities (e.g. push-ups and sit-ups). Therefore, this tool might not be the best solution for the analysis of the difference in the physical demand between the two studied conditions. It should be noted that its limitations were also indicated in assessing the physical demand in recreational handball, since the low physical intensities registered during recreational handball matches (27% and 10% of total match time in MVPA and vigorous activity, respectively) did not match the high physiological responses elicited (71% and 24% of total match time above 80% HR_{max} and 90% HR_{max}, respectively) [22]. In contrast, our findings demonstrated that on average players spent 95.6% and 71.9% of the time in MVPA and vigorous activities, respectively, in the recreational 3 × 3 basketball condition, matching the physiological demand measured via heart rate monitors. The discrepancy in these results might be due to the fact that recreational 3 × 3 basketball matches are characterized by shorter activities and resting time compared to recreational handball matches. Indeed, during resting times, high heart rate responses might be recorded following high-intensity actions, while no or minimal physical demands could be recorded from the accelerometers, particularly during static actions. This might not be the case during recreational 3 × 3 basketball, in which players are continuously moving on the court with a short rest time, resulting in less possibility of a discrepancy between physiological and physical demand. Therefore, the

adopted accelerometer might provide acceptable results for the analysis of recreational activities with a short rest time such as 3 × 3 basketball. However, this speculation should be further analysed with a future validation study.

Limitations and future studies

The results of this study suggest valuable indications for health practitioners about the potential of recreational 3 × 3 basketball, which might produce similar or larger health benefits over time compared to HIIT. However, the results can be referred only to active young adults with previous basketball experience, and different results might be produced in other populations (youth or older adults), in people with different initial physical activity levels (sedentary people) or those with no or limited previous basketball experience. Therefore, future studies should expand our findings, investigating also youth and older adults, active and sedentary people and those with or without previous basketball experience. Furthermore, future investigations should employ an intervention design to assess whether recreational 3 × 3 basketball can elicit better or similar adherence and health benefits in comparison to HIIT.

CONCLUSIONS

Our findings revealed that the analysis of the acute responses of recreational 3 × 3 basketball elicited higher $\%HR_{max}$, enjoyment, and physical activity intensities but lower BLa and RPE compared to HIIT in active young adults. Therefore, recreational 3 × 3 basketball might be considered as a potentially suitable activity able to increase the adherence and the health status in young adults.

Authors' contributions

DC conceived of the study, participated in the data collection and statistical analysis, and drafted the manuscript. SK participated in its design and coordination and helped to draft and review the manuscript. AK, KM, RK, AS, IL participated in the design of the study, contributed to data collection and interpretation of results. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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Testing distance characteristics and reference values for ice-hockey straight sprint speed and acceleration. A systematic review and meta-analyses.

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ABSTRACT: Ice-hockey requires high acceleration and speed sprint abilities, but it is unclear what the distance characteristic is for measuring these capabilities. Therefore, this systematic meta-analysis aims to summarize the sprint reference values for different sprint distances and suggest the appropriate use of ice-hockey straight sprint testing protocols. A total of 60 studies with a pooled sample of 2254 males and 398 females aged 11–37 years were included. However, the pooled data for women was not large enough to permit statistical analysis. The sprint distance used for measuring the reported acceleration and speed was between 4–48 m. Increased test distance was positively associated with increased speed ($r = 0.70$) and negatively with average acceleration ($r = -0.87$). Forward skating sprint speed increases with the measured distance up to 26 m and do not differ much from longer distance tests, while acceleration decreases with a drop below 3 m/s at distances 15 m and longer. The highest acceleration (5.89 m/s^2 peak, 3.31 m/s^2 average) was achieved in the shortest distances up to 7 m which significantly differs from 8–14 m tests. The highest speed (8.1 m/s peak, 6.76 m/s average) has been recorded between 26–39 m; therefore, distances over 39 m are not necessary to achieve maximum speed. Considering match demands and most reported test distances, 6.1 m is the recommended distance for peak acceleration and 30 m for peak speed. The sprint time, acceleration, and speed of each individual and the number of skating strides should be reported in future studies.

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INTRODUCTION

Because of the number and quickness of game situation changes, ice-hockey is considered to be one of the sports with the highest requirement for speed, rapid changes of direction, cognition, and decision making [1, 2]. All of these factors are limited by the speed of motion, or the ability to accelerate and decelerate. Since acceleration and speed ability are critical factors to successful elite ice-hockey performance, they have been investigated in populations at various training levels [2–6]. However, the normative standards for skating acceleration and sprint ability are not well described in the current literature, as it is done for the sprint in running [7]. This is in turn aggravated by the use of different testing distances across studies. On the other hand, there is enough data reported in terms of the distance-time series to summarize general patterns in skating acceleration and velocity.

Among the previous studies, skating acceleration has been reported in distances ranging from 4 m [8] up to 20 m [9], or alternately in terms of the distance achieved in the first four or seven starting strides [10, 11]. Similar inconsistencies are evident in terms of speed, where the distance considered ranges between 25 [12] and 48 m [13]. This inconsistency aggravates the comparison between studies and sprint conditions since hockey locomotion is based on the propulsion-gliding mechanism [14]. If the sprint distance is shorter, the skaters are less reliant on the gliding phase, whereas when the distance is longer and closer to the length of the hockey rink (60 m), it is difficult to perform a full-speed effort to the finish due to the risk of collision with the barrier. Moreover, it has been shown that the initial acceleration phase and wide of the skating stride are more important to achieve maximal skating speed over a 30 m distance than step-by-step acceleration during the final stages of the sprint [15]. Another testing complication is the differences between skating to running sprints because it is not suitable to simply predict the velocity–time curve with a bi-exponential function which is valid for running [7, 16]. For instance, Perez applied Samozino´s method to the 30 m running and 40 m skating sprints, finding no correlation between running and skating in theoretical maximal velocity, theoretical maximal force, and 5 m acceleration time [17]. At the same time, total running and

skating time were highly correlated (r = 0.80) [17], and 40 m skating sprint time had a moderate correlation [17]. Although the Samozino´s method provides sufficient reliability in skating [18] and correlates to some off-ice values [17] or resisted sprint values [19] its use has limits in evaluating ice friction [20] and lateral movement during skating strides [15].

High-intensity skating is a key factor in match performance and elite players skate at a speed above 17 km/h for at least 70 m each playing shift [21] and for about 2000 m per match [22]. This requirement varies by playing position and also between performance levels [23], which underlines its importance as a performance differentiating factor. However, the skating speed achieved depends also on the distance covered, where the skating slide helps to maintain the velocity, which is developed using a stride-by-stride acceleration strategy up to maximal speed [24]. Moreover, the skating start differs between performance levels in the knee, hip, and ankle kinematics [25], and in the skating economy [26]. Therefore, the distance to measure maximum acceleration and speed might differ between players but should be related to the expected stride span for the standard skating technique.

There are several approaches to identifying skating acceleration. Four stride accelerations cover 4 to 6 m distance [10] and are important for puck battles and spatial tactics. As the distance covered increases for each skating stride, the seven stride accelerations represent about 13.5 m distance [11] which is the distance from the center of the rink to the side barrier or the shortest distance between offence and defense zones. For longer distances skating should be performed using the full stride length but keeping stride by stride acceleration to achieve maximal skating speed [15] with stride frequency about 1.6 strides per second [27] and skating efficiency about 2.9 strides per $m^{-1} \cdot s^{-1}$ [28]. However, there is currently no comparison as to whether a distance of 20 m is enough to achieve maximum speed at full stride length, or whether the testing speed for 48 m represents the highest speed at a practically meaningful distance. Since the purpose of sprint testing is to compare different performance and age category groups, the uncertain distances for acceleration and speed testing impede the interpretation for the purposes of inter-individual or intra-individual condition evaluation and training recommendations.

As inconsistent distances are used for ice-hockey sprints, the aim of this systematic and meta-analysis is to summarize the sprint reference acceleration and speed values for different sprint distances and suggest the appropriate use of ice-hockey straight sprint testing. We hypothesize that the shortest acceleration distances of up to 7 m and the most used 30 m distance for speed testing are optimal for maximum acceleration and speed measures.

MATERIALS AND METHODS

This review was performed in accordance with the PRISMA 2022 statement [29] adaptation for sport science [30] and registered with International Platform of Registered Systematic Review and Meta-analysis Protocols (INPLASY) on 03.05.2022 [no INPLASY202250010, DOI: 10.37766/inplasy2022.5.0010 316637]. An initial search in PubMed, Scopus, Web of Science, ProQuest, SPORTDiscus was performed on May 14 2022 using the combined terms "ice hockey OR "Ice-hockey" for all searched databases. Searches were limited to articles in English published in peer-reviewed journals since 1985. The database reports were uploaded to EndNote X9, duplicates were automatically removed, and then articles were screened for eligibility. Following the title and abstract screening, the remaining records were screened manually using the same PICOS (Population, Intervention, Comparison, Outcomes and Study design) strategy as for the database search and exclusion criteria. The reference lists of the selected full text articles and reviews were also examined to find further eligible articles.

Eligibility criteria

The title and abstract screening was done by two researchers (PS and RR) who selected a set of articles for full text screening, where the inclusion criteria were: 1) male or female ice-hockey players; 2) any cross-sectional or intervention study; 3) tests of ice-hockey sprinting over any distance or any battery of conditioning tests that included straight-line sprints; and, 4) results reported straight-line sprint distance, speed, time, or acceleration. In the case of disagreement between the evaluating authors, the final decision was made by a third author (MV). The full text screening exclusion criteria were: 1) if the article was not in English; 2) the testing did not include straight-line sprinting; 3) the reported values did not include data distribution; 4) the study reported only maximum speed without skating time or average speed; 5) the end of the sprint was defined by the point the player stopped sprinting; 6) the measurement was made with a stopwatch; and, 7) the study had bias in item 3 or 7 according to JBI (Joanna Briggs Institute) Critical Appraisal Checklist for Analytical Cross Sectional Studies (Supplementary material 1). The maximum speed test was not included due to the uncertain velocity conditions at beginning of testing distance.

Data extraction

Participant descriptions, test parameters and test results (mean and SD or other description of data distribution) were extracted to an Excel sheet separately by two researchers (PS, DN), where the test results were sorted by sprint distance, and age category. The extracted data describing sprint times (s) were transformed to average velocity (m/s) and average acceleration (m/s^2) for the sprint distance.

Statistical analyses

The average acceleration and velocity values were pooled by distance ranges of 0–7 m, 8–14 m, 15–25 m, 26–32 m, 33–39 m and 40–48 m. The normality and equality of variance (Bartlett's test) of the original data was checked using the reported distribution in the original articles and weighted means with confidence intervals and standard error were calculated for each distance range. In the case

TABLE 1. The basic characteristic of selected studies on ice-hockey sprint performance.

Author	Participants n, gender, age (y), height (cm), BM (kg); specificity	Reported tests	Aim of the study	Main finding
Allisse et. al. 2019 [28]	24, male elite, 11–17 y, younger 150.4 ± 4.1 cm, 41.2 ± 7.3 kg; older 170.0 ± 13.2 cm, 68.4 ± 26.8 kg 11 pee-wee, 8 bantam 5 midget players from; Special study Saguenay, Quebec, CA	30.5 m sprint	To evaluate the robustness of equations to predict the oxygen requirement during different skating circumstances commonly found in ice hockey game situations (skating forward, backward, with and without controlling a puck, during cornering and stops and starts).	The skating execution time alone is a bad estimator of oxygen uptake. Age proved to be a determining factor with younger players showing an overall lower level of skating efficiency compared with older players.
Allisse et al. 2017 [33]	18 male 1: 13.1 ± 0.6 y, 50.5 ± 5.9 kg, 161.3 ± 5.8 cm 2: 13.6 ± 0.6 y, 54.2 ± 5.5 kg, 165.3 ± 5.4 cm 3: 14.2 ± 0.6 y, 58.6 ± 6.0 kg, 168.8 ± 4.7 kg elite Bantam from Montreal area in 3 session	30 m sprint forward and backward, 6 × 18 m with and without puck, anaerobic power test	To describe the evolution of morphological, physiological, and skating performance profiles of elite age-group ice hockey players based on repeated measures spread over one season.	Muscular variables improved significantly during and between the two hockey seasons ($p < 0.05$).
Bond et al. 2018 [34]	40 male, 16.2 ± 0.8 y, 1.76 ± 0.06 cm, 73.7 ± 9.8 kg, top tier Division 1 National Collegiate Athletic Association schools	Top speed, 15.24 m and Multiple repeated sprint test	To determine the reliability of on-ice sprint	All 3 tests may be used in team selection and identification of fatigue or overtraining. The Multiple repeated sprint test may be the most sensitive to short-term improvements related to ice hockey conditioning.
Buckeridge et al. 2015 [14]	9 male, 25.7 ± 3.7 y, 86.2 ± 7.8 kg, 180.0 ± 4.9 cm, 9 r recreational level, 36.9 ± 5.3 y, 86.3 ± 13.8 kg, 177.8 ± 5.6 cm, varsity level	15 × 30 m sprint	In this study a novel on-ice measurement approach was tested for reliability, and subsequently implemented to investigate the forward skating technique, as well as technique differences across skill levels.	The successful implementation of this on-ice mobile measurement approach offers potential for athlete monitoring, biofeedback and training advice.
Bundarick et al. 2020 [15]	9 elite male, 22.0 ± 1.0 y, 1.81 ± 0.08 m, 81.5 ± 8.4 kg, 16 ± 2 exp; 10 elite female, 21.0 ± 1.0 y, 1.72 ± 0.07 m, 71.2 ± 10.4 kg, 14.0 ± 1.0 exp; from Canadian Interuniversity Sport League	Sprint 15 m	To compare body centre of mass and lower body kinematic profiles from static start to maximal speed of high caliber male and female ice hockey players on the ice surface.	Males generated greater forward acceleration during the initial accelerative steps, but thereafter, both sexes had similar stride-by-stride accelerations up to maximal speed. In terms of technique, males demonstrated greater hip abduction ($p = 0.006$) and knee flexion ($p = 0.026$) from ice contact to push off.
Bracko and Fellingham 2001 [35]	77 males and 54 females, 19 females 10–11 y (10.95 ± 0.55 y, 143.43 ± 8.30 cm, 36.44 ± 7.13 kg, 3.80 ± 1.74 exp); 21 males 10–11 y (10.75 ± 0.65 y, 140.92 ± 4.11 cm, 35.66 ± 4.32 kg, 5.00 ± 0.89 exp); 20 females 12–13 y (12.75 ± 0.54 y, 158.60 ± 1.07 cm, 46.97 ± 7.95 kg, 4.25 ± 2.27 exp); 31 males 12–13 y (12.25 ± 0.52 y, 159.17 ± 8.68 cm, 48.28 ± 8.54 kg, 6.68 ± 1.06 exp), American hearing Impaired Hockey Association summer camp in Chicago	S-Corner, sprint 6.1 m and 44.80 m	To compare years of playing experience, off-ice fitness, on-ice performance skating, and on-ice anaerobic power of female and male ice hockey players between the ages of 10 and 15 years.	Differences between the female and male hockey players. The 10–11 females accelerated quicker over 6.1 m. In every age group, the males were faster on the speed test. On AGL, the 12–13-year males performed better. In every age group, the males produced more skating Anaerobic power.
Bracko 2001 [36]	23 females, 8 elite: 25 ± 5 y, 176 ± 2.3 cm, 68.9 ± 6.4 kg, 17 ± 6 exp; 15 non-elite: 19 ± 2 y, 168.2 ± 7.6 cm, 65.3 ± 6.6 kg, 8 ± 3 exp	S-Corner test, sprint 6.1 and 47.85 m, 15.20 full speed, Reed repeat sprint skate test	to compare skating performance and on-ice fitness of elite and non-elite women's ice hockey players.	These results suggest that elite women's ice hockey players are older, faster skaters; have a better drop-off percent, drop-off time, and sum of 6 repeats in a repeat skate test; and have greater on-ice anaerobic capacity than non-elite players.

TABLE 1. Continue.

Author	Participants n, gender, age (y), height (cm), BM (kg); specificity	Reported tests	Aim of the study	Main finding
Bracko and George 2001 [37]	61 females, 8–16 y, 12.8 ± 2.05 y, 155 ± 14.3, 44.4 ± 12.3, 4.68 ± 2.6 exp.	Sprint 6.1 m, 47.85 speed, S-Corner test	To identify the off-ice variables associated with high-performance skating acceleration, speed, agility, and on-ice anaerobic capacity and power in women's ice hockey players.	40-yd dash time is the strongest predictor of skating speed in women's hockey players ages 8–16 years old. Prediction equation was speed = 4.913– (0.0107 × kilograms) + (0.4356 × 36 m dash time).
Czeck et. al 2022 [38]	15, males, 20.8 ± 1.4 y, 183 ± 0.04 cm, 85.39 ± 7.55 kg 18 females, 20.86 ± 1.0 y,171 ± 0.4 cm, 74.57 ± 9.02 kg; NCAA Division I collegiate players	9, 18, 24, 42, 48, 66, 82, 132, and 148 m	To explore positional differences for an on-ice timed skate test and its relationship to body composition.	No differences between on-ice skating times between forwards and defensemen. Body fat percentage was correlated with on-ice skate times in male and female collegiate hockey players.
Dæhlin et al. 2017 [39]	16 male, U18 n = 9, 17.2 ± 1.0 y, 1.82 ± 0.03 m; U20 n = 7, 17.1 ± 0.7 y, 1.84 ± 0.05 m, NR, elite in Norway;	Sprint 10 and 35 m, skating multistage aerobic test	To compare the effect of combined plyometric and strength training on skating sprint performance	Plyometry and strength training gained a larger improvement in 10 m on-ice sprint performance than strength training ($P < 0.025$).
Delisle-Houde et al. 2019 [40]	18 male, 22.8 ± 1.4 y, 180.70 ± 6.40 cm, 87.10 ± 6.7 kg, University varsity team	Sprint 30 m forward and backward, On-ice pro agility left and right	To determine the predictability of common laboratory/field and novel laboratory tests for skating characteristics in Canadian college ice hockey players.	Pearson correlations and stepwise regression revealed relationships between on-ice forward sprint and Wingate relative peak power [r = -.62, $P < .01$], standing long jump [r = -.45, $P < .05$], off-ice proagility left [r = .51, $P < .05$], and vertical jump impulse [r = .60, $P < .01$].
Haukali and Lief 2016 [41]	18 elite male from Norwegian ice hockey club, T1 (pre test – end of season), 15.8 ± 0.9 y, 68.2 ± 9.6 kg, 176.7 ± 7.7 cm; T2 (start of new season), 16.0 ± 0.7 y, 69.9 ± 8.7 kg, 177.0 ± 7.6 cm; T3 (midseason), 16.2 ± 0.6 y, 70.7 ± 9.0 kg, 178.0 ± 7.7 cm	Sprint 36 m forward and backward, The Norwegian Hockey Federation's skate agility test.	To examine whether there exists a correlation between changes in off-season power and changes in in-season skating performance among young ice hockey players	An off-season training program that includes sprints and horizontal jumping exercises may have a positive effect on hockey players' linear skating speed.
Haukali and Lief 2015 [42]	32 juniors male, 16.4 ± 0.6 y, 70.9 ± 5.2 kg, 179.3 ± 5.2 cm	Sprint 36 m, skating speed 36 m, The Norwegian Hockey Federation's skate agility test.	To examine the relationship between specific off-ice variables and skating speed and agility among young ice hockey players.	No significant correlation between agility and speed skating, or between agility and sprint. Off-ice training program that includes sprint training and jumping exercises will have a positive effect on young hockey players' skating performance.
Farlinger and Fowles 2008 [3, 43]	34 juniors male and female, 16.4 ± 2.0 y, 70.4 ± 12.8 kg, 174.5 ± 4.2 cm	Sprint 35 m	To determine the effectiveness of a progressively "skating specific" periodized off-season training program on skating performance in competitive hockey players.	Significant improvements in on-ice 35-m skating sprint (1.0%; $P = .009$) with significant improvements of 5% to 12% in various off-ice testing measures were observed. On-ice 35-m skating sprint times improved by 2.3% with greater improvement in plyometric followed by simulator training (3.5%) versus simulator training followed by plyometric training (0.8%).

TABLE 1. Continue.

Author	Participants n, gender, age (y), height (cm), BM (kg); specificity	Reported tests	Aim of the study	Main finding
Farlinger et. al. 2007 [3]	36 males between 15–22 y, 16.3 ± 1.7 y, 175.6 ± 4.1 cm ,70.8 ± 10.4 kg,	Sprint 35 m, S-Corner test	To identify off-ice variables that would correlate to on-ice skating sprint performance and cornering ability.	The on-ice sprint test and cornering S test were strongly correlated ($r = 0.70$; $p < 0.001$). While many off- ice tests correlated with on-ice skating, measures of horizontal leg power (off-ice sprint and 3 hop jump) were the best predictors of on-ice skating performance, once weight and playing level were accounted for. These 4 variables accounted for a total of 78% ($p < 0.0001$) of the variance in on-ice sprint performance.
Federolf and Nigg 2008 [20]	20 males, 22.6 ± 0.9 y, 184 ± 5 cm, 87.3 ± 7.3 kg from University of Calgary ice team, NR	Maximum speed 45 m, Glide turn test, Sprint 10 m and 40 m	To test if a flared blade design measurably improves skating performance of ice hockey players in selected skating tests.	The results of this study show that relative simple modifications on ice hockey equipment can lead to measurable improvements in skating performance.
Geithner et al. 2006 [44]	112 female players, 21.4 ± 2.9 y, 168 ± 5 cm, 66 ± 7 kg, University of Alberta, Hockey Team the Pandas	Sprint 6.1 m, S-Corner Test, Modified 3-Repeat Sprint Skate Test	To describe and compare physical, fitness, and skating performance characteristics of forwards, defensemen and goalies.	Forwards had greater anaerobic power than defense, followed by goalie, and they tended to have greater aerobic capacity. Performance demands appear to the position specific.
Gilenstam et al. 2011 [13]	10 male, 23.0 ± 2.4 y, 181 ± 5 cm, 85.0 ± 7.8 kg; 11 females, 23.0 ± 3.0 y, 168 ± 3.5 cm, from 2nd division in Sweden	Sprint 6.1 and 47.85 m, S-Corner test, Full speed test for 15.2 m	To identify relationships between physiological off-ice tests and on-ice performance in female and male ice hockey players on a comparable competitive level.	Skating performance in female hockey players may be improved by increasing thigh muscle strength, oxygen uptake, and relative muscle mass.
Gupta et al. 2022 [45]	19 male juniors; 18.7 ± 2.2 y, 179.2 ± 11.6 cm, 77.8 ± 10.2 kg, from club UKS Zagłębie Sosnowiec, Poland	Skating Multistage Aerobic Test, sprint 5–10–30 m, Top speed test, Repeated sprint ability 5 × (54 + 35 m), Vertical jumps	To determine the relationships between vertical jumps and various on-ice skating performances of junior ice hockey players	Depth drop jump can be used as a predictor of all the ice skating speed tests, whereas squat jump can predict backward average skating speed and maximum skating speed. Repeated sprint ability performance cannot be predicted from vertical jumps of junior ice hockey players.
Hajek et al. 2021 [46]	10 male, U18 = 16.0 ± 1.0 y, 1.75 ± 0.1 m, 68.0 ± 9 kg; U14 = 12.0 ± 1.0 y, 1.57 ± 0.08 cm, 49.0 ± 9 kg; U18 and U14 top Austrian National Team	Sprint 40 m	To develop and validate a specific overall skating performance test for ice hockey (SOSPT)	The results of the study reveal reliability and validity of specific overall skating performance in ice hockey players and is more suitable compared with straight skating tests of the 40-m on-ice sprinting test.
Janot et al. 2015 [47]	26 male and females, 20.5 ± 1.4 y, 1.74 ± 1.0 m, 79.6 ± 13.5 kg, 14.0 ± 4.3 exp, NCAA Division III	S-Corner test, sprint 6.1, 15.20 and 44.8 m, Modified Repeated Skate	To determine if off-ice performance variables could predict on-ice skating performance	It was concluded that selected off-ice tests could be used to predict on-ice performance regarding speed and recovery ability in Division III male and female hockey players.
Janot et al. 2013 [48]	23 male players, 12.3 ± 1.1 y, 51.7 ± 18.5 kg, NR	Sprint 6.1, 15.2 and 44.8 m	Determine if on-ice BungeeSkate traing would improve on-ice speed and acceleration	Speed and top speed were significantly increased ($P < .05$) by 4.2% and 4.3%, respectively.

TABLE 1. Continue.

Author	Participants n, gender, age (y), height (cm), BM (kg); specificity	Reported tests	Aim of the study	Main finding
Jones et al. 1999 [49]	16 male, 27 ± 4 y, 1.81 ± 0.07 m, 85.5 ± 8.2 kg, British Super League Club	6 × 80 m skating sprint every 30 s, split taken at 47 m	To assess the effect of oral creatine monohydrate supplementation on multiple sprint cycle and skating performance in ice-hockey players.	Average on-ice sprint performance on 47 m was significantly faster at 10 days 6.88 ± 0.21 sec) a d 10 weeks 6.96 ± 0.19 sec than at baseline 7.17 ± 0.27 sec ($p < 0.005$).
Kaartinen et al. 2021 [50]	12 elite males, 18.4–22.0 y, 81.0 ± 6.0 kg, 1.82 ± 0.03 m, 25.2 ± 1.6 BMI kg/m^2, Finnish elite league	5 × 30 m sprint	To describe lower limb kinematic and muscle activation patterns and then to examine the potential associations between those variables and skating speed	A lower activity of the gluteus maximus ($r = -0.651$, $p = 0.022$, $\beta = -0.08$) and a reduced gluteus maximus to rectus femoris coactivity ($r = -0.786$, $p = 0.002$, $\beta = -3.26$) during the recovery phase were found to be associated with faster skating speed.
Kinnunen et al. 2019 [51]	14 females, 22 ± 3 y, 16–28 y 165 ± 5 cm, 67 ± 12 kg, Finnish championship	Sprint 11 and 34 m	To investigate High-intensity training related to neuromuscular adaptations, changes in force production, and on-ice performance in female ice hockey players during preseason.	High-intensity training can be used to improve athletes' capability to produce maximal and explosive forces, likely through enhanced voluntary activation of their muscles and reduced antagonist coactivation.
Lagrange et al. 2020 [52]	41 elite male, Group n = 21, 16.8 ± 1.3 y, 177.3 ± 6.1 cm, 166.8 ± 8.6 lbs, 24.1 ± 2.0 BMI,; Control group n = 20, 16.4 ± 1.7 y, 181.6 ± 5.3 cm, 169.6 ± 7.3 lbs, 23.6 ± 2.1 BMI, midget or junior hockey players	9 sprints of 40 m each (approximately 5 seconds) with 3 s rest	To measure the generating effects of Contrast Training on 6-hour post-activation potentiation and its influence on jumping and on on-ice repeated sprint performance in ice hockey players.	The contrast training generated PAP which had an acute performance enhancement on the on-ice hockey repeated sprint test performance.
Martini et al. 2018 [53]	59 male, 14.6 ± 2.1 y, 166.4 ± 12.8 cm, 60.4 ± 14.1 kg, 21.5 ± 2.6 BMI, 8.9 ± 3.1 exp.	Sprint 6.1 and 44.8, 7 × 7 m	To measure ice hockey players skills and analyze their fluctuations via a protocol that reproduces the demands of a hockey game	A significant decline in performance was observed for speed, acceleration, and shooting ($p < .01$). Inversely, participants seemed to adapt to puck control and passing stations, as they became faster without decreasing skating abilities.
Madden et al. 2019 [54]	15 college males (SP: skill performance), 22.1 ± 0.4 y, 83.3 ± 1.8 kg, 182 ± 2 cm; and 14 college males (scrimmage), 22.6 ± 0.4 y, 85.8 ± 2.3 kg, 182 ± 2 cm; both from Okananan Hockey Group and completed Western Hockey League Combines	Sprint 30 m forward and backward, transition agility, weawe agility, reaction with and without puck	To determine the effects of low-dose caffeine supplementation (3 mg/kg body mass) consumed 1 h before the experiment on rating of perceived exertion , skills performance (SP), and physicality in male college ice hockey players	A low dose of caffeine has limited impact on sport-specific skill performance and rating of perceived exertion but may enhance physicality during ice hockey scrimmage.
Naimo et al. 2015 [55]	24 male a, interval group: n = 12, 19.6 ± 1.3 y, 180.0 ± 7.0 cm, 79.9 ± 8.3 kg; continuous group: n = 12, 19.7 ± 2.1 y, 174.9 ± 7.9 cm, 74.9 ± 9.0 kg, Universtiy of Tampa	6 × 9 m stops, sprint 33 m, 127 m endurance test	To investigate the efects of a High intensity interval training program compared to traditional continuous endurance exercise training	High intensity interval training demonstrated a faster Δ sprint ($p < 0.02$) and a trend ($p = 0.08$) for faster Δ endurance test time to completion for IG.
Matthews et al. 2010 [56]	11 male, 22.09 ± 3.05 y, 83.47 ± 11.7 kg, 179 ± 6 cm, from the English National	Sprint 25 m	To investigate the acute effect of a heavy resisted sprint when used as a preload exercise to enhance subsequent 25-m on-ice sprint performance	These findings appear to suggest that the intensity and duration of a single resisted sprint in this study are sufficient to induce an acute (after 4 minutes of rest) improvement in 25-m sprint performance on ice.

TABLE 1. Continue.

Author	Participants n, gender, age (y), height (cm), BM (kg); specificity	Reported tests	Aim of the study	Main finding
Nigg 2020 [32]	20 male 1 female: 36.25 ± 12.91 y, 178.85 ± 8.64 cm, 81.36 ± 12.89 kg, 5.68 ± 8.93 exp, 5th German Player League,	S-Corner test, sprint 6.1 m and 35 m	Investigate which performance indicators were related to the plus-minus statistic in German recreational ice hockey players over a season.	Some performance and psychological indicators are related to recreational ice hockey players' plus-minus statistic over a season.
Novak et al. 2019 [8]	14 males: 14.8 ± 0.45 y, 61 ± 10.43 kg, 168.93 ± 9.72 cm, 9.07 ± 0.75 exp, highest junior league in Czech republic	Sprint 6.1 and 35 m, S-Corner test, test with brake, weave agility, reaction test	To compare the effects of on-ice and off-ice agility training on skating performance.	Off-ice agility have motor transfer to on-ice agility. Therefore, we recommend developing on-ice agility with additional off-ice agility training during the ice hockey season.
Novak et al. 2020 [57]	13 males from U12 in Czech republic, 13 ± 0.35 y, 152.23 ± 9.41 cm, 41.92 ± 8.76 kg, 17.91 ± 2.14 BMI	7 × 7 with and without puck, sprint 30 m forward and backward, 4 m sprint forward and backward with and without puck.	to compare the effects of training programs using change-of-direction speed exercises and partial skating task training on speed and agility performance in U12 ice hockey players.	Change of directional speed training on the ice improves short starts and agility with a puck, while partial skating tasks training target longer 30-m sprints and agility without a puck.
Peterson et al. 2015 [58, 59]	45 male between 18–24 from, Division I (n = 24): 184.92 ± 5.99 cm, 86.88 ± 6.69 kg, 11.46 ± 2.43 %fat; Elite Junior (n = 10): 180.70 ± 6.78 cm, 82.30 ± 5.62 kg, 9.40 ± 2.01 %fat; Division III (n = 11): 178.55 ± 3.50 cm, 82.30 ± 4.95 kg, 14.36 ± 2.29 %fat, Division I and III and Elite Junior level in Minneapolis	Repeated shift test	To examine the differences that may exist between these characteristics in Division I, Elite Junior, and Division III hockey players	No significant difference between Division I and Elite Junior players for any on or office performance variable. The results of this study indicate that performance differences between Division I and Division III hockey players seem to be primarily because of the rate of force production.
Peterson et al. 2016 [59]	45 male 18–24 y, 181 ± 9 cm, 84 ± 12 kg, 12.5 ± 4 %fat, Division I, II or Junior Level hockey in Minneapolis	Sprint 15.24 m, Repeated shift ability	To test whether conventional off-ice anaerobic power tests could predict on-ice acceleration, top speed, and repeated shift performance	Although conventional off-ice anaerobic power tests predict single bout on-ice acceleration and top speed, they neither predict the repeated shift ability of the player, nor are good markers for performance in ice hockey.
Perez et al. 2021 [17]	17 female, 21.6 ± 3.4 y, 166 ± 9 cm, 65.3 ± 9.9 kg, 14.6 ± 3.2 exp, elite French national team,	skating (5 and 40 m) sprint tasks	To investigate the correlations between players' mechanical capacities determined during off and on-ice tests	Performance variables (SJ height, 30-m running and 40-m forward skating split time) and Pmaxrel demonstrated the largest associations between jumping, running and skating tasks (r ranging from -0.81 for 30-m sprint running time to 0.92 for SJ height; $p < 0.001$). The capacity to generate high amounts of horizontal power and effective horizontal force during the first steps on the ice is paramount for forward skating sprint performance.
Perez et al. 2022 [60]	11 highly-trained females, 17.6 ± 4.0 y, 1.66 ± 0.06 m, 63.6 ± 6.3 kg, 10.5 ± 4.1 exp, French	Sprint 2 × 40 m	To ensure that the skating velocity describes a mono-exponential function in order to determine the reliability of radar-derived profiling results from skating sprint accelerations applying sprint running force-velocity assessment approach.	The current study indicates that radar-derived kinetics variables assessed during onice 40-m forward sprint skating demonstrate an acceptable level of relative and absolute reliability.

TABLE 1. Continue.

Author	Participants n, gender, age (y), height (cm), BM (kg); specificity	Reported tests	Aim of the study	Main finding
Renaud et. al. 2017 [10]	15 males, 7 high calibre males, 24.7 ± 3.1 y, 184.2 ± 6.4 cm, 87.1 ± 6.0 kg, 19.7 ± 3.9 exp; 8 low calibre males, 23.9 ± 3.1 y, 179.4 ± 3.4 cm, 81.3 ± 8.4 kg, 9 ± 6 exp, Montreal, CA.	3 repetition of a maximum effort forward skating start	To evaluate kinematic ice hockey skating start movement technique in relation to a skater's skill level.	Both skate groups had similar lower body strength profiles, yet high calibre skaters achieved greater velocity; skating technique differences most likely explained the performance differences between the groups.
Robert-Lachaine et al. 2012 [27]	10 males, 22.9 ± 2.2 y, 80.5 ± 9 kg, 178.3 ± 4.5 cm, 16.8 ± 3.4 exp	Crossover on outside leg (COO) and inside leg (COI), forward skating	To determine if these modifications resulted in biomechanical and performance changes during on-ice skating skills.	Modified skates demonstrated significant gains of 5°–9° in dorsi-plantarflexion ROM ($p < 0.05$). Total peak force occurred later during plantarflexion, suggesting a more prolonged and effective force generation with the modified skates during a given skating stride.
Roczniok et al. 2016 [61]	42 males, G1: 20, 24.70 ± 3.53 y, 182.9 ± 4.02 cm, 78.48 ± 7.15 kg, 24.19 ± 1.52 BMI; G2: 22, 24.82 ± 6.68 y, 179.18 ± 5.22 cm, 80.20 ± 9.27 kg, 24.94 ± 2.39 BMI, Poland top division	Sprint 30 forward and backward, 6 × 9 turns, 6 × 9 stops, 6 × 30 stops	To examine physiological and physical determinants of ice-hockey performance	The logistic regression model showed that the best predictors of success in the recruitment process of top level ice hockey players were time to peak power, relative peak power, VO_{2max} and 30 m sprint forwards on ice.
Roczniok et al. 2016 [62]	24 elite males, season 2012/2013 = 177.70 ± 4.19 cm, 79.43 ± 8.28 kg; season 2013/2014 = 177.80 ± 4.37 cm, 80.62 ± 8.19 kg, NR, Poland second league	Sprint 30 forward and backward, 6 × 9 turns, 6 × 9 stops, 6 × 30 stops	To determine the values of selected aerobic and anaerobic capacity variables, physical profiles, and to analyze the results of on-ice tests performed by ice-hockey players relegated to a lower league.	The study showed that playing in a lower league where games were less intensive, training sessions shorter and less frequent, had an adverse effect on the performance level of the investigated players.
Roczniok et al. 2012 [63]	21 males, NR, NR, Polish National Team, U20 World Championship 2009	Sprint 30 forward and backward, 6 × 9 turns, 6 × 9 stops, 6 × 30 stops	To determine the predictive value of the indexes of aerobic and anaerobic endurance in relation to specific on-ice tests performed by hockey players that focus on strength, power, speed as well as speed and strength endurance.	The obtained results found significant correlations between maximal power obtained from the Wingate test and certain aspects of the special physical fitness test, specifically the 6 × 9 turns, 6 × 9 stops and 6 × 30 m endurance tests. Significant correlations of the above-mentioned special physical fitness tests were also observed with the aerobic capacity parameter, VO_{2max}.
Rønnestad [64]et al. 2016 [64]	15 males from 2nd level in Norway, 21 ± 2 y, 79 ± 7 kg, 180 ± 5 cm	Sprint 10 and 20 m	To investigate the effect of body-loaded half-squats with added whole body vibration on subsequent 20 m on-ice sprint performance.	Improved well-being in the legs immediately after the preconditioning exercise with whole-body vibration ($p < 0.05$). Preconditioning exercise performed with WBV at 50 Hz seems to enhance on-ice sprint performance in ice-hockey players.
Runner et. al. 2016 [65]	40, elite male, NR, 181.30 ± 5.80 cm, 84.95 ± 5.58 kg, National Collegiate Athletic association Division I	27.4 m forward and backward acceleration, 15.2 m flying top speed test	To examine the relationship between commonly employed dry-land performance tests and skating speed in male collegiate ice hockey players.	Vertical jump showed significance in relation to skating speed ($p = 0.011$).

TABLE 1. Continue.

Author	Participants n, gender, age (y), height (cm), BM (kg); specificity	Reported tests	Aim of the study	Main finding
Shell et al. 2017 [66]	10 elite females, 21 ± 1 y, 14 ± 1 exp, 1.72 ± 0.07 m, 71.2 ± 10.4 kg; 9 elite males, 22 ± 1 y, 16 ± 2 exp, 1.81 ± 0.08 m, 81.5 ± 8.4 kg, players from Canadian Interuniversity sport league	Sprint 15.3 m	To evaluate the body movement kinematics of ice hockey skating starts between elite male and female ice hockey participants	Males' maximum skating speeds were greater than females. Females presented ~10° lower hip abduction throughout skating stance as well as ~10° greater knee extension at initial ice stance contact, conspicuously followed by a brief cessation in knee extension at the moment of ice contact, not evident in male skaters.
Secomb et al. 2021 [9]	13 male, 26.7 ± 6.7 years; 88.4 ± 18.1 kg; 181.9 ± 5.4 cm), semiprofessional males from Australian Ice Hockey League	Sprint 20 m, On-Ice Change of Direction (505)	To determine whether hip strength in joint angles specific to skating positions and countermovement jump performance explains sprint skating acceleration and change of direction performance.	Hip strength at joint angles functionally relevant to skating (e.g., at 25° and 50°), in combination with relevant countermovement jump variables, explained large and very large amounts of variance in sprint skating acceleration and change of direction performance in this cohort.
Schulze et al. 2021 [67]	104 male elite, 26.4 ± 5.62 y, 1.82 ± 0.06 m, 86.9 ± 8.70 kg, 64 forwards, 40 defenders, professional German Forward 3rd league	Ice-hockey specific complex test (sprint 10 and 30 m, transition and weave agility with and without puck, slap and wrist shot, stress)	To investigate position-specific reference data for Ice-hockey specific complex test	The only significant ($p < 0.002$) difference between forwards and defenders for performance were found for weave agility with puck ($p < 0.001$). Forwards showed a higher average performance in this parameter than defenders. Differences were also found in weave agility without a puck ($p = 0.008$), 30 m backward sprinting without puck ($p = 0.012$) and goals after test ($p = 0.030$).
Schwesig et al. 2018 [68]	20 male elite from Third German League, 27.0 ± 5.8 y, 1.82 ± 0.05 m, 88.3 ± 7.7 kg	10-m sprint, a 30-m transition with and without a puck	This study assessed the intra-rater reliability of an ice hockey-specific complex test that reflects the intense multidirectional and intermittent efforts required in ice hockey	The Ice-hockey specific complex test is currently the only ice hockey-specific complex test with scientifically tested reliability and validity that can analyze performance under conditions similar to the competition.
Schwesig et al. 2017 [69]	18 elite male, Third Professional German League, age 27 ± 6.0 y, 1.82 ± 0.05 m, 89.8 ± 7.5 kg	Ice-hockey specific complex test (sprint 10 and 30 m, transition and weave agility with and without puck	To examine the validity of an ice hockey-specific complex test Ice-hockey specific complex test and nonspecific off-ice tests for sports performance.	Stability indicator ($r^2 = 0.39$), weave agility with puck ($r^2 = 0.39$), maximal relative squat ($r^2 = 0.37$) and frequency band -8 ($r^2 = 0.35$) proved to be the most valid tests. However, with the match performance score as the dependent variable, 21 of 44 parameters tested (48%) explained 10% or more of variance.
Stenroth et al. 2020 [71]	12 male, 18.4–22.0 y, 83.9 ± 6.2 kg, 1.82 ± 0.03 m, 25.2 ± 1.8 BMI, eliteFinnish junior league	Sprint 30 m	The reliability and concurrent validity of force-velocity profiling based on split times when used for ice hockey skating. Which the start instant of the sprint is estimated based on optimization (time shift method), affects the reliability and validity of the method.	The time shift method tested here can be used as a reliable tool to test a player's physical performance characteristic underlying sprint performance in ice hockey skating.

TABLE 1. Continue.

Author	Participants n, gender, age (y), height (cm), BM (kg); specificity	Reported tests	Aim of the study	Main finding
Stetter et al. 2019 [72]	22 male, 32.1 ± 7.7 y, 178.7 ± 5.7 cm, 86.7 ± 10.5 kg, Calgary men's hockey team	Max effort 30 m sprint	To investigate the feasibility of using body worn accelerometers to identify previous highlighted performance-related biomechanical changes in terms of substantial differences across skill levels and skating phases.	High caliber players showed an increased stride propulsion (+22%, $P < 0.05$) and shorter contact time (-5%, $P < 0.05$). All three analysed variables highlighted substantial biomechanical differences between the accelerative and constant velocity phases ($P < 0.05$). Stride propulsion of acceleration strides primarily correlated to total sprint time ($r = -0.57$, $P < 0.05$).
Thompson et al. 2020 [73]	42 male, 23.0 ± 2.07 y, 175 ± 10 cm, 77.3 ± 12.5 kg, 24.98 ± 2.16 BMI University of Guelph	Sprint 15 m	To compare the suitability of common off-ice fitness tests and off-ice resisted sprints for predicting 15 m on ice skate time.	We conclude that resisted off-ice sprints have better predictive ability of on-ice skate time compared with commonly used off-ice tests.
Stanula et al. 2014 [74]	24 male, 25.2 ± 3.93 y, 182.9 ± 3.7 m, 86.9 ± 6.1 kg National Hockey Team of Poland,	Repeated Skate Sprint (6 × 89) with 30 rest	To determine a relationship between aerobic capacity (VO_{2max}) and fatigue from high-intensity skating	The 6 × 89 m test proposed in this study offers a high test-retest correlation coefficient ($r = 0.78$).
Stanula et al. 2021 [75]	19 male, forwards = 12, 23.4 ± 4.76 y, 179.8 ± 5.68 cm, 80.5 ± 7.57 kg; defenders = 7, 22.3 ± 5.2 y, 182.0 ± 3.46 cm, 87.1 ± 4.81 kg, Zagłebie Sosnowiec, Poland	Repeated Skate Sprint	The impact of two different passive recovery durations, two and three minutes, between sets of repeated sprint skating ability test on skating speed, speed decrement, and heart rate response.	This study concludes that three-minute recovery is beneficial over two-minute recovery by increasing skating speed.
Vigh-Larsen et al. 2020 [6]	30 male, 19.0 ± 1.0 y, 184.3 ± 6.2 cm, 83.4 ± 8.8 kg, 42.9 ± 5.2 muscle mass, 10.3 ± 0.7 %fat, Danish U20 national team	Repeated sprint ability	The present study investigated muscle metabolism and fatigue during simulated elite male ice hockey match-play.	Repeated-sprint ability was impaired (~3%; $P \leq 0.05$) postgame concomitant with a ~10% decrease in the number of accelerations and decelerations during the second and last periods ($P \leq 0.05$).
Vigh-Larsen et al. 2020 [4]	Male 179, Finish elite: 74, 25.9 ± 5.4 y, 183.0 ± 6.4 cm, 86.1 ± 7.8 kg, Danish Elite: 55, 23.9 ± 4.5 y, 182.3 ± 6.0 cm, 84.3 ± 8.3 kg, Finish U20: 19, 18.7 ± 0.9 y, 180.0 ± 7.2 cm, 78.6 ± 8.4 Danish U20: 17, 18.1 ± 1.7 y, 79.0 ± 5.9 cm, 75.7 ± 10.1 kg,	5-10-5 Pro-agility, sprint 10 and 30 m, Yo-Yo Intermittent Recovery Level 1 Ice Hockey Test	To compare fitness profiles and body composition in elite players of 2 different national standards in a large sample of players, applying specific on-ice and off-ice test procedures. To compare the fitness level of players of these elite standards with U20 players from both countries to test for potential age-related differences.	Large differences in on-ice performances were demonstrated between Finnish and Danish elite players for agility, 10- and 30-m sprint performance. Finnish U20 cohort had a similar performance level as the Danish elite players and superior 10-m sprint performance.
Vigh-Larsen et al. 2019 [5]	164 elite male 23.5 ± 4.4 y, 182.3 ± 5.2 cm, 85.7 ± 8.1 kg, 15.1 ± 4.0 %fat; 132 subelite 19.4 ± 2.9 y, 180.9 ± 6.8 cm, 80.8 ± 10.0 kg, 15.6 ± 6.5 %fat, Best and second Danish ice hockey division.	Yo-Yo heart rate max and submax, 5-10-5 pro-agility test, 0–10.85 and 10–33.15 sprint	To evaluate fitness profiles in elite (and subelite male ice hockey players.	In conclusion, elite-level ice hockey requires a high level of fitness in terms of muscle mass and explosive strength, as well as a well-developed high-intensity intermittent exercise capacity. In addition, these demands seem to apply for both forwards and defensemen.

TABLE 1. Continue.

Author	Participants n, gender, age (y), height (cm), BM (kg); specificity	Reported tests	Aim of the study	Main finding
Vigh-Larsen et. al. 2021. [76]	199 males: 65, 18–21 y, 182.5 ± 5.9 cm, 83.0 ± 8.2 kg, 71, 22–25 y, 183.5 ± 5.5 cm, 87.1 ± 7.2 kg, 40, 26–29 y, 181.5 ± 5.1 cm, 86.4 ± 6.4 kg, 23, 30–33 y, 184.2 ± 5.4 cm, 91.2 ± 9.6 kg	5-10-5 Pro Agility test, sprint 30 m, Yo-Yo heart rate max	To investigate relationships between age, body composition and performance in elite male ice hockey players.	Small-moderate associations between age and body composition were present. Lower high-intensity exercise performance was evident in the oldest and a lower body weight in the youngest players, whereas aerobic capacity was similar. This suggests that capabilities related to size, strength and power are the most critical parameters differing between young and old ice hockey players.
Wagner et al. 2021 [77]	13 = U15, 13.3 ± 0.5 y, 1.62 ± 0.1 m, 56 ± 10 kg; 18 = U17, 15.1 ± 0.7 y, 1.76 ± 0.7 m, 68.0 ± 9.0 kg; 19 = U20, 17.8 ± 2.0 y, 1.78 ± 0.05 m, 76.0 ± 5.0 kg; Swiss elite league	Sprint 6 and 30 m, specific overall skating performance test	To analyze the differences in on-ice and off-ice performance and relation between on-ice and off-ice performance	The stronger relationship between specific overall skating performance test performance and on-ice and off-ice performance in the younger compared to the older players revealed that general physical performance determined specific overall skating performance more often in youth players, whereas in junior und young adult players, an optimal skating technique is more important.
Williams and Grau 2020 [78]	12 male, 17.92 ± 0.9 y, 185 ± 8.45 cm, 83.17 ± 8.61 kg elite adolescent	Sprint 15 m, S-Corner test	To analyse the relationships between physical performance and game performance, as well as examining the relationships of physical performance and game performance dependent on competition level.	Results illustrated an inverse relationship between plyometric performance and offensive point shares. On-ice agility may be a relevant indicator of game performance dependent on competition level for individuals and sub-groups.
Wilson et. al 2021 [79]	17 females, 21 ± 2 y, 166.2 ± 6.4 cm, 61.9 ± 7.7 kg	7 × 15 m sprints every 15 s	To design and examine the reliability of a 7 × 15 m repeated on-ice skating sprint test for female ice hockey players	Players in the forward position had a faster mean 15 m time and lower total time compared to those in the defensive position ($p < 0.05$). These findings show that a 7 × 15 m repeated on-ice sprint test for varsity women ice hockey players was reliable. It was also found that forwards had a better mean of 7 sprint time and faster total time compared to players in the defensive position.

of acceleration, equality of variances was violated. Therefore, we used Welch's One Way Analysis of Variance (ANOVA) for unequal variances [31], followed by the Games-Howell post hoc test for multiple comparisons. For the speed analysis, we used One Way ANOVA with Tukey's post hoc test where variances at each distance range met the equality requirement [31].

Other statistics have been done without pooling to distance ranges. The Kendall rank correlation coefficient (τ) and regression coefficient was used to express the relation between sprint distance, average velocity and acceleration. The players age correlation was included due to possible mediation to speed and acceleration parameters. Regression functions with 95% confidence intervals were used to describe the dependence of velocity and acceleration on the skating distance. All statistical analyses were done in STATISTICA software (TIBCO, Palo Alto, CA, USA) with R software 3.2.1 integration using an a priori significance level of $p < 0.05$.

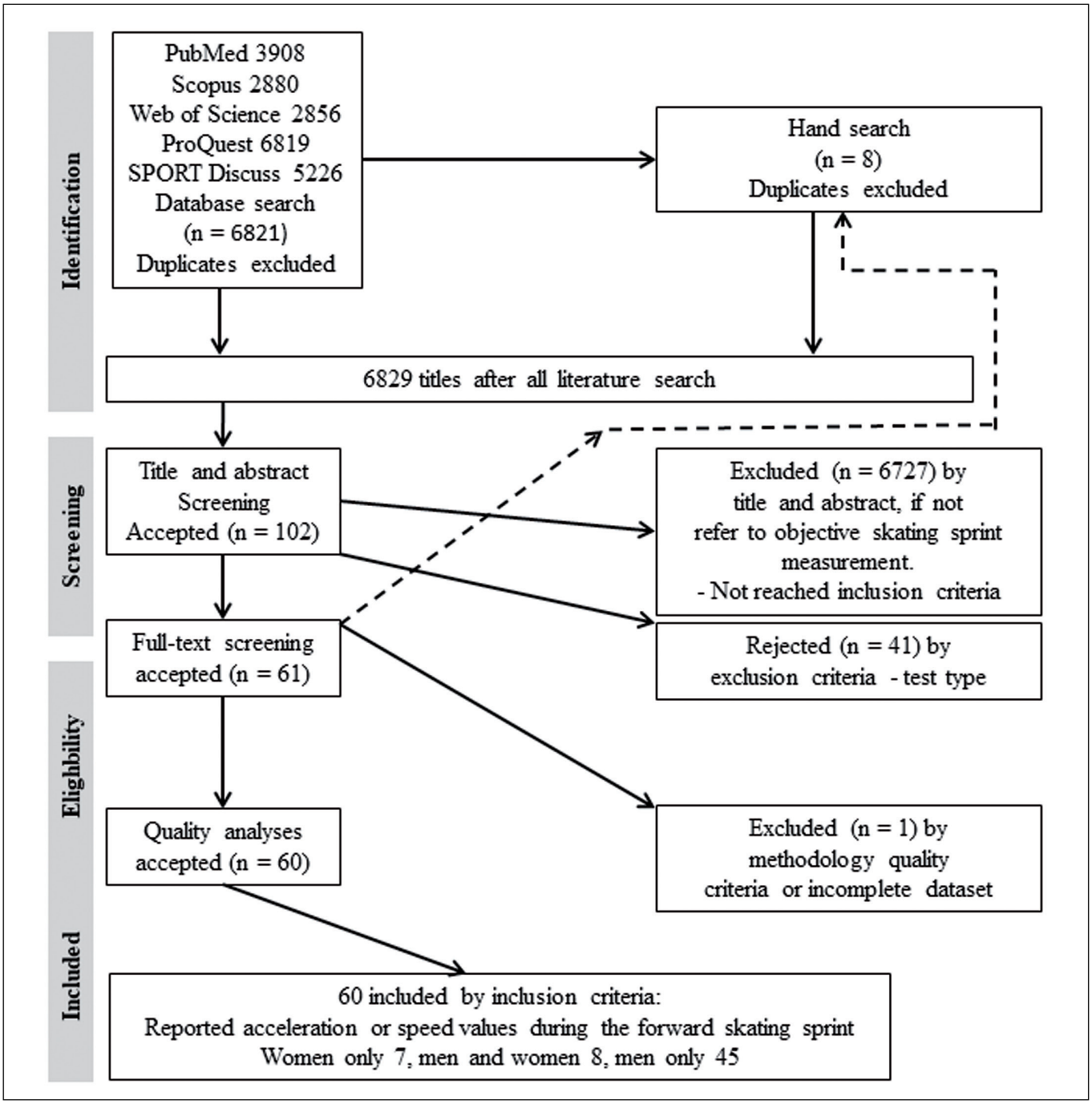


FIG. 1. The flow chart of the systematic search for articles including ice-hockey forward sprint or acceleration data.

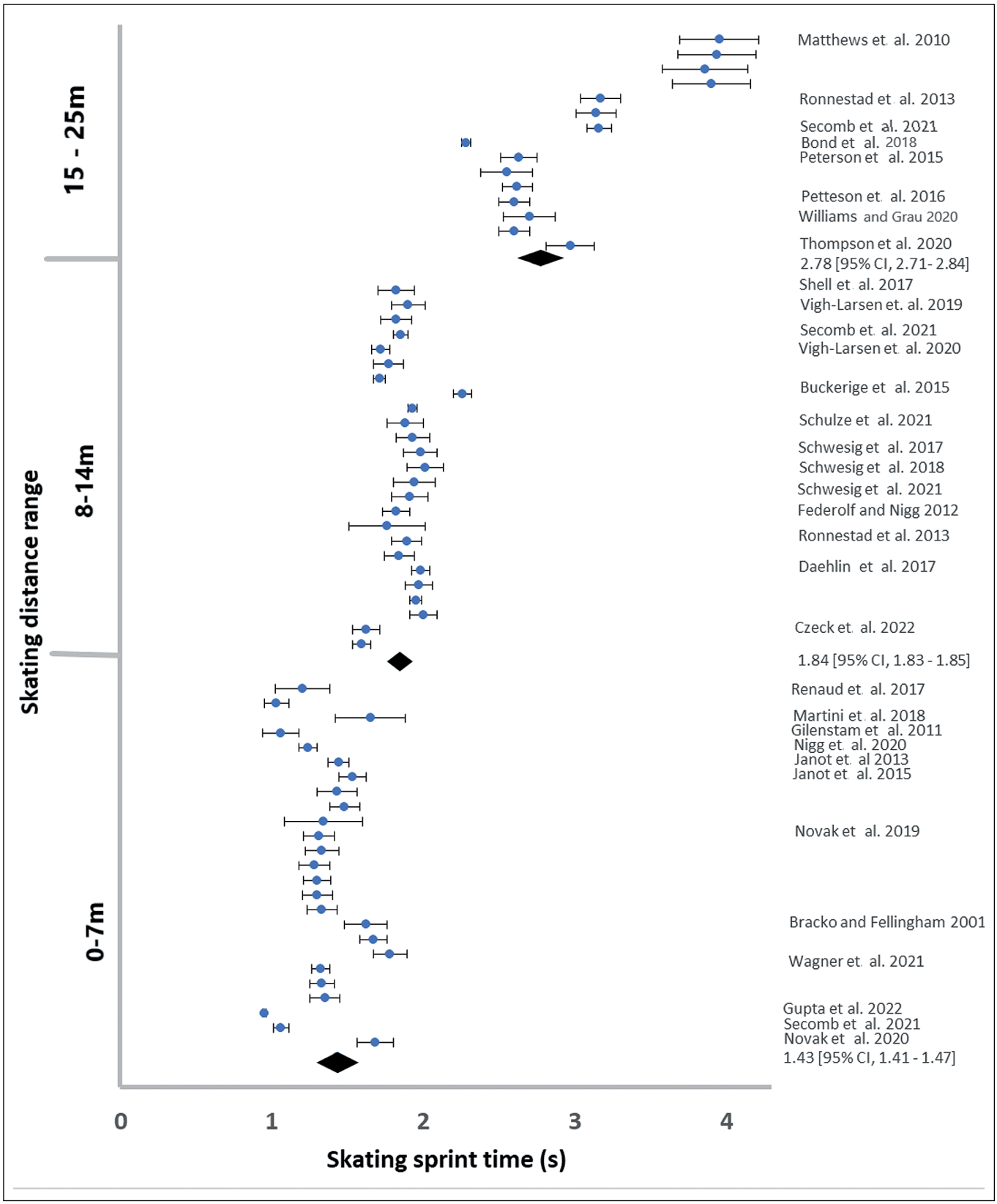


FIG. 2. The reported male sprint times during acceleration up to 25 m.

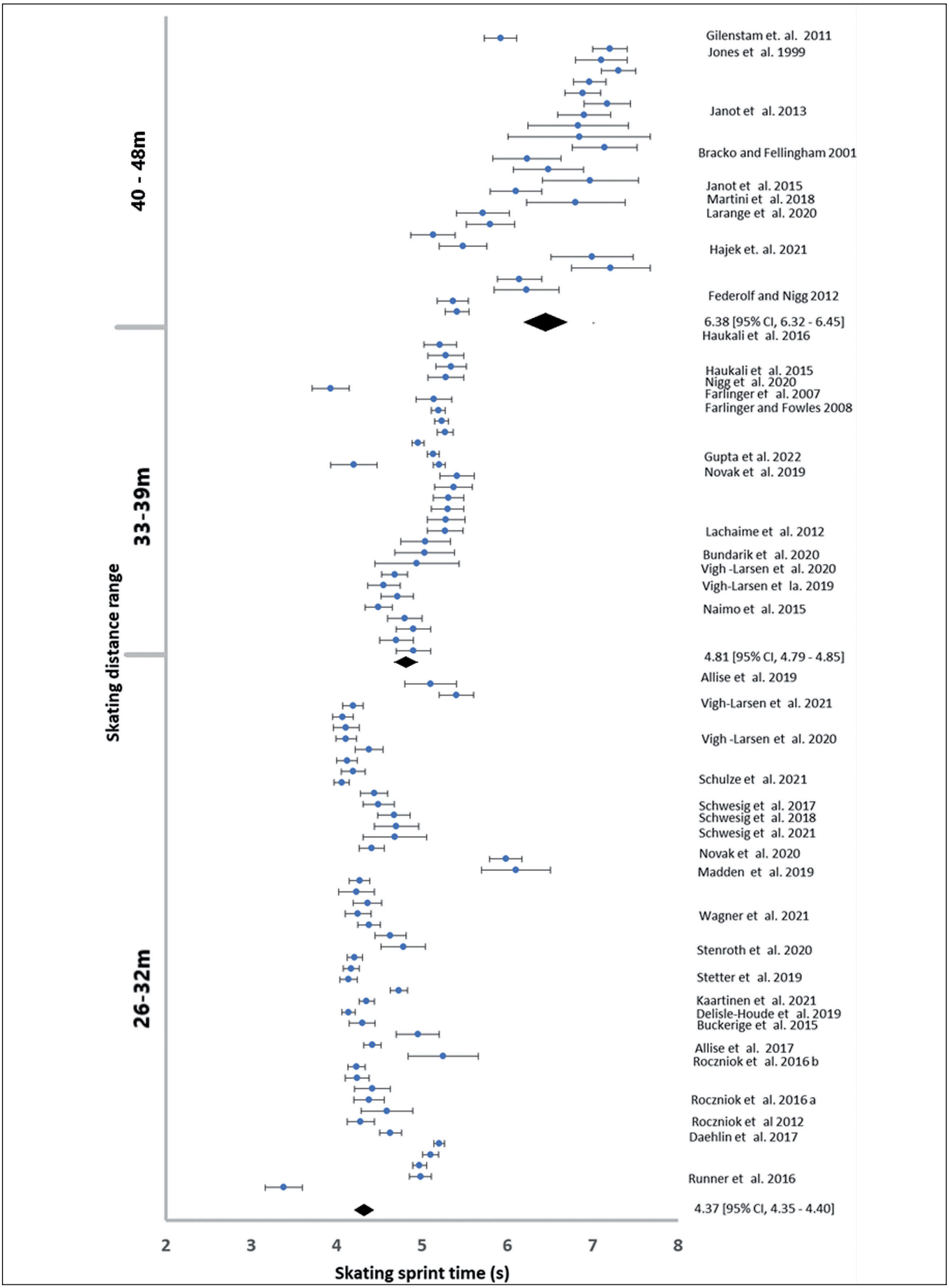


FIG. 3. The reported male sprint times during tests between 26 and 48 m distance.

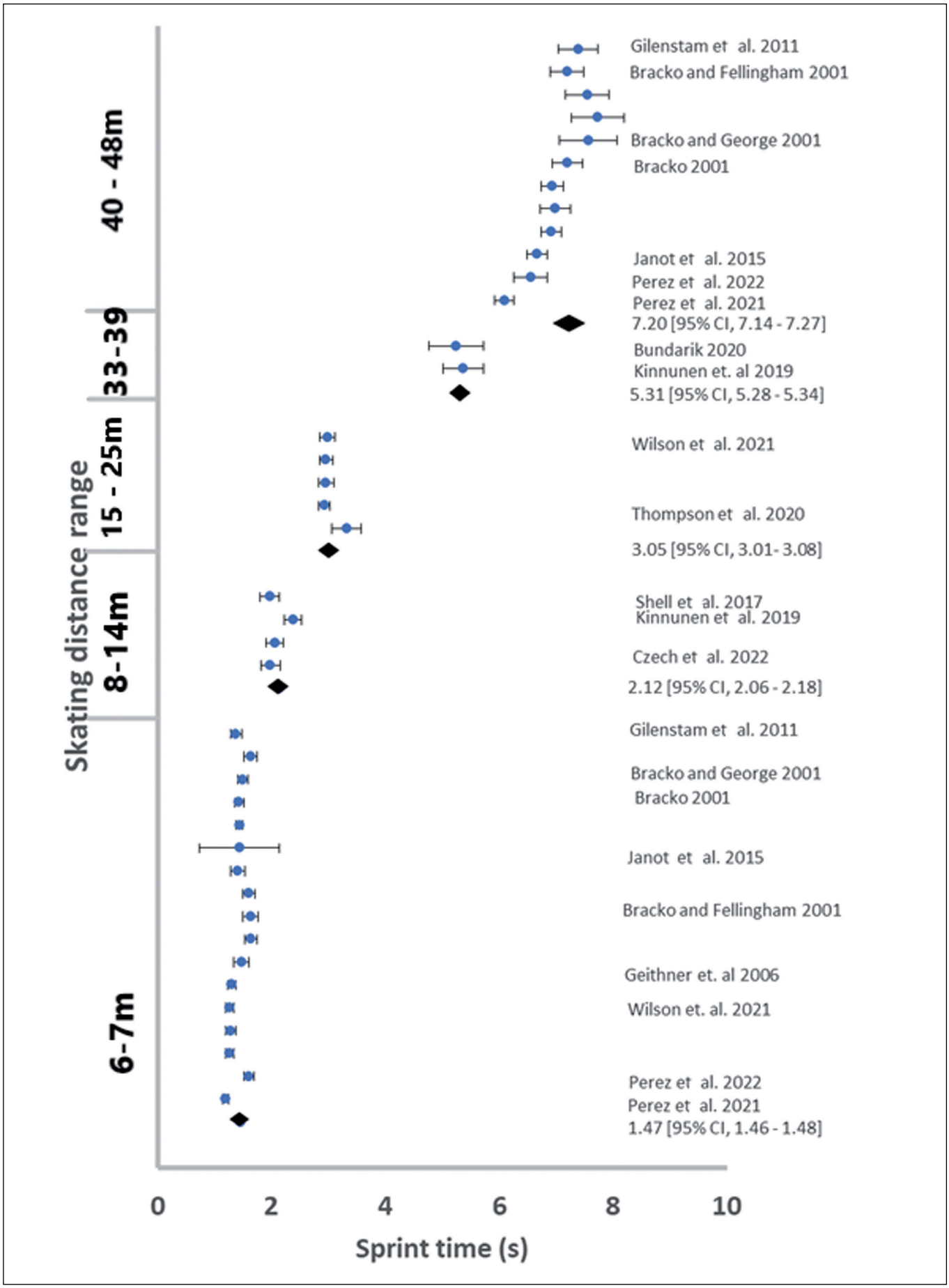


FIG. 4. The reported female sprint times during skating sprint tests.

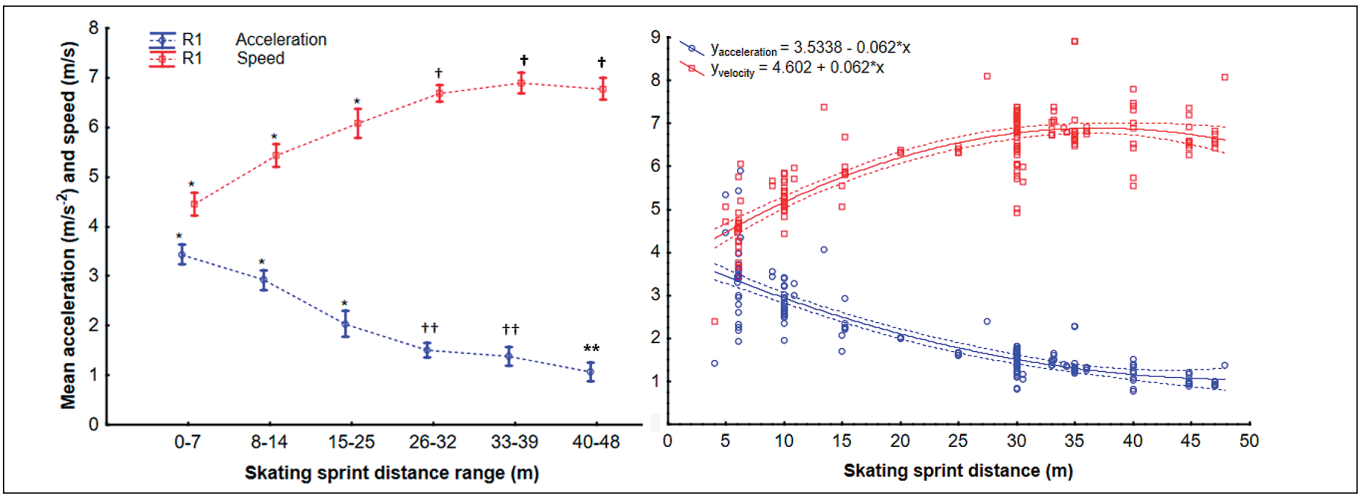


FIG. 5. Differences of forward skating acceleration and speed by testing distance (left graph) and their regression fit equation (right graph) with 95% confidence interval.

RESULTS

The database search resulted in 6821 titles after removing duplicates and 8 studies were added from the search of reference lists (Figure 1). Title and abstract screening identified 102 studies for full text screening. Of these, 41 studies were excluded due to data content and 1 study was excluded based on the quality criteria. Ultimately, 60 studies met all eligibility criteria and were included in the statistical analyses, of which 45 studies considered men only, 7 considered women only, and 8 studies included both genders (Table 1). The study of Nigg [32] included one female pooled into male group, therefore this study was presented as data on males. The average score of the JBI checklist for the articles included in this review was 81 ± 10%, ranging from 75% to 100% with 96% observed agreement between the two evaluators (PS, MV).

The full text screening resulted in excluded 41 studies which did not report the results of a straight sprint test. One study was excluded [80] due to reporting in unstandardized values. All other studies met the quality standards. The acceleration data from one study [15] were excluded as they repeated values from previously published data [11], however this study included additional information for a 34 m sprint which was included.

After data extraction there was a pooled sample of 2254 men and 398 women, where each participant is only counted once even if two or more tests (e.g., 6.1 and 30 m) were reported. The pooled data for men had a minimum of 201 participants and 14 studies in each distance range (Table 2; Figures 2 and 3). The pooled data for women was not large enough to permit statistical analysis (Table 2, Figure 4).

The assumption of data normality and equality of variance was violated for men in the distance range 40–48 m. The ANOVA analyses showed differences between mean acceleration Welch $F_{5, 164} = 66.08$, $p < 0.001$ and speed $F_{5, 164} = 71.9$, $p < 0.001$ at different sprint distance ranges. The skating acceleration increased between the 0–7 m, 9–14 m, 15–25 m and 26–32 m distance ranges, and did not differ between 26–32 m, 33–39 m (Figure 5). The 40–48 distance showed lower acceleration than all other distance ranges (Figure 2). The skating speed increased between the 0–7 m, 9–14 m, 15–25 m and 26–32 m distance ranges, and did not differ between 26–32 m, 33–39 m and 40–48 m (Figure 5, Left).

The correlation analyses showed an inverse relationship between straight sprint distance and mean acceleration ($\tau = -0.73$, $R^2 = -0.71$, $p < 0.001$) and a positive relationship between test distance and speed ($\tau = 0.52$, $R^2 = 0.49$, $p < 0.001$) (Figure 5, Right).

DISCUSSION

As hypothesize the forward sprint maximum acceleration was found in distances up to 7 m, on the other hand the presumption for maximum sprint speed was different since maximum velocity have been found between 26 and 39 m (Figure 5). The reported acceleration for the shortest distance range (0–7 m) was 3.31 m/s^2, which represents the four intensive skating strides [10] needed during 10% of the game time to compete for the puck or position [70, 81]. Moreover, this short acceleration is necessary for any longer sprint and before [82] or after change of direction maneuvers. Considering that seven of the eleven previous studies used an acceleration distance of 6.1 m (Table 1), this distance should be used for future acceleration evaluation to be easily comparable with to date findings. In the speed evaluation the distances between 25 m and 39 m resulted in a similar average speed (6.68–6.89 m/s), where 30 m was reported most frequently (in 23 studies, Table 1). The 25–39 m distance typically means the transition between the defensive and offensive zones, where the players' actions include puck carry, and the dump in and out the offensive

TABLE 2. Basic data of mean acceleration and speed pooled for analysis.

Distance range (m)	0–7	8–14	15–25	26–32	33–39	40–48
Men						
Number of mean values included	25	25	15	48	29	25
Number of subjects	325	663	201	928	445	246
Acceleration (m/s^{-2}) Mean ± SD)	3.43 ± 1.00*	2.92 ± 0.45*	2.03 ± 0.37*	1.51 ± 0.29††	1.38 ± 0.20††	1.07 ± 0.90**
Speed (m/s, Mean ± SD)	4.45 ± 0.75*	5.43 ± 0.53*	6.07 ± 0.42*	6.68 ± 0.63†	6.89 ± 0.44†	6.78 ± 0.57†
Women						
Number of mean values included	17	4	5	0	2	12
Number of subjects	317	42	39	0	24	160
Acceleration (m/s^{-2}) Mean ± SD)	2.80 ± 0.40	2.45 ± 0.59	1.64 ± 0.14	-	1.21 ± 0.03	0.92 ± 0.09
Speed (m/s, Mean ± SD)	3.98 ± 0.30	5.09 ± 1.01	4.96 ± 0.22	-	6.41 ± 0.08	6.43 ± 0.39

* significantly different to all other distance ranges, † higher than 0–7 m, 8–14 and 15–25 m distance range. †† lower than 0–7 m, 8–14 and 15–25 m distance and similar to other distances, ** lower that all other distance ranges.

and defensive zones [83]. Although there is no speed difference in the distance ranges, there is an expectation that the most frequently used 30 m distance is the foundation for defensive to offensive transition and provides the same speed information as longer sprints. Therefore, we recommend using 30 m distance as a standard for future research.

The regression function (Figure 5) showed that ice-hockey sprint speed increases along with skating distance (τ = 0.52) up to 39 m but then plateaus or possibly decreases over longer distances. Moreover, the reported values over 40 m showed more variability and the longer track might not differentiate whether players developed near maximum velocity quickly enough. This plateau in skating speed for longer than 39 m, might be also caused by the limit of the ice-hockey ring (61 m) when sprinting over 40 m the finish will be uncomfortably close to the rink barrier (since the sprint skating instructions should be to skate to maximum to 45 m target). At the same time as the average speed increases, the average acceleration decreases (Figure 5), which is specifically evident for short distances during each skating stride [15]. Therefore there is a need to also evaluate the skating technique at which the sprint performance was done as players have to be skilled in the propulsion, swing phase and glide typical for larger stride lengths and wide in highly trained players [24]. Therefore, a critical metric for skating technique is the stride count for the distance covered, which is included e.g. in skating efficiency index for sprints (between stride and time r = 0.342) [28], and might be evaluated automatically from a single accelerometer on skate [84]. Thus the ices-hockey sprint testing protocol for any distance should include the stride count along with reported time, acceleration, and velocity.

One of the crucial aspects of conditioning testing is the game requirements and performance relevance. Although sprint performance has been clearly associated with ice-hockey performance levels [5, 85, 86], the evidences in skating abilities during real games are scarce [23]. Moreover, the current method of tracking players' acceleration and velocity within a match is based on local positioning systems (LPS) or accelerometers, which do not allow direct transfer to testing by photocells out of match conditions. For example, we found the average speed of longer maximum effort sprints (26–48 m) to be 24.3 ± 2 m/s, but match analyses differentiate between skating intensities (fast speed and sprint) using a value of 24 km/h [21, 22]. This difference might be caused by the speed/velocity calculation as when the straight sprint is measured by photocells only the average speed in one direction can be calculated, whereas LPS and accelerometry systems measure the velocity in any direction including side to side direction of stride during forward skating, crossovers, and other changes of direction. However, the velocity ranges [21, 22] currently used in match analyses are taken from soccer recommended values, where the motion does not include any gliding. Therefore, the sprint velocity borderlines for LPS systems should be validated in a separate study. The other possibility is to distinguish the skating intensity by acceleration values, where our results would preliminarily suggest the ranges of ≥ 3, 2–3, 1–2 m/s^2 for very high, high, and moderate accelerations, respectively. However, this separation might still have limits in the assessment of acceleration at higher velocities, where additional acceleration at high velocity requires high intensity effort. A previous study [87] used 2 m/s^2 acceleration as the criterion for intensive skating, which might mean moderate effort while starting from stationary position or very high effort when already skating at a speed over 17 km/h. Therefore, the validation of skating intensity should be done in combination with velocity and the additional acceleration each stride.

The main limitation of this study is in the use of average acceleration and velocity which is influenced by the testing distance and the inconsistent ages and performance levels. A previous study that evaluated skating performance and age showing that sprint time did not differ between 18–30 year old players, however, was lower in players over 30 [88]. Since there were incomparable standards across selected studies, we were not able to rank participants performance levels, however the selected distance ranges a reference values should be able to distinguish performance differences as one the testing purpose. The photocell method is unable to distinguish vertical, side to side and forward acceleration and velocity, which do differ by performance level [10], and might be resolved by using accelerometers or 3D kinematics. Future research should avoid these limitations by using the same distance and reporting the skating efficiency by referring to the skating stride number, frequency, or skating efficiency coefficient. This study finds that ice-hockey testing is less reported in females, which should be amended in future research.

CONCLUSIONS

Forward skating sprint speed increases with the measured distance up to 26 m and do not differ much from longer distance tests, while acceleration decreases with a drop below 3 m/s at distance longer 15 m and longer. The highest acceleration (5.89 m/s^2 peak, 3.31 m/s^2 average) was achieved in the shortest distances up to 7 m which significantly differs from 8–14 m tests. Since 6.1 m is the most often reported acceleration distance, we recommend this as an apropriate testing reference. The forward skating speed reaches its peak between 25–39 m, where 30 m is the most often reported distance and is recommended as the most practical standard for game situations and the ability to develop near maximal speed quickly. Speed measures for longest distances 40–48 m are unnecessary because 30 or 35 m provide similar or possibly higher speed values than longer distances. Future research should validate accelerometer and LPS system values to the recommended 6.1 m acceleration and 30 m sprint distance testing in all ice-hockey levels.

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Conflicts of interest/Competing interests

The authors declare no conflict of interest directly relevant to the content of this article.

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Arbitrary absolute vs. individualized running speed thresholds in team sports: A scoping review with evidence gap map

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ABSTRACT: The aims of this scoping review were (i) to characterize the main methodological approaches to assessing individualized running speed thresholds in team sports players; (ii) to assess the use of traditional arbitrary (absolute) thresholds compared to individualized running speed thresholds in team sports players; (iii) to provide an evidence gap map (EGM) about the approaches and study designs employed in investigations in team sports and (iv) to provide directions for future research and practical applications for the strength and conditioning field. Methods studies were searched for in the following databases: (i) PubMed; (ii) Scopus; (iii) SPORTDiscus and (iv) Web of Science. The search was conducted on 15/07/2022. Risk of bias was assessed using the Risk of Bias Assessment Tool for Nonrandomized Studies (RoBANS). From 3,195 potentially relevant articles, 36 were eligible for inclusion in this review. Of the 36 included articles, 27 (75%) focused on the use of arbitrary and individualized running speed thresholds to describe the locomotor demands (e.g., high intensity running) of players. Thirty-four articles used individualized speed running thresholds based on physical fitness assessments (e.g., 40-m linear sprint) or physical performance (e.g., maximal acceleration). This scoping review supported the need for a greater focus to be placed on improving the methodological aspects of using individualized speed running thresholds in team sports. More than just creating alternatives to arbitrary thresholds, it is essential to increase the replicability of methodological conditions whilst ensuring that research comparing the most adequate measures and approaches to individualization takes into consideration the population and context of each study.

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INTRODUCTION

Monitoring the locomotor demands of team sport players during training sessions and matches is a common practice by coaches and has become a popular research topic over the last decade [1–3]. The evolution of microelectromechanical systems such as Global Positioning Systems (GPS), Local Position Systems, Ultrawide Band or inertial measurement units have facilitated accurate evaluations of the locomotor demands that are placed on team sport players [4–6]. This evolution has enabled coaches and researchers alike to characterize both the volume and intensity that players must sustain during training and competition [7, 8]. The importance of monitoring these demands has been recognized by coaches, sports scientists and players as observed in a survey, conducted in soccer, in which all stakeholders reported GPS-derived training data as being at least 'somewhat important' [9]. In another survey of strength and conditioning coaches working in professional soccer, it was reported that 94% of the respondents reported using GPS-based technologies for the above mentioned purposes in their sport [10].

A concern regarding the monitoring of locomotor demands in sport is the establishment of appropriate running speed thresholds that facilitate the proper quantification of intensity and volume [11]. Despite

variability in fitness levels, a recurrent practice in the monitoring of locomotor demands is the use of arbitrary (player-independent) running speed thresholds [12, 13]. The use of arbitrary thresholds is often necessitated by software-based constraints that typically require fixed running speeds for analytical purposes. However, such thresholds are also required due to the methodological challenges associated with the individualization of running speeds which may vary from player to player and from sport to sport. Whilst arbitrary absolute running speed thresholds may allow coaches to benchmark players' values (across different contexts) and simplify the data monitoring process, they may also impede the individualization of training prescription because running speed can be physical fitness and context-dependent [14]. Moreover, although using arbitrary running speed thresholds has become common practice, these thresholds are not consistent across measurement instruments and contexts thus making it very difficult to summarize evidence in this domain [15].

The use of individualized running speed thresholds has been proposed as a way of overcoming the weaknesses associated with arbitrary thresholds [16]. This process is based on the physical fitness level of the individual player, aiming to mitigate between-player variability through the identification of a unique running speed threshold [17]. However, the selection of appropriate methods of individualization based on physical fitness levels represents a primary challenge that has been observed in the literature [18]. Different approaches have been utilized with individualized thresholds being based on maximal aerobic speed (MAS) [11], maximal sprint speed (MSS) [19] and anaerobic speed reserve (ASR) [14]. Besides the diversity of approaches used to establish individualized thresholds, other challenges have also emerged with, for example, the calculation of MAS being dependent on the type of test used to determine an athlete's performance [20]. On this, different tests used for establishing MAS (e.g., laboratory, field-based) have failed to find consistent agreement across analyses using gold-standard methods [21, 22]. Moreover, the specificity of the test (e.g., distance-based or time-based) can affect the derived MAS value [20] and, still more, since ASR is MAS-dependent [20], the ASR method is similarly compromised. Using MSS can also be challenging due to minimal changes in performance occurring over the course of a season [23] and because sprinting threshold is affected by the biomechanical profile of the individual [13].

An alternative approach to the development of physical-fitness-based thresholds is the use of a data analytics approach to defining running speed zones [24]. As an example, a study conducted in female soccer players used a *k*-mean, Gaussian mixture model and spectral clustering to define four running speed zones based on information extracted from players over 52 international soccer matches. In another example, spectral clustering was used to determine velocity thresholds in Gaelic football referees [25].

The diversity of approaches for defining running speed thresholds in team sport players is apparent in the extant literature [12, 26, 27]. Identifying how these methodological approaches have been established and tracking the technologies as they develop may help researchers and practitioners to define the next steps in standardizing thresholds within and between sports. To date, no scoping review has been conducted on the body of literature relating to individualized running speed thresholds in team sport players. Such a review is necessary in terms of mapping the extant literature and facilitating an evaluation of the landscape of the methodological approaches. Accordingly, the purposes of this study are to: (i) characterize the main methodological approaches to assessing individualized running speed thresholds in team sports players; (ii) assess the use of traditional arbitrary (absolute) thresholds compared to individualized speed thresholds in team sports players; (iii) provide an evidence gap map (EGM) on the approaches and study designs adopted in team sports; and (iv) provide future directions for research and practical applications for the sports science field.

MATERIALS AND METHODS

This scoping review followed the PRISMA 2020 guidelines [28] and took into consideration the recommendations for scoping reviews checklist (PRISMA-ScR) [29].

Protocol and registration

The scoping review protocol was preliminarily submitted and published on the Open Science Framework, with the registration number 10.17605/OSF.IO/92HWU, on 15th July 2022. The protocol can be accessed via the web address https://osf.io/bt5nc/?view_only = 42c3045fb7ba42ef97fb58f359719f6c, as well as through the registration number 10.17605/OSF.IO/92HWU.

Eligibility criteria

Studies published in peer-reviewed journals, including those with the status of "in press" or "ahead-of-print", were considered. No date limitations were set, and studies undertaken in all languages were considered [30]. The eligibility criteria were established based on the PECOS (population, exposure, comparator, outcome, study design) approach: (i) population: team sports players, of any age, male or female, who were integrated into team training routines (i.e., not injured or with any reported pathology or health problems). Excluded were disabled athletes or those competing in adapted sports. (ii) exposure: exposed to analysis of individualized running speed thresholds in training sessions and/or matches; (iii) comparator: exposed to traditional arbitrary running speed thresholds in training sessions and/or matches; (iv) outcome(s): the time and/or distance and/or percentage of time and/or distance spent in different running speed thresholds (either in arbitrary/absolute or individualized thresholds); (v) study design: observational studies or interventions (both single-arm [if with two different metrics, for example, individualized vs. arbitrary] and multi-arm investigations were considered).

Information sources

The following databases were searched: PubMed, Scopus, SPORTDiscus and Web of Science (Core collection). After performing the

protocol registration (ID: 10.17605/OSF.IO/92HWU), the searches were conducted on the same day (15/07/2022). In addition to the database searches, manual searches were performed on the reference lists of included studies to identify potentially relevant titles. The abstracts of these articles were checked for relevant inclusion criteria and, if necessary, the full-text was referred to. Snowballing citation tracking, preferentially in Web of Science, was also conducted whilst two external experts (as recognized by Expertscape at the *Worldwide* level: https://expertscape.com/ex/soccer) were also consulted. Finally, errata and article retractions were analyzed for any articles that were included in the review [31].

Search strategy

In the search, the Boolean operators AND/OR were applied. No filters or limitations were used (e.g., date; language; study design) to maximize the chances of identification of appropriate studies [32]. The main search strategy was as follows:

[Title/Abstract] bandy OR baseball* OR basketball* OR cricket OR floorball* OR football* OR futsal OR handball* OR hockey OR hurling OR korfball* OR lacrosse OR netball* OR polo* OR rugby OR "sepak takraw" OR soccer OR softball* OR slamball* OR "Team Sport*" OR volleyball*
AND
[All fields/Full text] individual* OR personalized
AND
[All fields/Full text] speed OR velocity OR quickness OR intensity OR running OR sprint*
AND
[All fields/Full text] threshold* OR zone*

The full search strategy can be observed in the following Table 1.

Selection process

Two of the authors (HS and JA) independently screened the retrieved records (namely titles and abstracts). The same authors also independently screened the gathered full texts. Disagreements between the two authors were discussed in a joint reanalysis. In the case of no consensus being reached, a third author (FMC) made the final decision. Where and when required, all co-authors shared opinions

TABLE 1. Full search strategy for each database.

Database	Specificities of the databases	Search Strategy
PubMed	None to report	(((bandy[Title/Abstract] OR baseball*[Title/Abstract] OR basketball*[Title/Abstract] OR cricket[Title/Abstract] OR floorball*[Title/Abstract] OR football*[Title/Abstract] OR futsal[Title/Abstract] OR handball*[Title/Abstract] OR hockey[Title/Abstract] OR hurling[Title/Abstract] OR korfball*[Title/Abstract] OR lacrosse[Title/Abstract] OR netball*[Title/Abstract] OR polo*[Title/Abstract] OR rugby[Title/Abstract] OR "sepak takraw"[Title/Abstract] OR soccer[Title/Abstract] OR softball*[Title/Abstract] OR slamball*[Title/Abstract] OR "Team Sport*"[Title/Abstract] OR volleyball*[Title/Abstract]) AND (individual* OR personalized)) AND (speed OR velocity OR quickness OR intensity OR running OR sprint*)) AND (threshold* OR zone*)
Scopus	Search for title and abstract also includes keywords	(TITLE-ABS-KEY (bandy OR baseball* OR basketball* OR cricket OR floorball* OR football* OR futsal OR handball* OR hockey OR hurling OR korfball* OR lacrosse OR netball* OR polo* OR rugby OR "sepak takraw" OR soccer OR softball* OR slamball* OR "Team Sport*" OR volleyball*) AND ALL (individual* OR personalized) AND ALL (speed OR velocity OR quickness OR intensity OR running OR sprint*) AND ALL (threshold* OR zone*))
SPORTDiscus	None to report	AB (bandy OR baseball* OR basketball* OR cricket OR floorball* OR football* OR futsal OR handball* OR hockey OR hurling OR korfball* OR lacrosse OR netball* OR polo* OR rugby OR "sepak takraw" OR soccer OR softball* OR slamball* OR "Team Sport*" OR volleyball*) AND TX ("individual*" OR personalized) AND TX (speed OR velocity OR quickness OR intensity OR running OR sprint*) AND TX (threshold* OR zone*)
Web of Science	Search for title and abstract also includes keywords and its designated "topic"	

with regard to any doubts raised in the selection process, with a view to supporting the final decision. The EndNote™ 20.3 software (Clarivate™) was used for managing records, namely the removal of duplicates either automatically or manually.

Data extraction process

The data extraction process was firstly performed by the lead author (FMC) and was verified by two co-authors (RRC and HS) to confirm the accuracy and details of the data. A specially designed Microsoft® Excel datasheet was created and used to contain the data and the main information. The Excel datasheet can be observed in the supplementary material. In the case of relevant data being missing from a full text of a study, the primary author (FMC) directly contacted the corresponding author of that study by email and/or ResearchGate to obtain the required information.

Data items

The descriptive characteristics of participants that were collected were sport, age, sex, competitive level and training frequency. The characterization of competitive level followed the Participant Classification Framework [33]: Tier 0: sedentary (not included in our context); Tier 1: recreationally active (not included in our context); Tier 2: trained/developmental; Tier 3: highly trained/national level; Tier 4: elite/international level; Tier 5: world class.

Context-related information: this included, but was not restricted to, period of the season, context of the assessment (period of rest before analysis, time of the day), the number of sessions/matches considered.

Methodological-related included the method used for the individualization (e.g., MAS, ASR, MSS) and the arbitrary/absolute running speed thresholds that were collected. It also included information about the instruments of measurement such as GPS, local positioning systems, or ultrawide band, and the regularity of the tests performed (if more than once).

Main outcome: considering the goal of executing a scoping review with an EGM, the main outcomes were those associated with the methodological approaches of the studies and not the specific results presented in each article. Accordingly, running speed thresholds were the variable of interest.

Additional information: this included, but was not limited to, citation details, year, country of data collection, funding sources, and competing interests.

Study risk of bias assessment

The risk of bias was independently assessed by two authors (JA and HS). In the case of disagreements, both reanalyzed the process. In the case of no subsequent consensus being reached, a third author (FMC) made the final decision. The Risk of Bias Assessment Tool

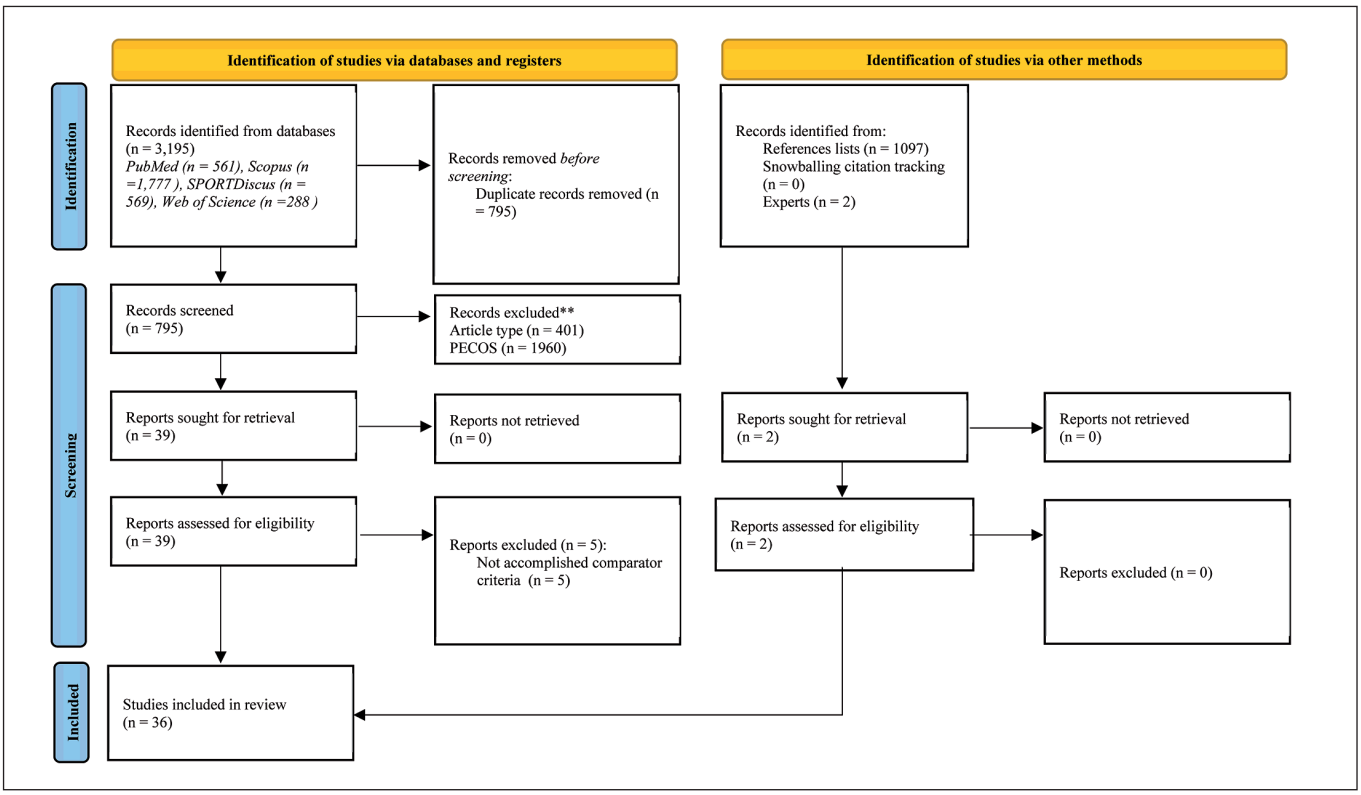


FIG. 1. PRISMA 2020 flow diagram.

for Nonrandomized Studies (RoBANS) was used to assess the risk of bias of the included studies [34]. This scale has shown moderate reliability and good feasibility and validity [34]. The tool comprises six domains: the selection of participants; confounding variables; the measurement of exposure; the blinding of the outcome assessments; incomplete outcome data; and selective outcome reporting. The domains are classified as 'low', 'high' and 'unclear' risk of bias [34] (Table 2).

Data management and synthesis methods

An EGM was built to graphically represent the type of studies and the evidence collected on the main topic of research. The EGM summarized the findings and provided a brief overview of the evidence and research gap [35–37]. A narrative review also accompanied the results, while specific information about the number and/or percentage of studies and the topics of interest was outlined. Table 1 presents an example how information was collected regarding the scoping review context and outcomes.

RESULTS

Study identification and selection

The initial search yielded a total of 3,195 titles (Figure 1). The data were imported to the EndNote™ reference manager software (version 20.2, Clarivate Analytics, Philadelphia, PA, USA). Duplicates (795 titles) were subsequently removed, either automatically or manually. The remaining 2,400 titles were screened for their relevance based on their titles and abstracts. Of those, 2,361 titles were removed. The full texts of the remaining 39 titles were then inspected and from there, five more were removed based on the reasons presented in Supplementary material #1. After the automatic search, 34 articles remained for data extraction and further analysis. Following revision of the list of 34 articles by the experts, two further eligible titles were suggested, reviewed, and integrated. In total, 36 articles were included in the final scoping review.

Methodological quality

With regard to risk of bias, confounding variables were unclear in

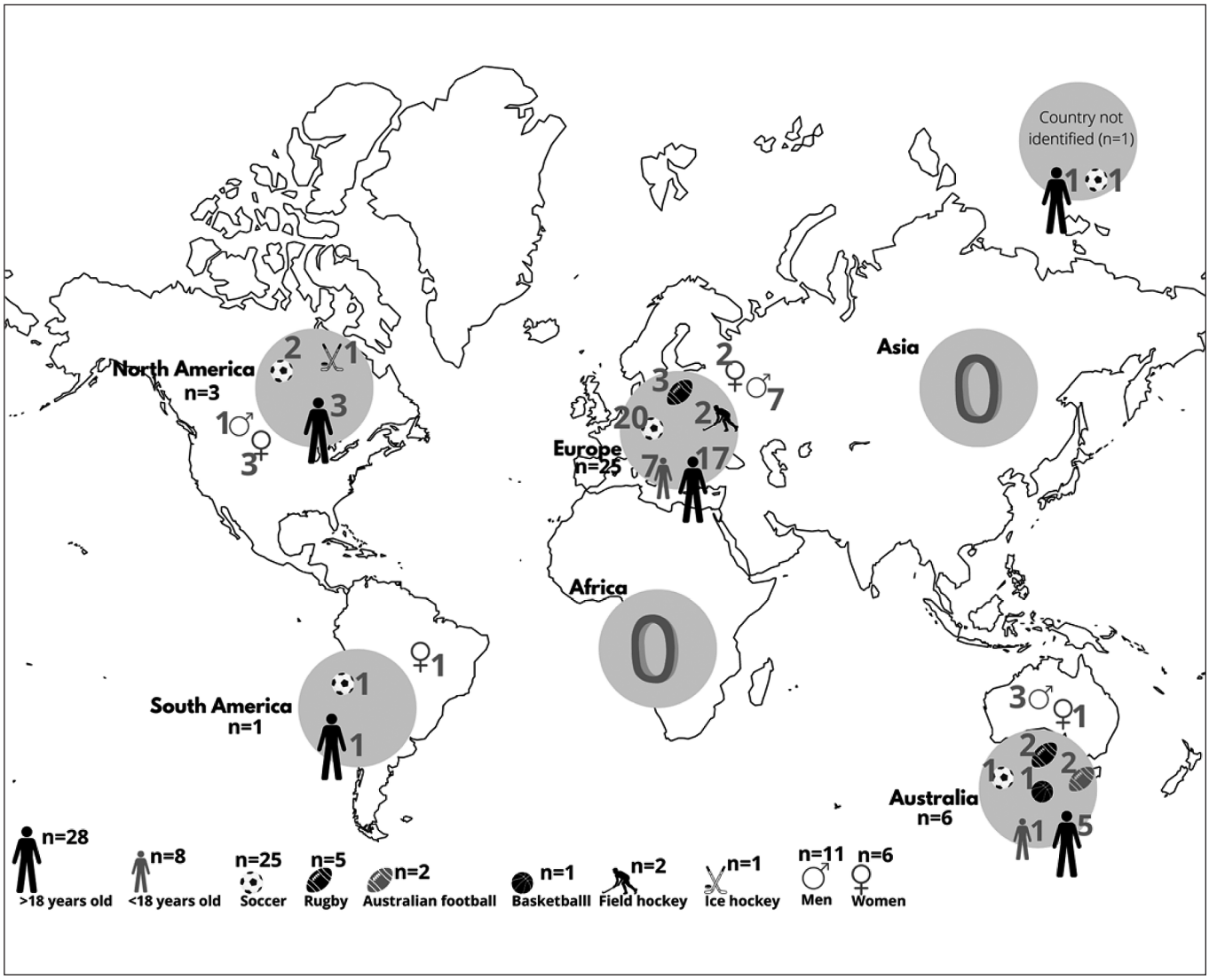


FIG. 2. Distribution of the included studies per continent, age-group and team sport.

TABLE 2. Risk of bias assessment of non-randomized studies.

Study	Selection of participants	Confounding variables	Measurement of exposure	Blinding of outcome assessments	Incomplete outcome data	Selective outcome reporting
Abbott et al. [51]	Low	Unclear	Unclear	Low	Low	Low
Abt et al. [26]	Low	Unclear	Unclear	Low	Low	Low
Beato et al. [57]	Low	Unclear	Unclear	Low	Low	Low
Carling et al. [75]	Low	Unclear	High	Low	Low	Low
Casamichana et al. [76]	Low	Unclear	Low	Low	Low	Low
Castellano et al. [77]	Low	Unclear	Unclear	Low	Low	Low
Castellano et al. [78]	Low	Unclear	Unclear	Low	Low	Low
Clarke et al. [38]	Low	Unclear	Unclear	Low	Low	Low
Darbellay et al. [43]	Low	Unclear	High	Low	Low	Low
Fitzpatrick et al. [11]	Low	Unclear	Low	Low	Low	Low
Gabbett et al. [45]	Low	Unclear	High	Low	Low	Low
Gamble et al. [79]	Low	Unclear	Low	Low	Low	Low
Goto et al. [80]	Low	Unclear	High	Low	Low	Low
Hunter et al. [19]	Low	Unclear	Unclear	Low	Low	Low
Jastrzebski et al. [39]	Low	Unclear	Low	Low	Low	Low
Jastrzebski et al. [40]	Low	Unclear	Low	Low	Low	Low
Lovell et al. [41]	Low	Unclear	Unclear	Low	Low	Low
Martínez-Cabrera et al. [49]	Low	Unclear	Unclear	Low	Low	Low
Martínez-Cabrera et al. [50]	Low	Unclear	Unclear	Low	Low	Low
Massard et al. [81]	Low	Unclear	High	Low	Low	Low
Murray et al. [44]	Low	Unclear	High	Low	Low	Low
Nakamura et al. [52]	Low	Unclear	Low	Low	Low	Low
Núñez-Sánchez et al. [82]	Low	Unclear	Unclear	Low	Low	Low
O'Connor et al. [56]	Low	Unclear	High	Low	Low	Low
Ortega-Gálvez et al. [42]	Low	Unclear	High	Low	Low	Low
Park et al. [24]	Low	Low	Low	Low	Low	Unclear
Rago et al. [46]	Low	Unclear	High	Low	Low	Low
Rago et al. [14]	Low	Unclear	High	Low	Low	Low
Reardon et al. [16]	Low	Unclear	High	Low	Low	Low
Scanlan et al. [83]	Low	Unclear	High	Low	Low	Low
Scott et al. [17]	Low	Unclear	Unclear	Low	Low	Low
Scott et al. [47]	Low	Unclear	Unclear	Low	Low	Low
Siegle et al. [54]	Low	Low	Low	Low	Low	Low
Taylor et al. [48]	Low	Unclear	Unclear	Low	Low	Low
Taylor et al. [84]	Low	Unclear	Unclear	Low	Low	Low
Taylor et al. [85]	Low	Unclear	Low	Low	Low	Low

TABLE 3. Characterization and contextual information of the included studies.

Study	Sport	Comp. Level	N	Age (years)	Sex	Country	Training frequency (per week)	Training sessions analyzed	Matches analyzed	Period of observation	Regularity of the physical assessment	Instrument used
Abbott et al. [51]	Soccer	Tier 3	31	19.4 ± 1.7	M	UK	4–5	23	4	4 weeks	1 (pre-season)	OptimEye (10 Hz, GPS)
Abt et al. [26]	Soccer	Tier 3	10	27 ± 5	IU	UK	IU	0	3	IU	1 (3rd week of the season)	ProZone (multicamera tracking system)
Beato et al. [57]	Soccer	Tier 4	20	28.4 ± 4.3	M	Italy	IU	IU	6	42 days	1	Apex STATSports (10 Hz, GPS)
Carling et al. [75]	Soccer	Tier 4	12	25 ± 3	IU	France	IU	0	31	One season	1 (beginning of the season)	AMISCO Pro (multicamera tracking system)
Casamichana et al. [76]	Field H.	Tier 4	16	25.5 ± 2.9	M	Spain	4	0	17	Two seasons	Every match	GPSport (10 Hz, GPS)
Castellano et al. [77]	Soccer	Tier 2	24	13.3 ± 0.5	IU	Spain	4	9	0	5 weeks	1 (before observation period)	MinimaxX (10 Hz, GPS)
Castellano et al. [78]	Soccer	Tier 2	44	12.1 ± 0.4 and 13.3 ± 0.5	IU	Spain	3–4	9	0	5 weeks	1 (before observation period)	MinimaxX (10 Hz, GPS)
Clarke et al. [38]	Rugby	Tier 4	12	23.5 ± 4.9	W	Australia	IU	0	6	First round of the season	1	GPSport (5 Hz, interpolated to 15 Hz GPS)
Darbellay et al. [43]	Soccer	Tier 4	88	26.5 ± 5.8	M	UK	IU	IU	IU	First round of the season	1	FieldWiz (10 Hz, GPS)
Fitzpatrick et al. [11]	Soccer	Tier 3	14	17 ± 1	IU	Switzer-land	4–5	2	13	6 weeks	2 (start and end of the observation period)	MinimaxX S4 (10 Hz, GPS)
Gabbett et al. [45]	Rugby	Tier 2	90	13.7 ± 0.9	M	Australia	IU	0	18	IU	1	MinimaxX (10 Hz, GPS)
Gamble et al. [79]	Ice H.	Tier 2	46	20.0 ± 1.4 and 21.9 ± 1.1	M; W	Canada	IU	IU	24	One season	Every match	Kinexon (20 Hz, LPS)
Goto et al. [80]	Soccer	Tier 2	81	10.2 to 16.2	IU	UK	3	0	IU	IU	1 (start of he season)	GPSport (1 Hz, GPS)
Hunter et al. [19]	Soccer	Tier 3	12	Under-18	IU	UK	5–6	0	22	Two seasons	4 (6 in 6 weeks)	MinimaxX (5 Hz, GPS)
Jastrzebski et al. [39]	Soccer	Tier 4	16	27.5 ± 4.1 and 19.1 ± 3.1	M; W	Poland	5–7	1	0	2 weeks	1	MinimaxX 4.0 (10 Hz, GPS)
Jastrzebski et al. [40]	Soccer	Tier 3	13	27.1 ± 5.2	IU	Poland	5–7	2	0	2 weeks	1	MinimaxX 4.0 (10 Hz, GPS)
Lovell et al. [41]	Soccer	Tier 3	8	24 ± 5	IU	UK	IU	IU	IU	Two seasons	IU | 6 in 6 weeks	ProZone (multicamera tracking system)
Martínez-Cabrera et al. [49]	Soccer	Tier 3	26	17.3 ± 1.1	IU	Spain	4–5	0	18	IU	1	GPSport Pro X (15 Hz, GPS)
Martínez-Cabrera et al. [50]	Soccer	Tier 3	26	17.3 ± 1.1	IU	Spain	4–5	0	18	IU	1	GPSport Pro X (15 Hz, GPS)
Massard et al. [81]	Soccer	Tier 2	47	22.9 ± 4.1	IU	Australia	3	67	23	One season	2 (end of preseason and mid of the season)	MinimaxX S4 (10 Hz, GPS)
Murray et al. [44]	Aust. Foot.	Tier 4	45	22 ± 3	IU	Australia	IU	IU	IU	39 weeks	1 (beginning of the season)	Optimeye S5 (10 Hz, GPS)
Nakamura et al. [52]	Soccer	Tier 3	11	21.0 ± 3.0	W	Brazil	IU	0	10	IU	1 (beginning of the season)	GPSport SPI Elite (5 Hz, GPS)

TABLE 3. Characterization.

Study	Sport	Comp. Level	N	Age (years)	Sex	Country	Training frequency (per week)	Training sessions analyzed	Matches analyzed	Period of observation	Regularity of the physical assessment	Instrument used
Núñez-Sánchez et al. [82]	Soccer	Tier 2	20	26.6 ± 4.1	IU	Spain	14 hours/ week	0	4	Pre-season	1	GPSport SPI Pro (15 Hz, GPS)
O'Connor et al. [56]	Aust. Foot.	Tier 3	53	24.4 ± 3.7	M	Australia	IU	114	0	Two preseasons and one and half in-season	IU	Optimeye S5 (10 Hz, GPS)
Ortega-Gálvez et al. [42]	Field H.	Tier 3	15	23.7 ± 4.1	W	Spain	IU	0	4	Two months	1	GPSport SPI HPU (15 Hz, GPS)
Park et al. [24]	Soccer	Tier 5	27	24.6 ± 3.8	W	USA	IU	0	52	Three years	IU	MinimaxX S4 (10 Hz, GPS)
Rago et al. [46]	Soccer	Tier 3	13	25.8 ± 3.5	M	Italy	IU	42	3	8 weeks	1	BT-Q1000 Ex, QStarz (10 Hz, GPS)
Rago et al. [14]	Soccer	Tier 3	13	25.8 ± 3.5	M	Italy	IU	45	0	8 weeks	1	BT-Q1000 Ex, QStarz (10 Hz, GPS)
Reardon et al. [16]	Rugby	Tier 3	36	27.2 ± 3.9	IU	Ireland	IU	0	20	9 months	1	V5 and S5 Catapult (10 Hz, GPS)
Scanlan et al. [83]	Basketball	Tier 2	13	20.4 ± 4.6	M	Australia	2–4	10–25	0	6 weeks (pre-season)	1	Optimeye S5 (10 Hz, GPS)
Scott et al. [17]	Soccer	Tier 4	22	28.3 ± 21.9–39.5	W	IU	IU	21	0	21 days	1	Optimeye S5 (10 Hz, GPS)
Scott et al. [47]	Soccer	Tier 3	36	23.2 to 25.3	W	USA	IU	0	11.6	Two pre-seasons	2	Optimeye S5 (10 Hz, GPS)
Siegle et al. [54]	Soccer	Tier 5	IU	Adults	M	Italy France	IU	0	1	1 day	1	ASpoGAMo system (25 Hz, multicamera tracking system)
Taylor et al. [48]	Soccer	Tier 2	31	15.3 to 18.9	IU	UK	3–12	5 weeks	IU	5 weeks	1	Statsports APEX (10 Hz, GPS)
Taylor et al. [84]	Rugby	Tier 3	10	18.4 ± 1.0	IU	UK	4–6	7.8	6	6 weeks	1	Catapult S5 (10 Hz, GPS)
Taylor et al. [85]	Rugby	Tier 3	12	17 to 18	IU	UK	IU	3	0	3 weeks	3	Catapult S5 (10 Hz, GPS)

Aust. Foot.: Australian Football; Comp.: competitive; GPS: Global Positioning System; H: hockey; IU: information unavailable; M: men; N: number of participants; UK: United Kingdom; USA: United States of America; W: women;

34 out of 36 (94.4%) of the articles as physical fitness assessments and performance measures were not controlled in relation to recovery status, hours of sleep, diet, nutritional supplementation on the day of assessment or monitoring of well-being. The risk of bias in the measurement of exposure was high in 12 of 36 (33.3%) of the included articles as physical fitness assessments were not conducted in close time proximity (> 4 weeks) to the point of data collection. This may compromise the individualization of running speed thresholds because adaptations can occur in the elapsed time between the test and the collection of data. Moreover, the risk of bias in the measurement of exposure was unclear in 15 of 36 (41.7%) of the included studies because the assessment was not conducted on a regular basis (< 1 week), or the identification of the process was not made clear by the authors. All of the included studies presented a low risk of bias in the selection of participants, and in the blinding of outcome assessments as the blinding process was not considered to exert an influence on the final outcomes in these studies (i.e., experimental studies). In addition, incomplete data was of low risk of bias in the included studies.

Study characteristics and context-related information

The characteristics and context-related information of the included studies can be observed in Table 3. Seventeen out of 36 studies (47.2%) used only match-related data, while 10 from 36 studies (27.8%) used only training session data. Five out of 36 studies (13.9%) used both training and match-related data. Thirty-one of 36 (86.1%) used GPS systems to collect data and 4 from 36 studies (11.1%) used multicamera tracking systems. Just one study (2.8%) used local positioning systems.

Figure 2 presents the distribution of the included studies per continent, age-group and team sport. Of the 36 included articles, 69.4% were conducted in soccer, 13.9% in rugby, 5.6% in Australian football, 5.6% in field hockey, 2.8% in basketball and 2.8% in ice hockey. Twenty-five studies (69.4%) were conducted in European populations while six studies (16.7%) were conducted in Australians. Three studies were conducted in North America (8.3%), and one in South America (2.8%), while one study did not report location information (2.8%). Twenty-eight (77.8%) of the studies were conducted in populations with average ages greater than 18 years old,

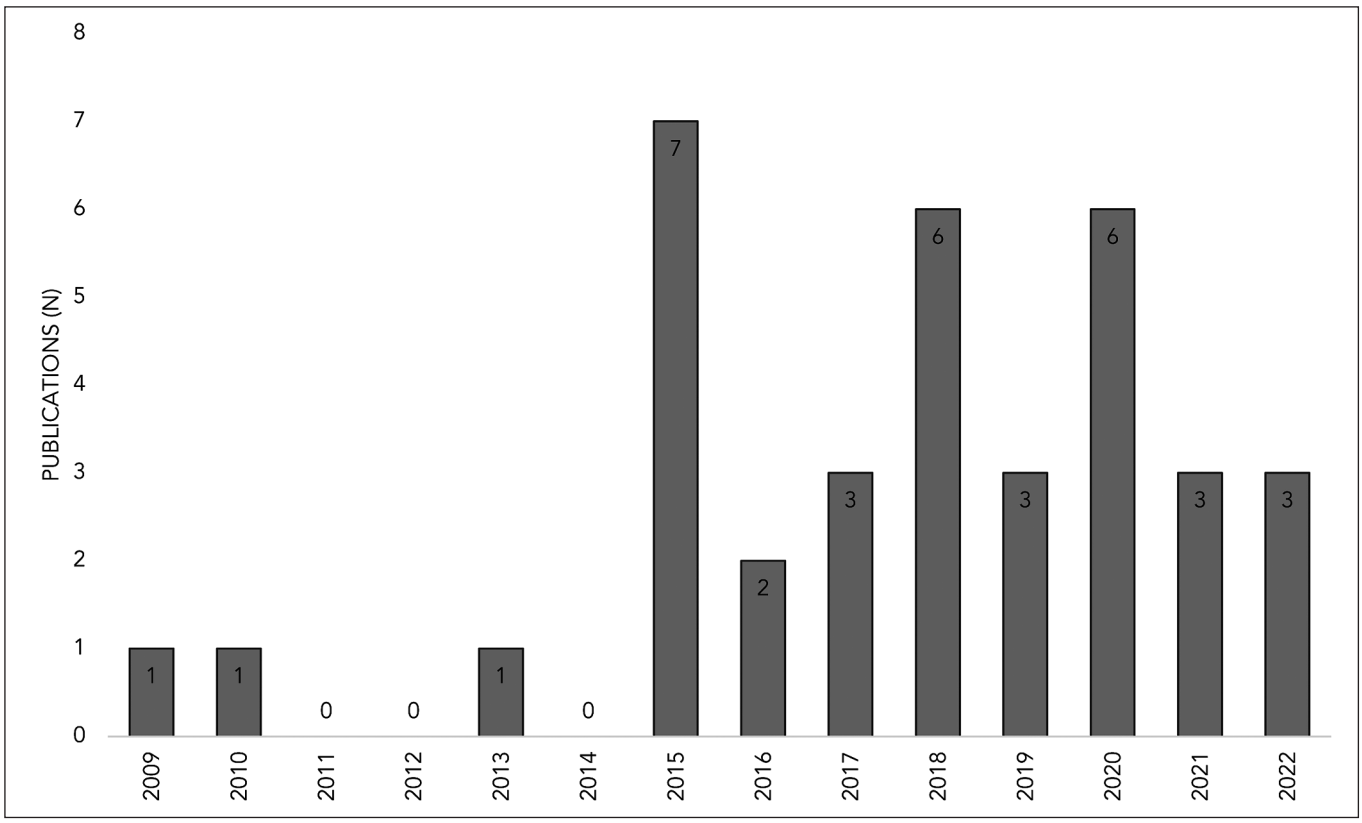


FIG. 3. Articles published per year related to individualized running speed thresholds.

while eight studies (22.2%) were undertaken in participants below 18 years old. In relation to competitive level, 17 studies (47.2%) were conducted in populations from tier 3, nine studies from tier 2 (25.0%), eight studies from tier 4 (22.2%), and two studies from tier 5 (5.6%). Ten studies (27.8%) were exclusively conducted in men, six studies (16.7%) were exclusively conducted in women and two studies (5.6%) were conducted in both sexes. Eighteen studies (50%) did not report the sex of the participants.

Figure 3 presents the included articles published per year relating to individualized running speed thresholds. Of the 36 studies included, 58.3% (n = 21) were published in the last five years (2018–2022), while the year with the most publications was 2015 (n = 7; 19.4%).

Methodological characteristics of the included studies

Table 4 summarizes the main methodological characteristics of the included studies. Of the 36 included articles, 34 (94.4%) used individualized running speed thresholds based on physical fitness assessments or physical performance while two (5.6%) used alternative approaches (Q-Q-plots for visual inspection of intersection points and machine learning algorithms). Of the included studies, 15 (41.7%) used maximal sprint speed as a measure to individualize the running speed thresholds, while 11 studies (30.6%) used a combination of MAS, MSS, and ASR. Five studies (13.9%) used respiratory compensation threshold or second ventilatory threshold and two (5.6%) used MAS for individualization of running speed thresholds.

The term "high intensity running" was defined differently across the studies. Namely, it was classified as the second ventilatory threshold [26] [38], the between lactate threshold-80%MSS [39] [40], the between RCT and MAS [41], > 87% MAS [42], 100% MAS, 30% ASR and 20 to 35 W/kg metabolic power zone [43]. The term "high speed running" was defined as meters covered above MAS [11] [44] , (50–70% MSS) [45], RCT-95% of maximal oxygen uptake, 80–99% MAS, 50–59% MSS 80–99% MAS [19], 100%MAS-29%ASR [46] [14], 5 m/s^2 divided by the average of MSS of the group [16], 80%MAS at VAM-EVAL, 80% at Yo-Yo Intermittent Recovery Test level 1, 50% MSS [17], 60% MAS, 50% MSS [47] or 87% MAS [48]. The term "high intensity accelerations" were consistently classified as > 75% maximal acceleration [49] [50] [51]. The term "sprint" was classified as > 90% MSS [52] or 80% MSS [42] [48].

Figure 4 represents the list of tests used for assessing the measures that were used for establishing the standardized running speed thresholds. The 40-m linear sprint was the test most commonly used to assess MSS (n = 11), followed by the peak speed attained by players in training sessions/matches (n = 8). Moreover, the 40-m

TABLE 4. Methodological characteristics of the included studies.

Study	Objective of research	Tests used for indivi-dualization	Method of individualization	Arbitrary thresholds used	Individualized thresholds used
Abbott et al. [51]	Analyze the differences between arbitrary and individualized acceleration thresholds in training sessions and matches	40-m linear sprint	Maximum rate of acceleration during 40-m linear sprint	Low-intensity acceleration (1–2 m/s^2); Moderate-intensity acceleration (2–3 m/s^2); High-intensity acceleration (> 3 m/s^2).	Low-intensity acceleration (25–50% of maximal acceleration); Moderate-intensity acceleration (50–75% of maximal acceleration); High-intensity acceleration (> 75 of maximal acceleration).
Abt et al. [26]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in matches	Incremental treadmill test	The 2nd ventilatory threshold was used to determine the point of high intensity speed threshold.	High intensity running (distances covered at > 19.8 km/h)	High intensity running (2nd ventilatory threshold)
Beato et al. [57]	Analyze the workload of professional soccer players using arbitrary and individualized outcomes	Peak speed registered in training sessions/ matches	Peak speed attained in training sessions/matches	Distance covered above 20 km/h Distance covered above 25 km/h	High-speed distance (80% MSS)
Carling et al. [75]	Analyze the variability of locomotor demands between matches	Incremental treadmill test	MAS was determined and used to classify match activities	Total high-speed running distance (average running speed ≥ 19.8 km/h); High speed running distance (average running speed from 19.8 to 25.2 km/h); Total sprint distance (average running speed > 25.2 km/h).	Between 80–100% MAS; > 100% MAS; ≥ 80% MAS.
Casamichana et al. [76]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in matches	Peak speed in match	Peak speed attained during the season (in match)	Moderate speed running (15.1–18.9 km/h); High speed running (> 19 km/h); Very high speed running (> 24 km/h); Sprint running (> 30 km/h).	Distances covered at ~30%, 50%, 60%, 75% and 95% of the average peak speed of the players.
Castellano et al. [77]	Analyze the influence of different small-sided games on locomotor and physiological outcomes in small-sided games	30-m linear sprint	Individualized to MSS	Distance at 0–3 km/h; Distance at 3–8 km/h; Distance at 8–13 km/h; Distance at 13–16 km/h; Distance at > 16 km/h.	Distance at > 40% MSS; Distance at 40–60% MSS; Distance at > 60% MSS.
Castellano et al. [78]	Analyze the influence of different small-sided games on locomotor and physiological outcomes in small-sided games	30-m linear sprint	Individualized to MSS	Distance at 0–3 km/h; Distance at 3–8 km/h; Distance at 8–13 km/h; Distance at 13–16 km/h; Distance at > 16 km/h.	Distance at > 40% MSS; Distance at 40–60% MSS; Distance at > 60% MSS.
Clarke et al. [38]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in matches	Incremental treadmill test	The 2nd ventilatory threshold was estimated and used for the individualization of high intensity running.	High intensity running (5 m/s); High intensity running (group mean 2nd ventilatory threshold); Low-speed running (< 2 m/s); Sprint (acceleration at > 2.5 m/s^2 for a minimum of 1 second).	High intensity running (individualized to the 2nd ventilatory threshold)
Darbellay et al. [43]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in small-sided games and matches	Yo-Yo Intermittent Recovery Test level 1 and 40-m linear sprint	The MAS was obtained from the latest stage achieved in the progressive running test, while the ASR was estimated based on the difference between MSS and the MAS. Additionally, the metabolic power (resulted from speed and acceleration data) was also used as individualized method.	Low intensity (0 to 8 km/h); Moderate intensity (8 to 13 km/h); Intermediate speed (13 to 16 km/h); High intensity (16 to 19 km/h); Very high intensity (> 19 km/h).	Low intensity (0 to 60% MAS or 0 to 10 W/kg metabolic power zone); Moderate intensity (60 to 80% MAS or 10 to 15 W/kg metabolic power zone); Intermediate speed (80 to 100% MAS or 15 to 20 W/kg metabolic power zone); High intensity (100% MAS to 30% ASR or 20 to 35 W/kg metabolic power zone); Very high intensity (> 30% ASR or > 35 W/kg metabolic power zone).

TABLE 4. Continue

Study	Objective of research	Tests used for indivi-dualization	Method of individualization	Arbitrary thresholds used	Individualized thresholds used
Fitzpatrick et al. [11]	Compare dose-response relationship between arbitrary and individualized speed threshold with changes in aerobic fitness	1500-metre time trial and 40-m linear sprint	The MAS was obtained from the 1500-metre time trial, while the ASR was estimated based on the difference between MSS and the MAS.	High speed distance (above 17 km/h) – match to group average of MAS; High speed distance (above 21 km/h) – match to group average of 30% ASR.	Meters covered above MAS; Meters covered above 30% ASR.
Gabbett et al. [45]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in matches	40-m linear sprint	The MSS in the interval of 20–40-linear sprint test was obtained to estimate the peak velocity.	Low speed (0–3.5 m/s); Moderate speed (3.6–5.0 m/s); High speed (> 5.0 m/s).	Low speed (0–25% MSS); Moderate speed (25–50% MSS) High speed (50–70% MSS); Very high speed (> 70% of the peak velocity).
Gamble et al. [79]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in matches	Peak speed in match	Peak speed attained during the season (in match)	1.0–10.9 km/h; 11.0–13.9 km/h; 14.0–16.9 km/h; 17.0–20.9 km/h; 21.0–24.0 km/h; > 24 km/h	< 20% of the peak speed; 20–39% of the peak speed; 40–59% of the peak speed; 60–79% of the peak speed; 80–90% of the peak speed; > 90% of the peak speed.
Goto et al. [80]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in matches	10-m linear sprint	The flying 5-m linear sprint time was used to estimate the MSS and to split into five equal individualized speed zones	Speed zone 1 (0.0–0.5 m/s); Speed zone 2 (1.6–3.0 m/s); Speed zone 3 (3.1–4.5 m/s); Speed zone 4 (4.6–6.0 m/s); Speed zone 5 (> 6.0 m/s).	Speed zone 1 (slowest: 0.0–1.1 m/s; fastest 0.0–1.5 m/s); Speed zone 2 (slowest: 1.2–2.2 m/s; fastest 1.6–3.0 m/s); Speed zone 3 (slowest: 2.3–3.3 m/s; fastest 3.1–4.5 m/s); Speed zone 3 (slowest: 3.4–4.4 m/s; fastest 4.6–6.0 m/s); Speed zone 3 (slowest: > 4.4 m/s; fastest > 6.0 m/s).
Hunter et al. [19]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in matches	Incremental treadmill test and 40-m linear sprint	MAS and the RCT were obtained from the incremental treadmill test and were used as measures for individualization. The MSS was obtained in the fastest 10-m split. The ASR resulted from the subtraction of MSS by the MAS.	Low speed running (< 14.99 km/h); High-speed running (15.0–17.99 km/h); Very-high speed running (18.0–24.99 km/h); Sprinting (25.0–35.0 km/h).	Low speed running (< RCT; or < 79%MAS; or < 49%MSS; or < 79% MAS); High-speed running (RCT-95% of maximal oxygen uptake; or 80–99% MAS; or 50–59% MSS; or 80–99% MAS); Very-high speed running (95% of maximal oxygen uptake-29% ASR; or 100–139% MAS; or 60–79% MSS; or 100% MAS-29% ASR); Sprinting (30% ASR-MSS; or 140% MAS-35 km/h; or 80–100% MSS; or 30% ASR-MSS)
Jastrzebski et al. [39]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in small-sided games	Incremental treadmill test and 40-m linear sprint	The lactate threshold was estimated during the incremental treadmill test, while applying the Dmax method. The MSS was determined in the 40-m linear sprint.	Standing, walking (0–2 m/s); Jogging (2–4 m/s); Running (4–5.5 m/s); High-speed running (5.5–7 m/s); Sprinting (> 7 m/s).	Walking (0–1 m/s); Walking, jogging (1–2 m/s); Low intensity running (2 m/s-lactate threshold); High-intensity running (lactate threshold-80%MSS); Sprinting (> 80% MSS).
Jastrzebski et al. [40]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in small-sided games	Incremental treadmill test and 40-m linear sprint	The lactate threshold was estimated during the incremental treadmill test, while applying the Dmax method. The MSS was determined in the 40-m linear sprint.	Standing, walking (0–2 m/s); Jogging (2–4 m/s); Running (4–5.5 m/s); High-speed running (5.5–7 m/s); Sprinting (> 7 m/s).	Walking (0–1 m/s); Walking, jogging (1–2 m/s); Low intensity running (2 m/s-lactate threshold); High-intensity running (lactate threshold-80%MSS); Sprinting (> 80% MSS).

TABLE 4. Continue

Study	Objective of research	Tests used for indivi-dualization	Method of individualization	Arbitrary thresholds used	Individualized thresholds used
Lovell et al. [41]	Compare arbitrary and individualized speed thresholds on locomotor outcomes in match	Incremental treadmill test	The 1st ventilatory threshold, the RCT and MAS were estimated during the incremental treadmill test.	High-speed running (≥ 14.4 km/h); Very-high speed running (≥ 19.8 km/h).	Low (< 1st ventilatory threshold); Moderate (1st ventilatory threshold-RCT); High (RCT-MAS).
Martínez-Cabrera et al. [49]	Compare arbitrary and individualized speed thresholds on high-intensity acceleration in match	40-m linear sprint starting from standing, 6, 10.8 and 15 km/h	The maximal acceleration attained in the 40-m linear sprint test was used for the individualization.	High-intensity acceleration (> 3 m/s^2).	High-intensity acceleration (> 75% maximal acceleration).
Martínez-Cabrera et al. [50]	Compare arbitrary and individualized speed thresholds on high-intensity acceleration in match	40-m linear sprint starting from standing, 6, 10.8 and 15 km/h	The maximal acceleration attained in the 40-m linear sprint test was used for the individualization.	High-intensity acceleration (> 3 m/s^2); High-intensity acceleration (> 4 m/s^2).	High-intensity acceleration (> 75% maximal acceleration & > 21 km/h); High-intensity acceleration (> 75% maximal acceleration).
Massard et al. [81]	Compare arbitrary and individualized speed thresholds regarding the impact on workload measures and non-contact injury	40-m linear sprint starting or peak speed attained in match demands (players not assessed for 40-m sprint) and 30–15 Intermittent Fitness test for MAS	The final velocity achieved at 30–15 Intermittent Fitness test was used as reference for the high-speed running individualized threshold.	High-speed running (19.8 km/h or 5.5 m/s^2).	High-speed running (> MAS)
Murray et al. [44]	Compare arbitrary and individualized speed thresholds regarding the impact on injury likelihood and workload measures	Peak speed attained in training demands	The average MSS (32.1 km/h) was used as reference to create the relative thresholds for each speed zone.	Low (< 6 km/h); Moderate (6–18 km/h); High (18–24 km/h); Very high (> 24 km/h).	Low (0–19.99% MSS); Moderate (20–54.99% MSS); High (55–74.99% MSS); Very high (> 75% MSS).
Nakamura et al. [52]	Compare arbitrary and individualized speed thresholds on sprinting and repeated-sprints in matches	20-m linear sprint	Mean speed over 20-m linear sprint was used as MSS.	Sprint (> 20 km/h)	Sprint (> 90% MSS)
Núñez-Sánchez et al. [82]	Compare arbitrary and individualized speed thresholds on locomotor demands in matches	40-m linear sprint	The MSS obtained in the 40-m linear sprint was used for the individualization process.	Very low intensity running (0–7 km/h); Low intensity running (7–13 km/h); Medium intensity running (13–18 km/h); High intensity running (18–21 km/h)	< 10% MSS; 10–20% MSS; 20–30% MSS; 30–40% MSS; 40–50% MSS; 50–60% MSS; 60–70% MSS; 70–80% MSS; 80–90% MSS; > 90% MSS.
O'Connor et al. [56]	Compare arbitrary and individualized speed thresholds regarding the impact on non-contact injury	Peak speed in training/match	Peak speed in training/match was considered as MSS for individualization process.	Sprint threshold (> 24.9 km/h)	Sprint threshold (> 75% MSS; > 80% MSS; > 85% MSS; > 90% MSS; > 95% MSS)
Ortega-Gálvez et al. [42]	Compare arbitrary and individualized speed thresholds on locomotor demands in matches	40-m linear sprint starting and 30–15 Intermittent Fitness test for MAS	The final velocity achieved in the 30–15 Intermittent Fitness test was considered as MAS for individualization. The peak speed attained in the best 10-m split was considered as MSS.	Moderate (13.1–18.6 km/h); Sprint (20 km/h)	Moderate intensity (68% MAS); High intensity (> 87% MAS); Sprint (80% MSS)

TABLE 4. Continue

Study	Objective of research	Tests used for indivi-dualization	Method of individualization	Arbitrary thresholds used	Individualized thresholds used
Park et al. [24]	Compare arbitrary and individualized speed thresholds on locomotor demands in matches	Spectral Clustering, k-means and Gaussian mixture model	The algorithms were used to identify velocity zones in each computed half match, while linear-mixed modelling determined generic squad thresholds	High-velocity running (Generic: 4 m/s, Bradley and Vescovi: 3.34 m/s); Very-high velocity running (Generic: 5.5 m/s, Bradley and Vescovi: 4.45 m/s); Sprinting (Generic: 7 m/s, Bradley and Vescovi: 5.56 m/s)	k-means: High-velocity running (1.05 m/s); Very-high velocity running (2.10 m/s); Sprinting (3.60 m/s); Gaussian mixture model: High-velocity running (0.56 m/s); Very-high velocity running (1.53 m/s); Sprinting (3.05 m/s); Spectral Clustering ($\beta = 0.1$): High-velocity running (3.46 m/s); Very-high velocity running (5.29 m/s); Sprinting (6.26 m/s); Spectral Clustering ($\beta = 0.01$): High-velocity running (3.54 m/s); Very-high velocity running (5.38 m/s); Sprinting (6.30 m/s); Spectral Clustering ($\beta = 0.001$): High-velocity running (3.56 m/s); Very-high velocity running (5.39 m/s); Sprinting (6.30 m/s); Spectral Clustering ($\beta = 0$): High-velocity running (3.58 m/s); Very-high velocity running (5.41 m/s); Sprinting (6.27 m/s);
Rago et al. [46]	Analyze the relationship between locomotor and physiological demands, while considering arbitrary and individualized speed thresholds in matches.	Yo-Yo intermittent recovery test level 1 and peak speed attained in training sessions.	The final velocity attained in the Yo-Yo intermittent recovery test level 1 was considered for the estimation of the MAS. The peak speed attained in training sessions was considered as the MSS. The ASR was calculated from the difference of MSS and MAS.	Moderate speed running (14.4–19.8 km/h); high-speed running (19.9–25.1 km/h); sprinting ($>$ 25.2 km/h).	Moderate speed running (80–99.9% MAS); high-speed running (100%MAS-29%ASR); sprinting ($>$ 30% ASR).
Rago et al. [14]	Compare arbitrary and individualized speed thresholds on locomotor demands in matches	Yo-Yo intermittent recovery test level 1 and peak speed attained in training sessions.	The final velocity attained in the Yo-Yo intermittent recovery test level 1 was considered for the estimation of the MAS. The peak speed attained in training sessions was considered as the MSS. The ASR was calculated from the difference of MSS and MAS.	Moderate speed running (14.4–19.8 km/h); high-speed running (19.9–25.1 km/h); sprinting ($>$ 25.2 km/h).	Moderate speed running (80–99.9% MAS); high-speed running (100%MAS-29%ASR); sprinting ($>$ 30% ASR).
Reardon et al. [16]	Compare arbitrary and individualized speed thresholds on locomotor demands in matches	Peak speed attained in matches.	The peak speed attained in matches was considered as the MSS.	High speed running (5 m/s^2).	High speed running (5 m/s^2 divided by the average of MSS of the group).
Scanlan et al. [83]	Compare arbitrary and individualized PlayerLoad thresholds in training sessions.	Peak instantaneous PlayerLoad intensity recorded in training.	The peak instantaneous PlayerLoad intensity was used to individualized threshold.	PlayerLoad zone 1 (0–1 A.U.); PlayerLoad zone 2 (1–2 A.U.); PlayerLoad zone 3 (2–3 A.U.); PlayerLoad zone 4 (3–4 A.U.); PlayerLoad zone 5 (4–6 A.U.); PlayerLoad zone 6 (6–10 A.U.).	PlayerLoad zone 1 (0–10% peak PlayerLoad); PlayerLoad zone 2 (10–20% peak PlayerLoad); PlayerLoad zone 3 (20–30% peak PlayerLoad); PlayerLoad zone 4 (30–40% peak PlayerLoad); PlayerLoad zone 5 (40–60% peak PlayerLoad); PlayerLoad zone 6 (60–100% peak PlayerLoad).

TABLE 4. Continue

Study	Objective of research	Tests used for indivi-dualization	Method of individualization	Arbitrary thresholds used	Individualized thresholds used
Scott et al. [17]	Determine dose-response relationship between locomotor and physiological demands while use arbitrary and individualized speed thresholds in training sessions.	40-m linear sprint, the modified version of Montreal Track Test (VAM-EVAL) and the Yo-Yo Intermittent Recovery Test level 1	The best peak speed obtained in the splits of 10-m were considered as MSS. The last stage attained at VAM-EVAL and the Yo-Yo Intermittent Recovery Test level 1 were used to estimate the MAS.	High-speed running (12.67 km/h); Very high-speed running (17.82 km/h)	High-speed running (80%MAS at VAM-EVAL; or 80% at Yo-Yo Intermittent Recovery Test level 1; or 50% MSS); Very high-speed running (100%MAS at VAM-EVAL; or 100% MAS at Yo-Yo Intermittent Recovery Test level 1; or 65% MSS)
Scott et al. [47]	Examine the dose-response relationship between match-player demands and ratings of fatigue and soreness, while using arbitrary and individualized thresholds.	40-m linear sprint, and the 30–15 Intermittent Fitness Test	The fastest sprint in splits of 10-m was considered as the MSS. The final velocity of 30–15 Intermittent Fitness Test was estimated as a MAS measure. The ASR was calculated based on the difference between MSS and MAS.	High-speed running (12.5 km/h); Very high-speed running (19.0 km/h); Sprinting (22.5 km/h).	High-speed running (60% MAS; 50% MSS); Very high-speed running (80% MAS; 65% MSS); Sprinting (30% ASR; 80% MSS).
Siegle et al. [54]	Analyze inter-individual differences in the locomotor speed and compare with general approach in match.	Q-Q-Plots	Q-Q-Plots were used to graphical inspection of intersection point.	Walking (qualitative approach); Jogging (qualitative approach); Cruising (qualitative approach); Sprinting (qualitative approach).	Walking/Jogging (intersection point in movement velocity, average: 2.06 m/s^2); Jogging-Cruising/sprinting (intersection point in movement velocity, average: 4.53 m/s^2).
Taylor et al. [48]	Compare the training load in different age-groups, while using arbitrary and individualized speed thresholds.	30-m linear sprint, and the 30–15 Intermittent Fitness Test	The peak speed at 30-m linear sprint was used as MSS. The final velocity of 30–15 Intermittent Fitness Test was estimated as a MAS measure.	High-speed running (> 19.8 km/h); Sprint running (> 25.2 km/h).	High-speed running (87% MAS); Sprint running (80% MSS).
Taylor et al. [84]	Identify the dose-response relationship between training load measures, while considering arbitrary and individualized speed thresholds.	Incremental treadmill test	The velocities at 2 mmol/L and 4 mmol/L lactate were estimated to individualization of speed thresholds.	High-speed distance (> 15 km/h); Very high-speed distance (> 18 km/h).	High speed distance thresholds (velocity at 4 mmol/L lactate, range: 8.7 to 13.1 km/h)
Taylor et al. [85]	To assess the relationships between external and internal load ratios, while considering arbitrary and individualized speed thresholds.	Incremental treadmill test	The velocities at 2 mmol/L and 4 mmol/L lactate were estimated to individualization of speed thresholds.	High-speed distance (> 15 km/h); Very high-speed distance (> 18 km/h).	High speed distance thresholds (velocity at 4 mmol/L lactate, range: 8.7 to 13.1 km/h)

ASR: anaerobic speed reserve; Aust. Foot.: Australian Football; Comp.: competitive; GPS: Global Positioning System; H: hockey; IU: information unavailable; LPS: local positioning system; M: men; MAS: maximal aerobic speed; MSS: maximal sprint speed; N: number of participants; RCT: Respiratory compensation threshold; UK: United Kingdom; USA: United States of America; W: women.

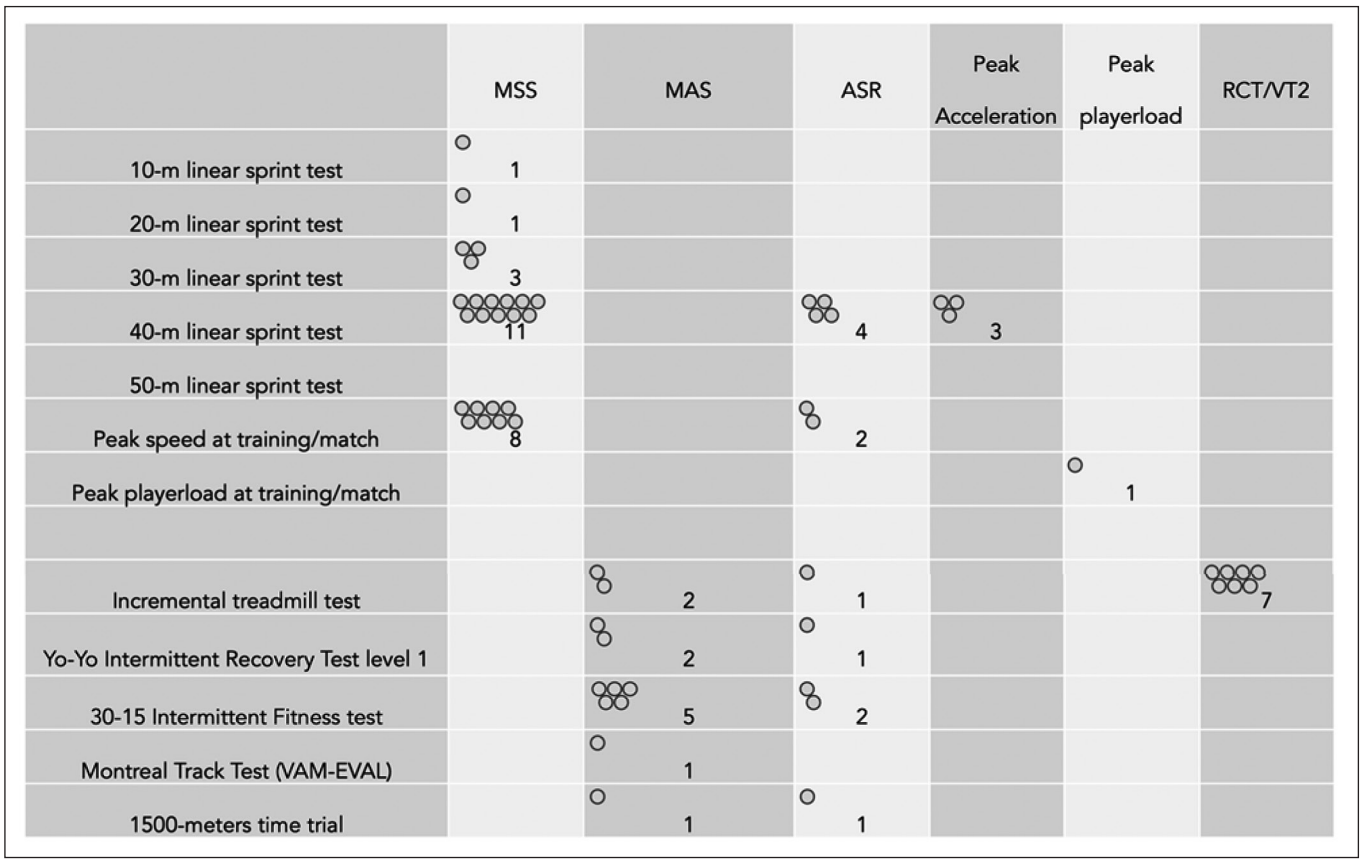


FIG. 4. Interaction between physical fitness assessment and main outcomes used in the individualized running speed thresholds. MSS: maximal sprint speed; MAS: maximal aerobic speed; ASR: anaerobic speed reserve; RCT: Respiratory compensation threshold; VT2: second ventilatory threshold. Open circles represents the number of studies.

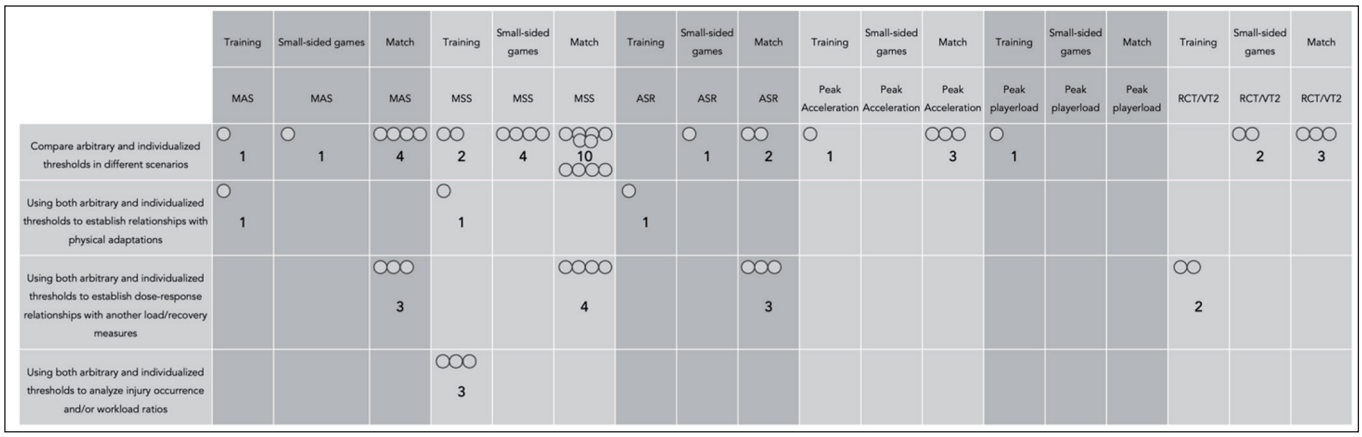


FIG. 5. Evidence gap map regarding main topics of study and main measures used for establishing the individualized running speed threshold. MSS: maximal sprint speed; MAS: maximal aerobic speed; ASR: anaerobic speed reserve; RCT: Respiratory compensation threshold; VT2: second ventilatory threshold. Open circles represents the number of studies.

linear sprint test was the only test used for assessing peak acceleration (n = 3).

Figure 5 presents the EGM of individualized running speed thresholds compared with arbitrary thresholds. Of the 36 included articles, 27 (75%) centered on the use of arbitrary and individualized running speed thresholds to describe the locomotor demands on players, while 5 (13.9%) centered on establishing relationships between arbitrary and individualized running speed thresholds and training load measures. Three articles (8.3%) used the approaches to establish relationships with injury likelihood or occurrences, and just one study (2.8%) focused on establishing relationships between arbitrary and individualized running speed thresholds and physical fitness adaptations.

DISCUSSION

Most individualized approaches to establishing running speed thresholds in team sports are focused on the measuring of physical fitness to meet the locomotor demands of those sports. Among other measures, MSS, MAS and respiratory compensation threshold were the main measures used for individualization of running speed thresholds. One of the notable trends found amongst the articles was the diversity of individualized approaches used, with few studies focusing on determining the best method of individualization or comparing different methods to define which might be the most appropriate. Hereafter, the discussion will center on the methodological characteristics and potential bias found during the review.

Participation characteristics

There was a lack of consensus on the use of terms (e.g., elite, professional) to describe study participants amongst the included studies. Such terms help to provide relevant information about the competitive level of study participants, however, populations such as youth athletes are not easy to classify given their relative lack of experience and variation between countries and sports. This may also be applicable at the so-called "elite" level as professional status can relate to having competed in any one of several different tiers of varying playing standard [53]. In an effort to improve the standardization of athletes' competitive levels, we recommend that researchers follow the Participant Classification Framework [33] which categorizes players based on their level of practice, volume of training and ranking. The organization of study participants into well-defined tiers may help to standardize information for the scientific community, leading to more accurate appraisals of studies such as those in the current scoping review and the subsequent development of more useful knowledge that can be transferred to practitioners. In this scoping review, we have attempted to classify study participants based on the aforementioned framework, however, in some cases, this was challenging because basic information, such as training and match frequency and hours of training per week, were not available in the gathered studies. More accurate information such as participant skill level or level of competition (tier of league structure, competitions in national or international play) are highly important to better characterize samples. Most of the studies in this review were conducted in tiers 2 (trained/developmental) and 3 (highly trained/national level) indicating that it remains difficult to undertake observational studies in international level or world class athletes. More research should focus on the elite level of sport with studies on world-class female soccer players [24] and the finalists of the men's world cup [54] being excellent examples of this.

In relation to the diversity of origins of the studies in this review, no studies came from Africa or Asia and only a small number came from the Americas. Of the 36 included studies, 25 were from continental Europe and six came from Australia, indicating that research on this topic is concentrated in specific regions of the world. This may constitute a potential issue for the generalizability of research results and may compromise the establishment of similar performance benchmarks in other regions of the world. Another significant imbalance in the gathered data related to the diversity of team sports that were studied. Soccer was the most commonly studied (n = 25) and was followed by rugby (n = 5) in a distant second place. This makes it difficult to consolidate findings for sports other than soccer as the amount of analyzable evidence is small. In addition to this, another limitation is the sample size in published studies. The number of participants per study ranged from eight to 90. There was a notable absence of the rationale for the various sample sizes utilized in the studies. Even considering the difficulty of performing observational studies in competitive sporting environments, it must be acknowledged that small sample sizes and highly specific contexts can compromise the generalizability of evidence extracted from the analyses. In addition to this, it is highly important that researchers report effect sizes to add context to the outcomes of their hypothesis testing [55]. Finally, another reporting issue which must be improved upon relates to the sampling strategies utilized by researchers. Most investigations comprise of convenience samples with data from just a single team usually analyzed thus undermining the generalizability of this data. Studies with larger samples that are obtained via more robust sampling strategies should be prioritized by researchers. However, another challenge that may emerge in such scenarios is the replicability of the conditions in any given scenario (which, albeit, may be relatively simple to guarantee if the sample comprises of just one team).

Although several studies reported the characteristics of the participants such as body mass and height, most of the included articles did not report this information clearly making it difficult to fully evaluate the extant evidence and compare results for future research. Likewise, although the requirement to protect sensitive or personal data is understandable, it is vital to indicate the sex of study participants as physical fitness and running speed thresholds may vary based on this characteristic [12]. This is also vital in terms of upholding the replicability of a given study. From the minority of studies which reported the sex of participants, men were more researched (n = 12) than women (n = 6).

Sample collected

A highly diversity body of data were collected from the included studies. As an example, training volume varied from a minimum of two sessions [11] to a maximum of 114 [56]. Similarly, the number of matches analyzed varied from one (single match) [54] to 52 (collected over three years) [24]. Aside from the substantial difference in the amount of data collected, other issues were also apparent. For example, the period of observation was unreported in six studies with the remaining typically failing to provide any additional contextualization such as the period of the season the data was collected in and the schedule of matches that the teams were exposed to. In future studies, we recommend that researchers accurately describe the period of observation with relevant dates and information on the specific period and the content of the training week(s). Such information can be added as a supplementary file to journal submissions. Encouragingly, all the gathered studies reported on the brand and model of the instruments used to collect data with the accuracy and level of measurement precision also very well described.

Physical fitness assessment – context-related information

Most (34/36) of the included studies used physical fitness assessment or performance analysis elements to individualize speed running thresholds. However, a particularly vital methodological issue related to the lack of accuracy in reporting the regularity of these assessments. Most of the studies used more than a single game to analyze running speed thresholds, and the range of the observation periods varied from two weeks [39] to three years [24]. Information about the regularity of the assessments and, most particularly, the time between the assessments and the range of matches analyzed was surprisingly scarce in most of the articles. Some studies reported the exact time of assessment (e.g., start of the pre-season or the week before the matches being assessed) [44, 52] and others detailed the regularity of assessment (e.g., six measurements in six weeks) [41, 19]. The availability of more accurate timelines, such as figures or supplementary files with schedules, could make it easier to identify which matches were associated with each fitness assessment. For example, in the case of an assessment performed on, say, 30th October, it could be questioned as to whether that assessment would be relevant to the six subsequent scheduled matches or to the three matches before and the three matches after 30th October. This would be particularly relevant during periods of the season when congestion in the match schedule results in multiple games being played within a very short timeframe [57]. Questions such as these arise from studies' reporting processes which can compromise the replicability of the methods.

Another issue commonly considered to cause a risk of bias is the absence of information on players' personal habits at the time of the assessment. Studies tended not to report many important factors related to readiness and performance strategies such as players' sleep habits (i.e., number of hours and quality of sleep the night before assessment) [58], the composition of dietary intake [59], recovery status (i.e., rest times, ratings of perceived exertion) [60] or the sequence of how the tests were conducted. Moreover, it is also important to emphasize the need to report the validity and reliability of the physical fitness tests employed in each study [61].

Physical tests – specificities and methodological considerations

In the gathered studies, it was apparent that the individualization process was fundamentally associated with the estimation of MSS or the analysis of a cardiorespiratory marker. The 40-m linear sprint was the most utilized test, featuring in 11 studies and this was followed by the 30-m linear sprint. The 40-m linear sprint appears to be an appropriate distance with which to identify MSS regardless of the sport in question [13, 62]. Moreover, the validity and reliability of linear sprint tests are also very high [62].

Despite the above, some methodological issues were found during the inspection of the articles. For example, when measuring sprint speed, some researchers have placed photocells every 10-m [19] or 20-m [52] along the plotted course to estimate the average running speed of a participant over the chosen distance. However, previous research has revealed that photocells that are positioned every 5-m appear to be a more accurate way to estimate average running speed in comparison to the gold-standard radar gun [63]. It is nonetheless worth noting that measuring average speed in splits of 10-m or 20-m may underestimate the peak speed which a performer achieves and this can result in the inaccurate individualization of running speed thresholds. Moreover, it was commonly observed that there was an absence of detail regarding the method for setting (e.g., split, parallel), the height of photocells as well as determining the distance between the starting line and the first pair of photocells. These factors can also be confounding variables since the starting position of the participant can affect the final recorded time in a sprint test [64]. So too can the height of photocells [65] and the distance between the foot and the first pair of photocells and we encourage researchers to control for and report these factors when conducting studies.

Although the use of a radar gun could be the most recommended approach, the major alternative method to using photocells in the included studies was GPS. Previous studies suggest that GPS with 10 Hz (the most widely used in the gathered articles) can provide valid and reliable information about a player's peak speed [66]; however, GPS can present some fluctuations in reliability level depending on the position of the device [67]. Accordingly, it is important to detail how a given GPS was used and, in the report, to highlight the accuracy and precision level for estimating peak speed.

A further question associated with the individualization process was the test used to estimate cardiorespiratory fitness. MAS is a marker that was used in eleven of the included articles. However, MAS was estimated using a variety of different measures and instruments such an incremental treadmill test, the Yo-Yo Intermittent Recovery test, the 30–15 Intermittent Fitness Test, the Montreal track test, and the 1500-meter time trial. This can introduce substantial heterogeneity between studies as output for this marker is particularly

protocol-dependent (e.g., variations in time of exposure per velocity, transition rhythm) meaning that the variability of the outcome can drastically change the final interpretation and individualization of thresholds [20]. Indeed, a field-based test such as the 30–15 Intermittent Fitness test can overestimate MAS and the overall effect of repeated changes of direction in the test can affect the final score [68].

Definition of the thresholds based on physical fitness measures

Multiple different approaches to establish the individualized running speed thresholds were observed in the gathered studies. The most common were MSS, MAS and the respiratory compensation threshold. Additionally, ASR, maximal acceleration, and maximal player load were also used. As an alternative, Q-Q plots or machine learning algorithms were utilized. The methods mentioned above may extensively impact upon the variables in a typical match analysis such as high-intensity running distance, high-speed running distance, and sprinting distance.

The lack of definition in the approach to speed threshold individualization was apparent in the gathered studies. As an example, sprinting was classified as both > 90% [52] and > 80% [42, 48] of MSS as estimated in a test, or in the peak speed observed during a training session or match. Currently it is unclear which of these standards constitutes a sprint action. One advantageous reason for using MSS is the lower level of variability that can be observed across time [69]. This stability gives the measure a level of consistency that may not be possible when using MAS.

The use of MAS for establishing the threshold of high-speed running was observed in different studies. For some authors, high-speed running was the point at which MAS was attained [11, 44], while others defined this as being between 50–70% [45] or 80–99% of MAS [19]. A recent systematic review [70] adequately characterizes this methodological dilemma. Furthermore, although the same locomotor demands can be placed on two individuals, the associated physiological demands of movement can vary, thus implying a different physiological representation of high-speed running. Moreover, since MAS is protocol-dependent, this process becomes even more complex to address. Finally, physical qualities can vary in the short term (based on the applied stimulus) [71, 72] meaning that if some forms of physical fitness are not tested every six weeks, it can be challenging to set thresholds that are aligned to a player's capabilities at the time of match data capture and analysis. This also raises the issue of 'training residuals' and the effect that they might have on the estimation of running speed thresholds. Whilst it has been demonstrated that physical qualities such as aerobic endurance and maximal strength can remain for up to 30 days following the reduction or cessation of training, the residual of maximal speed training, and its associated physiological adaptations, is only five days in duration [23]. This means that in order to ensure that a player's running speed threshold remains as accurate as possible throughout a season, some form of maximal sprint stimulus must occur at least every five days to retain maximal performance of this particular physical quality. If this does not occur, theoretically, a player could lose sprinting speed and subsequent estimations may be inaccurate relative to their best potential performance.

Future research

In line with the article of Beato et al [13], the commentary of Drust [73] and the letter to the editor of Kavanagh and Carling [74], more effort is required to consolidate methodological approaches to the study of individualized running speed thresholds in team sports. There are clear methodological concerns in the published literature on this topic which we discuss in the current scoping review. Accordingly, some recommendations should be considered by researchers who wish to progress work in this area. In relation to study participants, it is important to increase sample sizes, create more representation across competitive levels and standardize reporting on competitive level, training frequency, player origin and context of practice. Considering measurement instruments, it is important to detail accuracy and precision ensuring that reliability and validity are at the forefront of researchers' effort to characterize running speed thresholds. Regarding the reporting of study details, it is important to provide a timeline that indicates the exact point of observation using dates and the specific juncture at which data collection occurred. To do this, researchers might perhaps consider adding supplementary files to their journal submissions. Also, it is important to contextualize the data collection process, namely controlling confounding variables of physical fitness assessments. To do this, researchers could use surveys of sleep, standardize players' nutritional intake, control the effects of environmental conditions and measure the readiness of their participants to perform. The regularity of fitness assessments must also be improved in terms of the amount of elapsed time between measurements.

Future research must focus on comparing different individualization approaches (e.g., using multiple measures combined or isolated), testing across different periods of time (between the assessment and utilization) and identifying the practical effects on workload and injury risk. Moreover, clarification of the debate on the use of physical fitness markers versus machine learning that uses standards based on players' match demands can also be focused on further. Additionally, analysis of the impact of moderators and mediators such as time of the season, type of population and players' level of training experience must be also considered.

Limitations of the scoping review

The current scoping review may present some limitations that should be highlighted. One of these limitations relates to the utilized search strategy and eligibility criteria. We executed a search strategy that our group of authors and experts unanimously accepted. However, as with any other search strategy, this may not uncover all eligible articles. Even so, we have used a comprehensive search strategy to mitigate this potential source of bias. Despite the use of two independent researchers to select the articles, in addition to world experts

whose status is based on measures of overall scientific impact, this may not ensure that all relevant articles were identified. We focused on scientific studies that included both individualized and non-individualized running speed thresholds which meant that some articles, which focused only on individualized running-speed, were not included in the review. However, our methodological approach was designed to conform to all aspects of the PRISMA statement which represents a progressive methodological step in relation to the execution of a traditional scoping review. Finally, we established a rationale for the presentation of our results which consisted of exploring the methodological approaches made by the original studies, and not explicitly focusing on the primary outcomes reported in these studies.

CONCLUSIONS

The current scoping review summarizes studies that reported on both arbitrary (absolute) and individualized running speed thresholds in team sports. Of the included studies, most used arbitrary and individualized running speed thresholds to compare distances covered in match or training sessions. However, there were also some studies that used individualized running speed thresholds to determine the dose-response relationship between locomotor demands and physiological responses, or to associate the exposure of locomotor demands with injury occurrence. In terms of methodological issues, most of the studies used physical fitness or physical performance measures to individualize running speed thresholds. However, the main risk of bias identified in terms of methodological quality was the regularity of assessment and its possible impact on the measurement. Additionally, information about the context of assessments and their replicability should be improved. This specifically relates to authors' providing information on player readiness, well-being and physical fitness status as well as the reliability of the associated data. Moreover, the techniques used to individualize were not consistent between studies and there was a specifically wide diversity of outcomes and tests used to ascertain running speed. In many cases, the established thresholds differed even when measured with the same tool or instrument (i.e. MAS). The most common measures used to individualize running speed thresholds were MAS, MSS, and the respiratory compensation threshold. Future research is needed on methodological issues and biases related to data collection and to define the most appropriate way to individualize running speed thresholds.

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Conflicts of interest

The authors declared no conflict of interest.

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SUPPLEMENTARY MATERIAL 1.

LIST OF INCLUDED AND EXCLUDED ARTICLES IN THE FULL-TEXT ROUND OF SELECTION.

1	2	3	4	5	6	7
Title	**(i) population: team sports players from any age and from both sexes integrated into team routines (i.e., not injured or with any reported pathology or health problems; also not included disabled or adapted sports);**	**(ii) exposure: exposed to analysis of individualized running speed thresholds in training sessions and/or matches;**	**(iii) comparator: exposed to traditional arbitrary running speed thresholds in training sessions and/or matches;**	**(iv) Outcome(s): the time and/or distance and/or percentage of time and/or distance spent in different running speed thresholds (either in arbitrary/fixed or individualized thresholds);**	**(v) study design: observational studies or interventions (both single-arm [if with two different metrics, for example, individualized vs. arbitrary] and multi-arm investigations)**	**Included**
Application of individualized speed thresholds to interpret position specific running demands in elite professional rugby union: A GPS Study	Yes	Yes	Yes	Yes	Yes	Yes
Match analysis of U9 and U10 english premier league academy soccer players using a global positioning system: relevance for talent identification and development	Yes	No	No	No	Yes	No
Individualisation of time-motion analysis: A method comparison and case report series	Yes	Yes	Yes	Yes	Yes	Yes
Use of Individual Relative Thresholds to Assess Acceleration in Young Soccer Players According to Initial Speed	Yes	Yes	Yes	Yes	Yes	Yes
Comparison of player-dependent and independent high-speed running thresholds to model injury risk in football	Yes	Yes	Yes	Yes	Yes	Yes
Individualizing acceleration in english premier league academy soccer players	Yes	Yes	Yes	Yes	Yes	Yes
Relationship between external load and perceptual responses to training in professional football: Effects of quantification method	Yes	Yes	Yes	Yes	Yes	Yes
High-intensity acceleration in soccer. Why is the evaluation method important?	Yes	Yes	Yes	Yes	Yes	Yes

SUPPLEMENTARY MATERIAL 1.
Continue.

1	2	3	4	5	6	7
Measurement properties of external training load variables during standardised games in soccer: Implications for training and monitoring strategies	Yes	No	No	No	Yes	No
The relation between movement velocity and movement pattern in elite soccer	Yes	Yes	Yes	Yes	Yes	Yes
Individualized and fixed thresholds to demarcate playerload intensity zones produce different outcomes	Yes	Yes	Yes	Yes	Yes	Yes
Greater association of relative thresholds than absolute thresholds with noncontact lower-body injury in professional australian rules footballers: Implications for sprint monitoring	Yes	Yes	Yes	Yes	Yes	Yes
Use of Relative Speed Zones Increases the High-Speed Running Performed in Team Sport Match Play	Yes	Yes	Yes	Yes	Yes	Yes
Match-to-match variability in high-speed running activity in a professional soccer team	Yes	Yes	Yes	Yes	Yes	Yes
Dose-response relationship between external load and wellness in elite women's soccer matches: Do customized velocity thresholds add value?	Yes	Yes	Yes	Yes	Yes	Yes
Default and individual comparison of physiological responses and time-motion analysis in male and female soccer players during small-sided games	Yes	Yes	Yes	Yes	Yes	Yes
The use of individualized speed and intensity thresholds for determining the distance run at high-intensity in professional soccer	Yes	Yes	Yes	Yes	Yes	Yes
Local Positioning System-Derived External Load of Female and Male Varsity Ice Hockey Players During Regular Season Games	Yes	Yes	Yes	Yes	Yes	Yes

SUPPLEMENTARY MATERIAL 1.
Continue.

1	2	3	4	5	6	7
An individual approach to monitoring locomotive training load in English Premier League academy soccer players	No	No	No	No	No	No
The dose-response relationship between training load and aerobic fitness in academy rugby union players	Yes	Yes	Yes	Yes	Yes	Yes
Individualization of Time-Motion Analysis: A Case-Cohort Example	Yes	Yes	Yes	Yes	Yes	Yes
Individualized speed threshold to analyze the game running demands in soccer players using GPS technology	Yes	Yes	Yes	Yes	Yes	Yes
External Training Demands in Women's Varsity Rugby Union Players Quantified by Wearable Microtechnology With Individualized Speed Thresholds	Yes	Yes	No	Yes	Yes	No
The use of generic and individual speed thresholds for assessing the competitive demands of field hockey	Yes	Yes	Yes	Yes	Yes	Yes
Physiologically based GPS speed zones for evaluating running demands in Women's Rugby Sevens	Yes	Yes	Yes	Yes	Yes	Yes
Individualisation of speed thresholds does not enhance the dose-response determination in football training	Yes	Yes	Yes	Yes	Yes	Yes
Monitoring Matches and Small-sided Games in Elite Young Soccer Players	Yes	Yes	Yes	Yes	Yes	Yes
The challenge of evaluating the intensity of short actions in soccer: A new methodological approach using percentage acceleration	Yes	Yes	No	Yes	Yes	No
Repeated-Sprint Sequences during Female Soccer Matches Using Fixed and Individual Speed Thresholds	Yes	Yes	Yes	Yes	Yes	Yes
Influence of the number of players and the relative pitch area per player on heart rate and physical demands in youth soccer	Yes	Yes	Yes	Yes	Yes	Yes

SUPPLEMENTARY MATERIAL 1.
Continue.

1	2	3	4	5	6	7
Number of Players and Relative Pitch Area per Player: Comparing Their Influence on Heart Rate and Physical Demands in Under-12 and Under-13 Football Players	Yes	Yes	Yes	Yes	Yes	Yes
Individual vs general time-motion analysis and physiological response in 4 vs 4 and 5 vs 5 small-sided soccer games	Yes	Yes	Yes	Yes	Yes	Yes
Dose-Response Relationship Between Training Load and Changes in Aerobic Fitness in Professional Youth Soccer Players	Yes	Yes	Yes	Yes	Yes	Yes
Reliability and validity of integrated external and internal load ratios as measures of fitness in academy rugby union players	Yes	Yes	Yes	Yes	Yes	Yes
The use of relative speed zones in Australian Football: Are we really measuring what we think we are?	Yes	Yes	Yes	Yes	Yes	Yes
Application of Individualized Speed Zones to Quantify External Training Load in Professional Soccer	Yes	Yes	Yes	Yes	Yes	Yes
Mind the “Gap”: A Comparison of the Weekly Training Loads of English Premier League Academy Soccer Players in Under 23, Under 18 and Under 16 Age-Groups	Yes	Yes	Yes	Yes	Yes	Yes
Motion analysis of U11 to U16 elite English Premier League Academy players	Yes	Yes	Yes	Yes	Yes	Yes
Quantification of the running demands in women`s field hockey using individualized thresholds	Yes	Yes	Yes	Yes	Yes	Yes
Velocity zone classification in elite women’s football: where do we draw the lines?	Yes	Yes	Yes	Yes	Yes	Yes
Workload Monitoring in Top-level Soccer Players During Congested Fixture Periods	Yes	Yes	Yes	Yes	Yes	Yes


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