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Match running performance characterizing the most elite soccer match-play

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ABSTRACT: In order to identify match running performance (MRP) characterizing the most elite soccer match-play, this study aimed to examine position-specific differences in the MRP of players competing in "big five" (BFLTs) and "non-big five" league teams (N-BFLTs). The data were obtained from 24 teams (BFLTs; n = 14, N-BFLTs; n = 10) during the UEFA Champions League (UCL) matches (n = 20) in the 2020/21 season using a semiautomatic video system. The differences in MRP between BFLTs and N-BFLTs, while controlling for contextual factors, were examined using linear mixed model. No differences in overall MRP between fullbacks, central midfielders, wide midfielders and forwards from BFLTs and their peers from N-BFLTs were found, while only central defenders from BFLTs covered more high-intensity running than central defenders from BFLTs (moderate effects size). For players on all playing positions from BFLTs, total- and low-intensity distance covered were lower in offensive phase of game and greater in defensive phase of game compared to their peers from N-BFLTs (all large effect sizes). This study demonstrated that the most elite match-play in soccer is characterized by increased efforts in defensive phase of game, and decreased efforts in offensive phase of game. Soccer training programmes should be adapted accordingly.

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INTRODUCTION

Match performance in soccer is highly dependent on the interactions between technical, tactical and physical performance [1]. Although technical–tactical performances are considered decisive for success in soccer [2], players must still be able to handle the high physical demands that contemporary soccer requires [3]. In addition, detailed knowledge about the physical performance of professional soccer match play is required to construct optimal training programs to respond to these needs [4]. For example, the distances covered by players in a match, according to their positions, can be used to prescribe more specific training or to consider new ways to improve the efficiency of team training [5]. For these reasons, many techniques (e.g., global and local positioning systems or multi-camera optical systems) have been used to establish the physical profiles of soccer players by quantifying match running performance (MRP) [6–10].

Previous research analysing MRP in soccer demonstrated that elite players can cover between 9 and 14 km, performing 0.7–3.9 km of high-speed distance and 0.2–0.6 km of sprint distance [11]. These performances are primarily determined by the different playing positions of the players in the match [12]. Specifically, the majority of studies reported that central midfielders cover the greatest overall distance and central defenders cover the lowest overall distance of all the playing positions [13, 14]. In addition, studies have typically reported greater high-intensity running distances (> 5.5 m/s) for wide midfielders and fullbacks compared to other positions, with central defenders performing the lowest high-intensity running distance among elite players [13, 14]. In addition to playing position, the MRP of soccer players can be further determined using specific match-related factors, such as match location or match outcome [15]. Controlling the influence of these factors when examining the MRP of soccer players is essential.

Soccer is no doubt one of the most popular sports in the world, played in more than 200 countries, with, currently, more than 500 million active players, of whom 300 million are registered soccer club members [16]. The most prestigious competition in soccer is the Union of European Football Associations (UEFA) Champions League (UCL) [17]. Millions of soccer supporters in Europe and throughout the world are interested in the games and title winners [17]. Together with the financial perspective, this attracts top-level soccer players from all over the world to join teams competing in the UCL. As a result, teams that compete in the UCL consist of some of the most elite soccer players in the world. Analyzing the MRP of such players can help to constitute activity profiles which can be used by coaches and players for reaching the most elite match-play [18]. Therefore, it is not surprising that researchers have put

forth great effort in providing knowledge about the MRP of players competing in UCL [3, 11, 19–22].

Briefly, Di Salvo et al. provided useful insight into position-specific sprinting activities during UCL matches [20]. Minano-Espin et al. analysed the high-intensity running patterns of UCL players according to the quality of the opposition [21]. The focus of Bradley et al. was on the gender differences between UCL players, indicating large differences in the physical indicators between male and female players [19]. Modric et al. evaluated position-specific MRP (overall and specifically for the offensive and defensive phases of the game) according to success in the UCL group stage [3, 22]. In addition, the same authors have provided information on match-related factors affecting MRP in UCL matches, demonstrating the influence of match outcome and match location over variables determining the intensity and volume of the match, respectively [11].

Although these studies provided some valuable information on the MRP in elite soccer, the real knowledge on MRP characterizing the most elite match-play is still limited. Specifically, despite the high standards of the teams competing in the UCL, representing the cream of each national league [20], the samples used in all the aforementioned studies also comprised teams from lower-standard national leagues [3, 19, 20,22]. Specifically, Di Salvo et al.'s sample included teams from the UEFA European League, Bradley et al.'s sample included the top 15 ranked teams in Europe, and Modric et al. analysed group-stage matches that typically include lower-standard teams [3, 19, 20, 22]. Furthermore, none of these studies controlled for the influence of contextual factors that may significantly affect the conclusions [15].

For all these reasons, further research, utilizing a more complex statistical approach that controls for contextual factors, is needed to provide true knowledge on the MRP of the most elite soccer players. According to the UEFA, Spanish La Liga, English Premier League, Italian Serie A, German Bundesliga and French Ligue 1 are the top five ranked professional soccer leagues [23]; therefore, players competing in UCL which national competitions play in one of these leagues can be considered as most elite soccer players in the world. Analysing the differences in MRP between such players and their peers from lower-standard teams may help soccer coaches to identify critical the MRP required for reaching elite match-play [18], while at the same time can be used to adapt soccer training programs accordingly. Therefore, the main objective of this study was to examine the position-specific differences in the MRP of UCL players from teams competing in "big five" or "non-big five" leagues.

MATERIALS AND METHODS

Participants and study design

The sample comprised 547 individual match observations of 378 outfield players who were members of 24 teams that competed in the group stage of the UCL in the 2020/21 season. Depending on whether they played national competitions in "big five" or "non-big five" leagues, teams were classified into two groups as: big five league teams (BFLTs; n = 14) and non-big five league teams (N-BFLTs; n = 10). The BFLTs included teams from Spanish La Liga (n = 4), Italian Serie A (n = 3), German Bundesliga (n = 3), England Premier League (n = 2) and France Ligue 1 (n = 2). N-BFLTs included teams from Russian Premier Liga (n = 3), Ukrainian First League (n = 2), Portuguese Primeira Liga (n = 1), Hungarian OTP Bank Liga (n = 1), Belgian First Division A (n = 1), Super League Greece (n = 1) and Austrian Football Bundesliga (n = 1).

All data were obtained from 20 matches from groups A (n = 3), B (n = 3), C (n = 4), E (n = 4), F (n = 3) and G (n = 3). Matches that included a player dismissal (red card) were not observed, and only results from players who participated in the whole match were analysed [20]. As a result, 244 match observations (BFLTs; n = 89, N-BFLTs; n = 155) were retrieved and classified according to soccer-specific playing positions as follows: central defender (CD; n = 79), fullback (FB; n = 65), central midfielder (CM; n = 55), wide midfielder (i.e., winger) (WM; n = 28) and forward (FW; n = 17).

Players' and teams' identities were anonymized per the principles of the Declaration of Helsinki to ensure confidentiality. The investigation was approved by the local university ethics board, while written permission for the data used was obtained from InStat Limited (Limerick, Republic of Ireland, 5 June 2021).

Procedures

All MRP data were recorded using a multicamera, semiautomatic optical tracking system (InStat Fitness, Instat Limited, Limerick, Republic of Ireland) with a sampling frequency of 25 Hz. The system passed the official Fédération Internationale de Football Association (FIFA) test protocol for electronic and performance tracking systems (EPTS) (authorization number: 1007382), demonstrating high levels of absolute and relative reliability [11].

The MRPs were observed separately for (i) overall match, (ii) offensive phase of the game and (iii) defensive phase of the game. The MRP in the offensive phase of the game was quantified when the team had the ball in their possession, while the MRP in the defensive phase of the game was quantified when the opponent had the ball in their possession [24].

The MRP variables included total distance covered (TD) (m), low-intensity running (LIR) (≤ 4 m/s) (m), moderate-intensity running (MIR) (4–5.5 m/s) (m), high-intensity running (HIR) (≥ 5.5 m/s) (m), TD in the offensive phase of the game (TD-O) (m), LIR in the offensive phase of the game (LIR-O) (m), MIR in the offensive phase of the game (MIR-O) (m), HIR in the offensive phase of the game (HIR-O) (m), TD in the defensive phase of the game (TD-D) (m), LIR in the defensive phase of the game (LIR-D) (m), MIR in the defensive phase of the game (MIR-D) (m), HIR in the defensive phase of the game (HIR-D) (m) [11, 22].

Statistics

The normality of the distributions was checked with the Kolmogorov–Smirnov test, and the descriptive statistics included the

means ± standard deviations. The homoscedasticity of all variables was confirmed with Levene's test. Linear mixed model was adjusted to examine the differences in MRPs (i.e., dependent variables) of players from BFLTs and N-BFLTs. For this purpose, a dummy variable "league" (coded as "1" if the team was a member of the "big five" leagues and "0" if the team was not a member of the "big five" leagues) was created and introduced in the model as fixed effect. Considering the very recent study which demonstrated that match outcome and match location may influence MRP in UCL [11], differences in MRP between BFLTs and N-BFLTs were examined while controlling for match location and match outcome. For this purpose, dummy variables "match outcome" (not-win/win) and "match location" (home/away) were created and introduced into the model as fixed effects. By adding these fixed effects, the pure differences between players from BFLTs and N-BFLTs can be more accurately assessed. To account for the repeated measurements, players' and teams' identities were modelled as random effects. The assumptions of homogeneity and normal distributions of residuals were without revealing specific problems. The main effect (i.e., BFLTs vs N-BFLTs) comparisons were summarized using least significant difference (LSD) [25]. The t-statistics from the mixed models were converted to effect sizes (Cohen's d) [26], and interpreted as follows: trivial (< 0.2), small (> 0.2–0.5), moderate (> 0.5–0.8) and large (> 0.8) [27]. The 95% confidence intervals were computed to assess the precision of the estimates. To determine most important metrics distinguishing most elite soccer players (i.e., from BFLTs) and their counterparts from lower-standard teams (i.e., from N-BFLTs), multivariate differences in MRP between BFLTs vs N- BFLTs were analyzed by canonical discriminant analysis. Comparison for MRPs between won and lost matches was examined using one-way analysis of variance. Differences in ball possession between BFLTs and N-BFLT were examined by Mann-Whitney U Test to support introduced assumptions. All the analyses were performed using the SPSS software (IBM, SPSS, Version 25.0).

RESULTS

The CDs from N-BFLTs covered less HIR than CDs from BFLTs (586 and 716 m, respectively; effect size (ES) (95% confidence interval [CI]) = -0.64 (-1.21; -0.07), while CMs, FBs, FWs, and WMs covered similar HIR irrespective playing in N-BFLTs or BFLTs. Players on all other playing positions covered similar TD (CDs: 10,165 m and 10,240 m, respectively; CMs: 11,815 and 11,967, respectively; FBs: 10,840 m and 11,069, respectively; FWs: 10,854 m and 10,318 m, WMs: 11,247 m and 10,843 m, respectively), LIR (CDs: 8013 m and 7948 m respectively; CMs: 8474 m and 8470 m, respectively; FBs: 8063 m and 8076 m, respectively; FWs: 8017 m and 7830 m, respectively; WMs: 8187 m and 7941 m, respectively), and MIR (CDs: 1569 m and 1577 m, respectively; CMs: 2499 m and 2504 m, respectively; FBs: 1843 m and 1925 m, respectively; FWs: 1803 m and 1679 m, respectively; WMs: 2048 m and 1780 m, respectively). As covariates, match outcome and match location did not impact TD, LIR, MIR and HIR (tables 1 and 2).

TABLE 1. Descriptive statistics for MRP of players from BFLTs and N-BFLTs while controlling influence of match outcome and match location (data are given as mean ± SD).

	Central defenders		Central midfielders		Fullbacks		Forwards		Wide midfielders	
	N-BFLT	BFLT	N-BFLT	BFLT	N-BFLT	BFLT	N-BFLT	BFLT	N-BFLT	BFLT
TD (m)	10165 ± 976	10240 ± 758	11815 ± 748	11967 ± 642	10840 ± 936	11069 ± 756	10854 ± 1045	10318 ± 785	11247 ± 911	10843 ± 686
LIR (m)	8013 ± 701	7948 ± 550	8474 ± 396	8470 ± 359	8063 ± 613	8076 ± 502	8017 ± 590	7830 ± 443	8187 ± 581	7941 ± 437
MIR (m)	1569 ± 400	1577 ± 313	2499 ± 487	2504 ± 427	1843 ± 407	1925 ± 326	1803 ± 481	1679 ± 361	2048 ± 423	1780 ± 346
HIR (m)	586 ± 284	716 ± 221	857 ± 328	1001 ± 277	954 ± 287	1072 ± 235	1038 ± 308	811 ± 230	1070 ± 272	1113 ± 204
TD-O (m)	4163 ± 869	3119 ± 732	5031 ± 938	3660 ± 831	4366 ± 873	3148 ± 776	3971 ± 928	2630 ± 716	4691 ± 1198	2972 ± 898
LIR-O (m)	3086 ± 711	2016 ± 637	3183 ± 664	2056 ± 618	2997 ± 709	1963 ± 631	2793 ± 654	1829 ± 504	3175 ± 828	1879 ± 648
MIR-O (m)	747 ± 227	674 ± 181	1368 ± 354	1076 ± 312	891 ± 201	718 ± 170	782 ± 280	550 ± 213	1051 ± 317	672 ± 256
HIR-O (m)	366 ± 152	420 ± 122	498 ± 143	520 ± 135	464 ± 126	469 ± 112	405 ± 145	252 ± 112	446 ± 165	420 ± 129
TD-D (m)	2965 ± 802	4097 ± 646	3382 ± 711	5018 ± 619	3218 ± 865	4572 ± 705	3518 ± 637	4635 ± 478	3289 ± 728	4700 ± 547
LIR-D (m)	2318 ± 641	3305 ± 519	2333 ± 581	3584 ± 504	2202 ± 551	3243 ± 469	2280 ± 571	3310 ± 427	2111 ± 526	3329 ± 412
MIR-D (m)	540 ± 248	607 ± 193	796 ± 278	1065 ± 237	624 ± 284	862 ± 227	717 ± 208	875 ± 157	696 ± 220	826 ± 186
HIR-D (m)	121 ± 160	185 ± 124	258 ± 248	363 ± 209	370 ± 198	471 ± 160	516 ± 209	450 ± 157	491 ± 230	542 ± 180

N-BFLTs – non-big five league teams, BFLTs – big five league teams; TD – total distance, LIR – low intensity running, MIR – moderate intensity running, HIR – high intensity running; TD-O – total distance in offensive phase of game, LIR-O – low intensity running in offensive phase of game, MIR-O – moderate intensity running in offensive phase of game, HIR-O – high intensity running in offensive phase of game; TD-D – total distance in defensive phase of game, LIR-D – low intensity running in defensive phase of game, MIR-D – moderate intensity running in defensive phase of game, HIR-D – high intensity running in defensive phase of game.

TABLE 2. The effect of league on overall MRP while controlling influence of match outcome and match location.

	Central defenders		Central midfielders		Fullbacks		Forwards		Wide midfielders	
	β	95%CI	β	95%CI	β	95%CI	β	95%CI	β	95%CI
TD										
Intercept	10297	(9967;10627)	12028	(11649;12408)	11289	(10876;11701)	10657	(9640;11674)	10930	(10325;11534)
League (N-BFLT)	-75	(-470;321)	-152	(-535;231)	-229	(-658;200)	536	(-462;1534)	404	(-256;1064)
Match outcome (not win)	35	(-214;284)	35	(-287;356)	-254	(-621;113)	-535	(-1631;561)	181	(-502;865)
Location (home)	-149	(-354;56)	-157	(-435;121)	-185	(-492;122)	-143	(-1084;798)	-355	(-883;172)
LIR										
Intercept	7991	(7738;8244)	8609	(8384;8834)	8278	(7995;8561)	8026	(7451;8600)	8034	(7649;8419)
League (N-BFLT)	65	(-220;351)	4	(-203;211)	-13	(-296;271)	187	(-377;751)	245	(-175;666)
Match outcome (not win)	26	(-187;238)	-170	(-373;32)	-269	(-527;-12)	-286	(-905;333)	61	(-372;494)
Location (home)	-112	(-291;68)	-109	(-293;75)	-134	(-354;85)	-105	(-637;427)	-246	(-581;89)
MIR										
Intercept	1615	(1471;1759)	2483	(2222;2745)	1985	(1812;2157)	1823	(1356;2290)	1880	(1612;2148)
League (N-BFLT)	-8	(-170;155)	-5	(-256;247)	-82	(-267;103)	124	(-334;583)	268	(-44;581)
Match outcome (not win)	-56	(-177;65)	91	(-139;322)	-85	(-234;64)	-154	(-657;350)	-85	(-479;309)
Location (home)	-20	(-122;81)	-49	(-255;156)	-34	(-157;88)	-135	(-567;298)	-115	(-382;153)
HIR										
Intercept	668	(569;768)	954	(799;1109)	1037	(905;1170)	805	(506;1104)	1089	(910;1267)
League (N-BFLT)	**-130**	**(-245;-15)**	-144	(-311;23)	-118	(-250;14)	227	(-66;520)	-43	(-240;153)
Match outcome (not win)	71	(-8;151)	77	(-45;198)	74	(-46;194)	-93	(-415;229)	86	(-125;296)
Location (home)	24	(-42;90)	18	(-83;119)	-4	(-105;98)	104	(-174;381)	-36	(-194;121)

β – estimate, CI – confidence interval; TD – total distance, LIR – low intensity running, MIR – moderate intensity running, HIR – high intensity running. Bold text denotes statistical significance of $p < 0.05$.

Players from N-BFLTs on all playing positions covered more TD-O (CDs: 4163 m and 3119 m, respectively; ES (95%CI) = 1.64 (0.98, 2.28), CMs: 5031 m and 3660 m, respectively; respectively; ES (95%CI) = 1.81, (1.06, 2.55), FBs: 4366 m and 3148 m, respectively; ES (95%CI) = 1.49 (0.92, 2.06), FWs: 3971 m and 2630 m, respectively; ES (95%CI) = 1.81 (0.50, 3.07), WMs: 4691 m and 2972, respectively; ES (95%CI) = 1.69 (0.74, 2.61)) and LIR O (CDs: 3086 m and 2016 m; respectively; ES (95%CI) = 1.60 (1.08, 2.12), CMs: 3183 m and 2056 m, respectively; ES (95%CI) = 2.22 (1.36, 3.07), FBs: 2997 m and 1963 m, respectively; ES (95%CI) = 1.56 (0.98, 2.13), FWs: 2793 m and 1829 m, respectively; ES (95%CI) = 1.85 (0.53, 3.12), WMs: 3175 m and 1879 m, respectively; ES (95%CI) = 1.78 (0.83, 2.71)).

In addition, CMs (1368 m and 1076 m, respectively; ES (95%CI) = 1.00 (0.35, 1.65)), FBs (891 m and 718, respectively; ES (95%CI) = 1.08 (0.46, 1.69)), and WMs (1051 m and 672 m, respectively; ES (95%CI) = 1.39 (0.47, 2.28)) from N-BFLTs covered more MIR-O than their counterpart from BFLTs. The FWs (405 m and 252 m, respectively; ES (95%CI) = 1.32 (0.11, 2.50) from N-BFLTs more HIR-O than FWs from BFLTs. As covariates, match outcome and match location did not impact TD, LIR, MIR and HIR (tables 1 and 3).

Players from N-BFLTs on all playing positions covered less TD-D (CDs: 2965 m and 4097 m, respectively; ES (95%CI) = -1.80 (-2.40, -1.19), CMs: 3382 m and 5018, respectively; ES (95%CI) = -2.84 (-3.70, -1.96), FBs: 3218 m and 4572 m, respectively; ES (95%CI) = -2.14 (-2.89, -1.37), FWs: 3518 m and 4635 m, respectively; ES (95%CI) = -2.33 (-3.76, -0.83), WMs: 3289 m and 4700 m, respectively; ES (95%CI) = 2.27 (1.23, 3.28)) and LIR-D (CDs: 2318 m and 3305 m, respectively; ES (95%CI) = -2.09 (-2.76, -1.40), CMs: 2333 m and 3584 m, respectively; ES (95%CI) = -2.69 (-3.54, -1.83), FBs: 2202 m and 3243 m, respectively; ES (95%CI) = -2.48 (-3.27, -1.68), FWs: 2280 m and 3310 m, respectively; ES (95%CI) = -2.38 (-3.83, -0.88), WMs: 2111 m and 3329 m, respectively; ES (95%CI) = -2.64 (-3.71, -1.53)).

In addition, CMs from N-BFLTs covered less MIR-D than CMs from BFLTs (796 m and 1065 m, respectively; ES (95%CI) = -1.23 (-1.92, -0.54)), while FBs from N-BFLTs covered less MIR-D (624 m and 862 m, respectively; ES (95%CI) = -1.12 (-1.75, -0.48)) and HIR-D

TABLE 3. The effect of league on MRP in offensive phase of game while controlling influence of match outcome and match location.

	Central defenders		Central midfielders		Fullbacks		Forwards		Wide midfielders	
	β	95%CI	β	95%CI	β	95%CI	β	95%CI	β	95%CI
TD-O										
Intercept	**3020**	**(2643;3396)**	**3555**	**(3041;4068)**	**3288**	**(2819;3758)**	**2981**	**(2079;3883)**	**3297**	**(2511;4082)**
League (N-BFLT)	1045	(678;1411)	1370	(884;1857)	1218	(801;1635)	1341	(453;2229)	1719	(856;2583)
Match outcome (not win)	229	(-125;583)	296	(-160;752)	-73	(-511;364)	-119	(-1104;866)	-76	(-1017;866)
Location (home)	-31	(-345;282)	-85	(-494;325)	-207	(-596;183)	-582	(-1397;233)	-575	(-1270;121)
LIR-O										
Intercept	1961	(1625;2298)	2045	(1654;2436)	2099	(1717;2480)	2032	(1396;2667)	2205	(1628;2781)
League (N-BFLT)	**1070**	**(763;1378)**	**1126**	**(771;1481)**	**1034**	**(695;1372)**	**964**	**(339;1590)**	**1296**	**(684;1908)**
Match outcome (not win)	186	(-136;509)	99	(-258;455)	-73	(-429;282)	44	(-649;738)	-148	(-805;510)
Location (home)	-77	(-367;212)	-76	(-407;254)	-199	(-515;118)	-451	(-1025;123)	-504	(-1012;4)
MIR-O										
Intercept	654	(567;741)	1018	(826;1209)	770	(670;869)	635	(363;907)	769	(567;970)
League (N-BFLT)	72	(-20;165)	**292**	**(110;475)**	**173**	**(79;267)**	232	(-35;499)	**379**	**(145;612)**
Match outcome (not win)	0	(-77;77)	139	(-30;307)	-56	(-148;35)	-44	(-338;251)	-44	(-295;206)
Location (home)	40	(-26;106)	-22	(-172;129)	-46	(-126;34)	-127	(-377;123)	-148	(-330;34)
HIR-O										
Intercept	376	(317;435)	470	(384;555)	427	(359;495)	305	(164;446)	340	(225;456)
League (N-BFLT)	-54	(-116;9)	-22	(-98;54)	-5	(-65;55)	**154**	**(15;292)**	26	(-96;148)
Match outcome (not win)	46	(-7;99)	64	(-14;142)	53	(-10;116)	-114	(-268;40)	108	(-24;239)
Location (home)	42	(-4;88)	36	(-36;108)	31	(-25;87)	8	(-119;135)	51	(-51;152)

β – estimate, CI – confidence interval; TD-O – total distance in offensive phase of game, LIR-O – low intensity running in offensive phase of game, MIR-O – moderate intensity running in offensive phase of game, HIR-O – high intensity running in offensive phase of game. Bold text denotes statistical significance of $p < 0.05$.

(370 m and 471 m, respectively; ES (95%CI) = -0.69 (-1.31, -0.06)) than their counterparts from BFLTs. As covariates, match outcome had an influence on TD-D for CMs, while match location did not impact TD-D, LIR-D, MIR-D and HIR-D (table 1 and 4).

Table 5 presents a discriminant canonical analysis of multivariate differences in MRP between N-BFLTs and BFLTs. The results show significant differentiation between N-BFLTs and BFLTs in MRP for all players (CanR = 0.80). The LIR-D most greatly contributed to the differentiation for all players (correlation with the discriminant function r = 0.87), with higher occurrence in BFLTs. A discriminant function correctly classified 91% of the cases (94% and 87% for N-BFLTs and BFLTs, respectively). Analysing soccer-specific playing position, significant differentiation between N-BFLTs and BFLTs in MRP was evidenced for CDs (CanR = 0.78), CMs (CanR = 0.79), FBs (CanR = 0.89), and WMs (CanR = 0.80) (i.e., it was not possible analyse FWs due to the limited sample for this position). The LIR-D was highly correlated with discriminant functions for all of them (r = 0.78–0.89), with higher occurrence in BFLTs. The discriminant functions correctly classified 91% of the cases for CDs and CMs, 93% for FBs, and 100% for WMs.

No differences for TD, LIR, MIR, and HIR in won and lost matches were found (all trivial ES). Lower TD-O (moderate ES), LIR-O (moderate ES) and HIR-O (small ES) were evidenced in won matches (3684 m, 2417 m, and 415, respectively) than in lost matches (4184 m, 2806 m, and 456 m, respectively). In addition, greater TD-D (moderate ES), LIR-D (moderate ES), and MIR-D (small ES) were evidenced in won matches (4009 m, 2949 m, and 743 m, respectively) than in lost matches (3433 m, 2454 m, and 671 m, respectively) (Table 6).

Analysis of differences in ball possession between N-BFLTs and BFLTs show that N-BFLTs (mean ± SD: 42.71 ± 7.83%; range: 30–55%) had significantly lower percentage of ball possession ($z = -12.12$, $p < 0.01$) than BFLTs (mean ± SD 62.21 ± 5.51%; range: 47–70%).

DISCUSSION

This study was the first to examine differences in MRP between the most elite soccer players (i.e., from BFLTs) and their counterparts from lower-standard teams (i.e., from N-BFLTs) who competed in the UCL while controlling for the influence of contextual factors. The

TABLE 4. The effect of league on MRP in defensive phase of game while controlling influence of match outcome and match location.

	Central defenders		Central midfielders		Fullbacks		Forwards		Wide midfielders	
	β	95%CI	β	95%CI	β	95%CI	β	95%CI	β	95%CI
TD-D										
Intercept	4162	(3844;4480)	5191	(4817;5565)	4658	(4264;5052)	4534	(3914;5154)	4746	(4268;5224)
League (N-BFLT)	**-1132**	**(-1463;-801)**	**-1636**	**(-2001;-1270)**	**-1354**	**(-1752;-955)**	**-1116**	**(-1725;-508)**	**-1412**	**(-1936;-887)**
Match outcome (not win)	-170	(-458;119)	**-344**	**(-669;-19)**	-223	(-579;133)	-261	(-929;407)	-40	(-690;609)
Location (home)	40	(-211;291)	-1	(-286;285)	50	(-253;352)	463	(-112;1037)	-51	(-489;387)
LIR-D										
Intercept	3318	(3061;3576)	3690	(3385;3994)	3310	(3033;3588)	3283	(2729;3837)	3328	(2962;3695)
League (N-BFLT)	**-987**	**(-1252;-722)**	**-1251**	**(-1550;-953)**	**-1041**	**(-1300;-782)**	**-1030**	**(-1574;-487)**	**-1218**	**(-1607;-829)**
Match outcome (not win)	-155	(-391;80)	-262	(-526;2)	-206	(-464;51)	-268	(-864;329)	-38	(-456;380)
Location (home)	129	(-76;334)	51	(-181;284)	72	(-154;298)	323	(-191;836)	39	(-284;362)
MIR-D										
Intercept	657	(571;743)	1086	(949;1223)	876	(760;991)	862	(660;1065)	843	(705;981)
League (N-BFLT)	-66	(-167;34)	**-269**	**(-411;-127)**	**-238**	**(-367;-108)**	-157	(-356;42)	-130	(-295;35)
Match outcome (not win)	-52	(-120;16)	-37	(-150;75)	-38	(-133;58)	-20	(-238;199)	-25	(-245;195)
Location (home)	-48	(-105;9)	-4	(-100;92)	11	(-66;88)	44	(-143;232)	-9	(-161;143)
HIR-D										
Intercept	197	(145;250)	394	(286;503)	468	(382;554)	394	(191;598)	572	(412;732)
League (N-BFLT)	-64	(-129;1)	-105	(-232;22)	**-100**	**(-191;-10)**	66	(-134;266)	-52	(-222;119)
Match outcome (not win)	4	(-32;41)	-25	(-97;47)	13	(-63;89)	23	(-197;242)	-12	(-194;171)
Location (home)	-29	(-58;1)	-37	(-93;20)	-8	(-72;55)	88	(-101;276)	-48	(-189;93)

β – estimate, CI – confidence interval; TD-D – total distance in defensive phase of game, LIR-D – low intensity running in defensive phase of game, MIR-D – moderate intensity running in defensive phase of game, HIR-D – high intensity running in defensive phase of game. Bold text denotes statistical significance of $p < 0.05$.

main findings show that players from BFLTs, in general, achieved a similar overall MRP when compared to players from N-BFLTs, with only CDs from BFLTs achieving greater HIR than CDs from N-BFLTs in HIR. In addition, players from BFLTs on all playing positions achieved greater TD-D and LIR-D, and lower TD-O and LIR-O than players from N-BFLTs.

In pursuit of reaching elite match-play, authors have repeatedly tried to identify MRP that characterize elite players and distinguish them from their counterparts from lower-standard teams [28–31]. For example, it was reported that lower distances were covered in total- and high-intensity running (≥ 19.8 km·h-1) in higher-rated teams compared with lower-standard divisions [28, 29]. On the other hand, older studies have shown that players at a higher standard of play perform more high-intensity running than their peers at lower standards [30, 31]. The possible explanation for such contrasting findings in the literature might be the use of different methods to determine competitive levels. Moreover, none of these studies controlled for the influence of contextual factors, which have been repeatedly demonstrated to affect MRP [15]. In the current study, when the influence of match location and match outcome (i.e., as most influential contextual factors in UCL matches [11]) was controlled for, the results showed similar MRP results among the most elite UCL soccer players and their counterparts from lower-standard teams. Specifically, we found similar TD, LIR, MIR and HIR between FBs, CMs, WMs and FWs from BFLTs and N-BFLTs.

Such results indicate that MRP of the most elite and lower-standard soccer players on all playing positions do not differ, with exception for CDs. Namely, CDs from BFLTs achieved greater HIR than CDs from N-BFLTs (moderate effect size). As in general higher standard players have superior technical–tactical qualities [32, 33], it is most likely that CDs from BFLTs, although primarily defensive players, were more involved in offensive actions then their peers from N-BFLTs. Given that this requires their deeper positioning in the opponent's half of the pitch [34], CDs from BFLTs consequently leaving larger spaces behind their backs. Considering that after losing ball in the attack phase, a rapid offensive transition by the opposing team regularly followed [35], CDs should utilize higher running speeds to outperform opponent players and successfully defend this space [34]. This may explain the increased HIR of the most elite CDs.

Taken altogether, it is evident that, overall MRPs were similar among the most elite and lower-standard soccer players. Such

TABLE 6. Comparison of MRPs between won and lost matches

	Lost	Won	ANOVA		Effect size
	Mean ± SD	Mean ± SD	f	p	Cohen's d (95%CI)
TD (m)	10,873 ± 926	10,935 ± 957	0.22	0.64	-0.06 (-0.34, 0.21)
LIR (m)	8089 ± 474	8165 ± 526	1.24	0.27	-0.14 (-0.43, 0.12)
MIR (m)	1905 ± 503	1920 ± 464	0.04	0.83	-0.03 (-0.3, 0.24)
HIR (m)	881 ± 291	853 ± 269	0.5	0.48	0.1 (-0.17, 0.37)
TD-O (m)	4184 ± 1075	3684 ± 931	12.15	0.01	0.54 (0.21, 0.76)
LIR-O (m)	2806 ± 830	2417 ± 732	12.24	0.01	0.53 (0.21, 0.76)
MIR-O (m)	922 ± 355	852 ± 278	2.28	0.13	0.25 (-0.06, 0.48)
HIR-O (m)	456 ± 145	415 ± 112	4.73	0.03	0.37 (0.03, 0.57)
TD-D (m)	3433 ± 847	4009 ± 1057	20.55	0.01	-0.54 (-0.9, -0.35)
LIR-D (m)	2454 ± 643	2949 ± 824	25.8	0.01	-0.6 (-0.98, -0.42)
MIR-D (m)	671 ± 240	743 ± 258	4.49	0.04	-0.28 (-0.57, -0.02)
HIR-D (m)	308 ± 205	317 ± 205	0.09	0.77	-0.04 (-0.32, 0.23)

Note: TD – total distance, LIR – low intensity running, MIR – moderate intensity running, HIR – high intensity running; TD-O – total distance in offensive phase of game, LIR-O – low intensity running in offensive phase of game, MIR-O – moderate intensity running in offensive phase of game, HIR-O – high intensity running in offensive phase of game; TD-D – total distance in defensive phase of game, LIR-D – low intensity running in defensive phase of game, MIR-D – moderate intensity running in defensive phase of game, HIR-D – high intensity running in defensive phase of game

TABLE 5. Multivariate differences between N-BFLTs and BFLTs in MRP defined by discriminant canonical analysis.

	CD	CM	FB	WM	All
	Root	Root	Root	Root	Root
LIR	0.06	-0.01	-0.03	-0.15	0.05
MIR	-0.03	0.02	-0.09	-0.17	0.02
HIR	-0.20	-0.19	-0.13	0.01	-0.10
LIR-O	0.63	0.56	0.60	-0.46	0.64
RUN-O	0.19	0.33	0.39	-0.35	0.25
HIR-O	-0.14	-0.03	0.02	-0.15	0.02
LIR-D	-0.78	-0.79	-0.89	0.80	-0.87
RUN-D	-0.22	-0.38	-0.46	0.21	-0.30
HIR-D	-0.21	-0.20	-0.23	0.08	-0.14
CanR	0.81	0.85	0.79	0.89	0.80
Wilks Lambda	0.35	0.27	0.36	0.20	0.35
p	0.001	0.001	0.001	0.001	0.001
C: N-BFLT	1.03	1.17	0.96	-1.41	1.03
C: BFLT	-1.77	-2.22	-1.76	2.55	-1.79

Note: CanR – canonical correlation; Root – structure of the discriminant function/root; C – centroid; N-BFLTs – non-big five league teams, BFLTs – big five league teams; TD – total distance, LIR – low intensity running, MIR – moderate intensity running, HIR – high intensity running; TD-O – total distance in offensive phase of game, LIR-O – low intensity running in offensive phase of game, MIR-O – moderate intensity running in offensive phase of game, HIR-O – high intensity running in offensive phase of game; TD-D – total distance in defensive phase of game, LIR-D – low intensity running in defensive phase of game, MIR-D – moderate intensity running in defensive phase of game, HIR-D – high intensity running in defensive phase of game.

findings are not surprising since previous research demonstrated that MRP in the context of ball possession is a more important determinant of elite (i.e., successful) match-play than pure MRP [22]. Supportively, comparison of MRPs between won and lost matches from current study showed that successful match-play (i.e., won matches) was characterized by similar overall MRPs, decreased MRPs in offensive phase of game, and increased MRPs in defensive phase of game. Indeed, in-depth analyses of MRP conducted specifically for the offensive phase of the game (i.e., when the team has ball possession) show that players from BFLTs on all playing positions covered less TD-O and LIR-O than players from N-BFLTs (all large effect sizes), indicating that MRP of the most elite soccer players in the offensive phase of game greatly differ compared with lower-standard players. Considering that results from our study confirm previous findings that higher standard players prefer to maintain ball possession [36], while ball possession strategies consequently enables greater execution of technical-tactical performance [37], such decreased activeness in the offensive phase game among the most elite soccer players game is almost certainly consequence of their greater orientation toward the execution of technical–tactical performance, which is typically related to covering shorter distances [38].

Further analysis of MRP in offensive phase of game revealed another important finding. Specifically, FWs from BFLTs achieved less HIR-O than FWs from N-BFLTs (large effect size). This suggest that the most elite FWs in offensive phase of game did not utilize large amount of HIR. It is possible that most elite FWs in attacking phase of game actually played as "false FWs" (usually known as "false nines") [39]. Typically, when a team has ball possession, such players drop deep into the midfield to search for the ball, which,

consequently, takes opposing CDs out of their defensive line, emptying the area in which CMs or WMs should run. In such cases, FWs do not behave like classic attackers (i.e., utilizing high-intensity running in attacking actions to create goal opportunities for themselves), which, consequently, results in their lower HIR-O.

One of the most robust findings in the current study comes from an analysis of MRP in the defensive phase of the game (i.e., when opponent have ball in possession). In particular, our results show that players from BFLTs on all playing positions achieved greater TD-D and LIR-D than players from N-BFLTs (all large effect sizes), indicating that running characteristics of the most elite soccer players in the defensive phase of game greatly differ compared with lower-standard players. Taking into account previously introduced assumption that higher standard players prefer to utilize ball possession strategies [36], such increased activeness of most elite soccer players in defensive phase of game is probably consequence of their collective attempts to regain ball possession from the opponent [37]. As ball possession strategies consequently enables greater execution of technical-tactical performance [37], which are considered as essential for match success in professional soccer [17], our findings suggest that greater running efforts in the defensive phase of the game are important determinants of the most elite match-play. This can be directly supported with results of canonical discriminant analysis which show that LIR-D most greatly contributed to the differentiation between most elite soccer players (i.e., from BFLTs) and their counterparts from lower-standard teams (N-BFLTs).

It is additionally noteworthy that FBs from BFLTs achieved more MIR-O (large effect size) and HIR-O (moderate effect size) than FBs from N-BFLTs. This suggest that the most elite FBs in defensive phase of covered greater distances at moderate and high intensities, what is most likely consequence of their behaviour in offensive phase of game. Specifically, as higher standard players have superior technical–tactical qualities [32, 33], FBs from BFLTs were probably offensively more engaged than FBs from N-BFLTs. To participate more easily in offensive actions, their positioning is much deeper into the opponent's half. On the other hand, as they are primarily defensive players, FBs travel deeply into their own half of the pitch to participate in defensive actions. Such greater involvement in offensive actions in combination of playing on a large field almost certainly results in greater physical demands (i.e., greater TD-D, LIR-D, MIR-D and HIR-D) observed in defensive phase of game [34].

Limitations

Some limitations should be considered when interpreting these findings. A relatively small number of matches were analysed, with a limited sample of players within certain playing positions. However, this is a very common obstacle in studies involving players who compete in high-level soccer [11]. For methodological reasons, we included only players who played a whole match, which reduced the number of observations and may have affected MRP. As players' technical-tactical performances were not available to confirm some considerations drawn from the current study, future research should analyse technical-tactical performances of the players together with MRP. Finally, for a detailed understanding of the MRPs of the most elite soccer players, future research should consider other contextual factors, such as team formations, match periods, current score, match importance and number of players on the field.

Practical applications

Sports scientists and performance analysts use data on match running performance to mainly aid coaches and practitioners in decision-making processes for structuring the elements of training and subsequent match preparation [40]. This research suggests two main practical applications. Firstly, reaching the most elite soccer match-play require increased efforts when opponent have the ball in possession (i.e., defensive phase of game) for players on all playing positions. Therefore, physical conditioning programmes need to be adapted accordingly, with special emphasize on training drills based on re-possession of the ball. Secondly, as that overall physical performance in highest-level soccer is not related to the playing standard, while highest-level soccer is physically highly demanding [3], optimal physical preparation should be ensured for all players competing in highest-level soccer irrespective playing in higher- or lower-standard teams.

CONCLUSIONS

The findings from this study show that the most elite soccer players on all playing positions experienced similar overall MRP as their peers from lower-standard teams. However, analysing separately offensive and defensive phase of game, noteworthy differences between the most elite soccer players and peers from lower-standard teams could be observed. Specifically, the most elite soccer players on all playing position run less in offensive phase of game, what is almost certainty consequence of their superior ball possession. On the other hand, the most elite soccer players on all playing position run more in defensive phase of game, possibly due to their greater efforts to regain ball possession. This study demonstrated that the most elite match-play in soccer is characterized by increased efforts in defensive phase of game, and decreased efforts in offensive phase of game.

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Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

1. Castellano J, Errekagorri I, Los Arcos A, Casamichana D, Martín-Garcia A, Clemente F, López-Del Campo R, Resta R, Echeazarra I. Tell me how and where you play football and I'll tell you how much you have to run. Biol Sport. 2022; 39(3):607–614.
2. Rampinini E, Impellizzeri FM, Castagna C, Coutts AJ, Wisløff U. Technical performance during soccer matches of the Italian Serie A league: Effect of fatigue and competitive level. J Sci Med Sport. 2009; 12(1):227–233.
3. Modric T, Versic S, Chmura P, Konefał M, Andrzejewski M, Jukic I, Drid P, Pocek S, Sekulic D. Match Running Performance in UEFA Champions League: Is There a Worthwhile Association with Team Achievement? Biology. 2022; 11(6):867.
4. Carling C. Influence of opposition team formation on physical and skill-related performance in a professional soccer team. Eur J Sport Sci. 2011; 11(3):155–164.
5. Clemente FM, Couceiro MS, Martins FML, Ivanova MO, Mendes R. Activity profiles of soccer players during the 2010 world cup. J Hum Kinet. 2013; 38:201.
6. M. Oliva-Lozano J, Gómez-Carmona CD, Fortes V, Pino-Ortega J. Effect of training day, match, and length of the microcycle on workload periodization in professional soccer players: a full-season study. Biol Sport. 2021:397–406.
7. Ju W, Doran D, Hawkins R, Evans M, Laws A, Bradley P. Contextualised high-intensity running profiles of elite football players with reference to general and specialised tactical roles. Biol Sport. 2022; 40(1):291–301.
8. Riboli A, Olthof SB, Esposito F, Coratella G. Training elite youth soccer players: area per player in small-sided games to replicate the match demands. Biol Sport. 2021; 39(3):579–598.
9. Szwarc A, Jaszczur-Nowicki J, Aschenbrenner P, Zasada M, Padulo J, Lipinska P. Motion analysis of elite Polish soccer goalkeepers throughout a season. Biol Sport. 2019; 36(4):357–363.
10. Castellano J, Martin-Garcia A, Casamichana D. Most running demand passages of match play in youth soccer congestion period. Biol Sport. 2020; 37(4):367–373.
11. Modric T, Versic S, Stojanovic M, Chmura P, Andrzejewski M, Konefał M, Sekulic D. Factors affecting match running performance in elite soccer: Analysis of UEFA Champions League matches. Biol Sport. 2022:409–416.
12. Thoseby B, D. Govus A, Clarke A, J. Middleton K, Dascombe B. Positional and temporal differences in peak match running demands of elite football. Biol Sport. 2022:311–319.
13. Bradley PS, Sheldon W, Wooster B, Olsen P, Boanas P, Krustrup P. High-intensity running in English FA Premier League soccer matches. J Sports Sci. 2009; 27(2):159–168.
14. Di Salvo V, Gregson W, Atkinson G, Tordoff P, Drust B. Analysis of high intensity activity in Premier League soccer. Int J Sports Med. 2009; 30(03):205–212.
15. Lago-Peñas C. The role of situational variables in analysing physical performance in soccer. J Hum Kinet. 2012; 35(1):89–95.
16. Milanović Z, Pantelić S, Čović N, Sporiš G, Krustrup P. Is Recreational Soccer Effective for Improving VO_2max A Systematic Review and Meta-Analysis. Sports Med. 2015; 45(9):1339–1353.
17. Lago-Peñas C, Lago-Ballesteros J, Rey E. Differences in performance indicators between winning and losing teams in the UEFA Champions League. J Hum Kinet. 2011; 27:135–146.
18. Harrop K, Nevill A. Performance indicators that predict success in an English professional League One soccer team. Int J Perform Anal Sport. 2014; 14(3):907–920.
19. Bradley PS, Dellal A, Mohr M, Castellano J, Wilkie A. Gender differences in match performance characteristics of soccer players competing in the UEFA Champions League. Hum Mov Sci. 2014; 33:159–171.
20. Di Salvo V, Baron R, González-Haro C, Gormasz C, Pigozzi F, Bachl N. Sprinting analysis of elite soccer players during European Champions League and UEFA Cup matches. J Sports Sci. 2010; 28(14):1489–1494.
21. Miñano-Espin J, Casáis L, Lago-Peñas C, Gómez-Ruano M. High Speed Running and Sprinting Profiles of Elite Soccer Players. J Hum Kinet. 2017; 58:169–176.
22. Modric T, Versic S, Drid P, Stojanovic M, Radziminski Ł, Bossard C, Aftański T, Sekulic D. Analysis of Running Performance in the Offensive and Defensive Phases of the Game: Is It Associated with the Team Achievement in the UEFA Champions League? Appl Sci. 2021; 11(18):8765.
23. Yi Q, Groom R, Dai C, Liu H, Gómez Ruano MÁ. Differences in technical performance of players from 'the big five'European football leagues in the UEFA Champions League. Front Psychol. 2019; 10:2738.
24. Gabbett TJ, Polley C, Dwyer DB, Kearney S, Corvo A. Influence of field position and phase of play on the physical demands of match-play in professional rugby league forwards. J Sci Med Sport. 2014; 17(5):556–561.
25. Kelly DM, Strudwick AJ, Atkinson G, Drust B, Gregson W. Quantification of training and match-load distribution across a season in elite English Premier League soccer players. Sci Med Footb. 2020; 4(1):59–67.
26. Lovell T, Bocking C, Fransen J, Kempton T, Coutts A. Factors affecting physical match activity and skill involvement in youth soccer. Sci Med Footb. 2018; 2(1):58–65.
27. Cohen J, Statistical power analysis for the behavioral sciences. 2013: Academic press.
28. Bradley PS, Carling C, Diaz AG, Hood P, Barnes C, Ade J, Boddy M, Krustrup P, Mohr M. Match performance and physical capacity of players in the top three competitive standards of English professional soccer. Hum Mov Sci. 2013; 32(4):808–821.
29. Di Salvo V, Pigozzi F, González-Haro C, Laughlin M, De Witt J. Match performance comparison in top English soccer leagues. Int J Sports Med. 2013; 34(06):526–532.
30. Andersson HA, Randers MB, Heiner-Møller A, Krustrup P, Mohr M. Elite female soccer players perform more high-intensity running when playing in international games compared with domestic league games. J Strength Cond Res. 2010; 24(4):912–919.
31. Mohr M, Krustrup P, Andersson H, Kirkendal D, Bangsbo J. Match activities of elite women soccer players at different performance levels. J Strength Cond Res. 2008; 22(2):341–349.
32. Yang G, Leicht AS, Lago C, Gómez M-Á. Key team physical and technical performance indicators indicative of team quality in the soccer Chinese super league. Res Sports Med. 2018; 26(2):158–167.
33. Collet C. The possession game? A comparative analysis of ball retention and team success in European and international football, 2007–2010. J Sports Sci. 2013; 31(2):123–136.
34. Modric T, Versic S, Sekulic D. Position Specific Running Performances in Professional Football (Soccer): Influence of Different Tactical Formations. Sports. 2020; 8(12):161.
35. Hewitt A, Greenham G, Norton K. Game style in soccer: what is it and can we quantify it? Int J Perform Anal Sport. 2016; 16(1):355–372.
36. Lago C. The influence of match location, quality of opposition, and match status on possession strategies in professional association football. J Sports Sci. 2009; 27(13):1463–1469.
37. Bradley PS, Lago-Peñas C, Rey E, Gomez Diaz A. The effect of high and low percentage ball possession on physical and technical profiles in English FA Premier League soccer matches. J Sports Sci. 2013; 31(12):1261–1270.

38. Lorenzo-Martinez M, Kalén A, Rey E, López-Del Campo R, Resta R, Lago-Peñas C. Do elite soccer players cover less distance when their team spent more time in possession of the ball? Sci Med Footb. 2021:1–7.
39. Castañer M, Barreira D, Camerino O, Anguera MT, Canton A, Hileno R. Goal Scoring in Soccer: A Polar Coordinate Analysis of Motor Skills Used by Lionel Messi. Front Psychol. 2016; 7:806.
40. Aquino R, Vieira LHP, Carling C, Martins GH, Alves IS, Puggina EF. Effects of competitive standard, team formation and playing position on match running performance of Brazilian professional soccer players. Int J Perform Anal Sport. 2017; 17(5):695–705.

Variability of peak speed and sprinting actions during the same small-sided games: within- and between-player variations inspected over four consecutive weeks

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ABSTRACT: This study aimed to analyze within- and between-player variations of peak speed and sprinting actions occurring in small-sided games (SSGs: 1 v 1 and 5 v 5). The study followed a cohort study design. Twenty male youth soccer players (age: 17 years old) from the same team were observed over four consecutive weeks. Each week, the players participated in two sessions (day one and day two) during which SSGs were applied. The 1 vs. 1 format was employed with four repetitions of thirty seconds interspaced with two-minute rest intervals, while the 5 vs. 5 format with four repetitions of four minutes and two-minute rest intervals between them. The players were monitored during all training sessions with the Polar Team Pro. The peak speed attained in each game, and the number of sprints were extracted as the primary outcomes. The between-player variability revealed a lower coefficient of variations for peak speed in the 1 vs. 1 (13.9%) and 5 vs. 5 (10.9%) formats than for sprints (1 v 1: 64.7%; 5 v 5: 65.5%). Considering the within-player variability, it was observed that sprints were more variable (1 vs. 1: 62.1%; 5 v 5: 65.7%) than peak speed (1 vs. 1: 16.4%; 5 v 5: 14.0%). The between-session analysis revealed that during week 1 (day 1), peak speed was significantly higher than during week 3 (day 1) in the 1 vs. 1 format (+3.0 km/h; $p = 0.031$; $d = 1.296$). Moreover, peak speed during week 3 (day 2) was considerably lower than during week 1 (–5.9 km/h; $p < 0.001$; $d = 1.686$) and week 2 (–5.0 km/h; $p = 0.001$; $d = 1.639$). The between-session analysis showed no significant differences in the sprint between the sessions on day 1 ($p > 0.05$). However, on day two, the sprint was substantially higher during week one than during week four in the 5 vs. 5 format (+5.40 n; $p = 0.002$; $d = 2.571$). In conclusion, this study revealed that peak speed presents lower within- and between-player variability than the number of sprints. Considering these two measures, there are no considerable variations between the weeks. Coaches should consider identifying strategies to stabilize the stimulus regarding the number of sprints if this represents one of the targets for employing SSGs.

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INTRODUCTION

Small-sided games (SSGs) are widely used in soccer training [1]. Among the main reasons they are such a common training tool is the possibility to integrate technical, tactical, and physical stimuli [2] and the constraints manipulation that allows directing adaptation towards training goals [3, 4]. However, as in all game-based training scenarios, small-sided games are subject to intrinsic variability from session to session (between-session variability) and from bout to bout (within-session variability), which might be seen as a threat to this training tool [5]. Although variations in match-related variables, due to the unpredictable nature of match-actions, are extensively reported in the literature [6], enormous variations in players' responses during training sessions with small-sided games might bias training planning. For example, a coach's ability to choose a specific format [7] to nurture a particular physical attribute (e.g.,

accelerations) might be impaired if the same SSG allows players to experience five accelerations per minute in one training session but only one action per minute in the following session. For this reason, it is worth investigating locomotor responses' within- and between-variability when adopting SSGs in soccer training.

Previous studies showed contradictory results on this topic. On the one hand, a recent systematic review indicated that high-intensity locomotor demands presented high between- and within-session variability [8]. However, total distance and distances at low speeds showed small-to-moderate within-session variability. On the other hand, another study revealed that both GPS and accelerometer-based variables showed excellent reliability (low variability) in the between-session analysis [9]. The differences in the study designs and the control of intervening variables might explain the dissimilarities in the results. Further research is required due to the need for more agreement in the literature on this topic.

Although SSGs might present inherent variability, the possibility of manipulating task constraints might affect the variability of responses across multiple trials [10]. For example, it has been shown that physiological responses were less variable in 4 vs. 3 than in the 3-a-side SSG [11]. On the other hand, another study concluded that increasing a format (from 2-a-side to 6-a-side) did not affect the variability of physical responses [12]. However, continuous SSGs showed lower variability when compared to interval formats. Similarly, there were no differences in reliability levels between games with and without the offside rule [9], although the non-offside condition is likely to increase spatial exploration [13]. These variations are not restricted to locomotor responses, as they are also evident in technical [14] and tactical [11] responses. Besides the inconclusive evidence of the influence of the SSG format on the variability of locomotor responses, different SSGs can elicit different responses from players. For example, larger formats are usually associated with larger areas, allowing players to cover distances at higher speeds than smaller formats [15, 16]. This indicates that manipulating the SSG format makes it possible to induce different adaptations from players. Consequently, by investigating the variability of responses of different SSGs – such as 1 vs. 1 and 5 vs. 5 – coaches can be provided with valuable information on which configurations might present more stable responses over time.

While variability might play an important role in youth soccer regarding tactical development [17], it might negatively affect the quality of the training prescription regarding locomotor responses. Previous studies showed that within the same session, players positively change their tactical responses [18]. Consequently, it is expected that within-session variability can be present due to players' adaptability to the task. Additionally, previous studies reported that SSGs could provide adequate stimuli to develop aerobic skills [19, 20]. Therefore, owing to physical improvements over time, between-session variability can also be expected, irrespective of the training format. Finally, as players tend to have more options to act and explore larger areas in larger formats, the format may affect variability and lower locomotor variations in smaller formats. Based on this

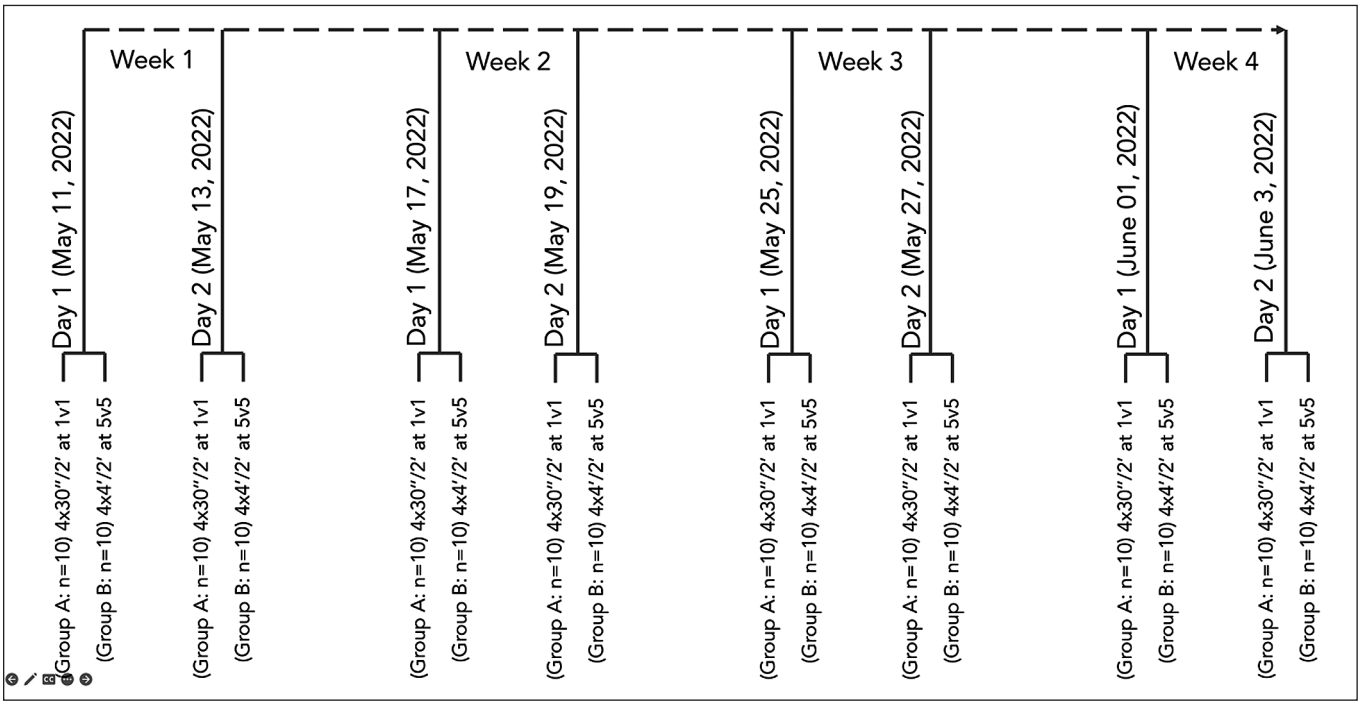


FIG. 1. Timeline of the study.

rationale, the aims of the study are twofold. Firstly, to investigate the within- and between variability in peak speed and sprinting actions during small-sided soccer games, and secondly, to compare variability between 1 vs. 1 and 5 vs.5. The formats were selected because the 1 vs. 1 represents the minimum format occurring in SSG (a duel) in which individual participation is exacerbated. The 5 vs. 5 was selected considering that it is one of the most typical formats employed in SSGs representing medium sided-game typically used for imposing a high metabolic effort while having the opportunities to explore the main tactical and collective principles of play and in which the individual participation is regulated for the collective dynamics.

MATERIALS AND METHODS

Study design

The current research followed a repeated measures design in which the same participants took part in each condition of the independent variable (format of SSGs). Half of the participants were enrolled in performing the 1 vs. 1 format two days (day one and day two) a week over four consecutive weeks, while the other half completed the 5 vs. 5 format two days (day one and day two) a week over four consecutive days.

Setting and context

Figure 1 presents the timeline of the study. The observation period started on May 11, 2022, and ended on June 3, 2022. The sessions began at the same time (5 pm) and were preceded by 24-h rest. The sessions always occurred at the same pitch (synthetic turf). The environmental conditions were as follows: May 11, temperature 23º and relative humidity 65%; May 13, temperature 21º and relative humidity 57%; May 17, temperature 26º and relative humidity 63%; May 19, temperature 19º and relative humidity 67%; May 25, temperature 17º and relative humidity 65%; May 27, temperature 16º and relative humidity 62%; June 01, temperature 28º and relative humidity 43%; and June 03, temperature 14º and relative humidity 68%.

Participants

A convenience sampling method was employed. The sample size was calculated a priori in G*power (version 3.1.9.6.). For power = 0.80, effect size = 0.5 (medium), the recommended total sample was 21. The participant recruitment was performed among 23 players of the same team. The inclusion criteria for the study were as follows: (i) outfield players; (ii) players who participated in all training sessions on the days of data collection (8 training sessions over four consecutive weeks); (iii) players who did not take any drugs or energy drinks, or who did not change any of the daily dietary routines. From an initial group of twenty-three players, twenty male youth soccer players were selected (age: 17 years old; 7.5 ± 1.5 years of experience; 176 ± 5.3 centimeters of stature; 67.4 ± 4.9 kilograms of body mass; final velocity at 30–15 Intermittent fitness test: 19.6 ± 2.1 km/h).

All of them volunteered to participate in the study. Simple randomization was performed to allocate the participants into two groups: a group of the 1v1 format (n = 10; enrolled in 8 sessions of the 1v1 format) and a group of the 5v5 format (n = 10; enrolled in 8 sessions of the 5v5 format). The participants and their legal guardians were introduced to the study design and informed about the risks and benefits of participating. They were also reminded of their right to withdraw from the research without penalty. Once the participants agreed to participate in the study, the guardians signed a consent form. The study followed the ethical standards for medical research involving human subjects described in the Declaration of Helsinki.

Small-sided games

The SSGs were preceded by the FIFA11+ warm-up programme [21]. The 1 vs. 1 and 5 vs. 5 formats was employed over eight sessions (two days a week over four consecutive weeks). One group of players

TABLE 1. Characteristics of the small-sided games.

	1v1	5v5
Scoring method	A small goal (2×2 m) without goalkeeper	A small goal (2×2 m) without goalkeeper
Pitch size	15×10 m	40×30 m
Length: width ratio	1.5	1.3
Area per player	75 m^2	120 m^2
Repetitions per session	4	4
Time per repetition	30 seconds	4 minutes
Rest between repetitions	2 minutes	2 minutes
Mode of rest	Passive	Passive
Verbal encouragement	No	No
Specific rules	No offside rule; Ball reposition with the foot	No offside rule; Ball reposition with the foot

(n = 10) performed only the 1 vs. 1 format, while the other group (n = 10) only used the 5 vs. 5 format. The characteristics of the 1 vs. 1 and 5 vs. 5 formats are presented in Table 1. The players were divided into teams based on the perception level of quality defined by the coach. The same players always had the same opponents and teammates (in the case of 5v5). [21]No verbal encouragement was given. The players were not provided with a strategic definition.

Monitoring peak speed and number of sprints

The players were monitored with the Polar Team Pro Global Positioning System (10 Hz, Polar, Finland). The devices had been previously tested and were found to have a good validity and reliability level to measure distances covered at different thresholds [22], particularly in determining peak speed [23]. The Polar Team Pro sensors were positioned in the center of each player's chest and fixed with a band. The players always had the same sensor and band to avoid inter-unit variability. For each repetition, the peak speed detected and the number of sprints performed (running action performed at or above 25 km/h) was collected. For each session (day), the highest peak speed of all repetitions and the average number of sprints across repetitions were registered. These were the main outcomes used for further data treatment.

Statistical procedures

The descriptive statistics is presented in a form of mean and standard deviation. The coefficient of variation (expressed as percentage) was also used to determine the between-session variability (heterogeneity of responses between the players) and the within-player variability (heterogeneity of responses of the same player across repeated measures). Normality of the data was checked using the Shapiro-wilk and was confirmed for different days and formats, taking into consideration both main outcomes ($p > 0.05$). Similarly, the Levene's test also confirmed homogeneity of the sample ($p > 0.05$). Based on these assumptions, a mixed ANOVA (time*format of SSGs) was executed to analyze the variations of the main outcomes between the observation days. Partial eta squared () was used as the effect size for the mixed ANOVA. The Bonferroni test was used as post-hoc test. Additionally, the standardized effect size of Cohen (pooled standard deviation method) was executed to estimate the effect size of pairwise comparisons. The statistical procedures were executed in the SPSS software (version 28.0.0.0, IBM, Chicago, USA) for a $p < 0.05$.

RESULTS

Table 2 presents the between- and within-player variability (expressed as coefficient of variation) for the 1 vs. 1 and 5 vs. 5 formats performed over a 4-week observation. The between-player variability (i.e., variability within the format and session) revealed a lower coefficient of variations for peak speed in the 1 vs. 1 (13.9%) and 5 vs. 5 (10.9%) formats than for sprints (1 vs. 1: 64.7%; 5v5: 65.5%). Considering the within-player variability (i.e., variability of the same player across different weeks), it was observed that sprints were more variable (1 vs. 1: 62.1%; 5v5: 65.7%) than peak speed (1 vs. 1: 16.4%; 5v5: 14.0%).

Figure 2 presents the within-player variability of the peak speed over the observation period. The Mixed ANOVA (time*format) revealed no significant influence on the peak speed of day one ($F = 1.463$; $p = 0.246$; = 0.075). However, there was a considerable impact on the peak speed of day two ($F = 3.276$; $p = 0.028$; = 0.154). There were no significant differences in the peak speed of day one between the 1 vs. 1 and 5 vs. 5 formats ($p = 0.385$) and day two ($p = 0.450$). The between-session analysis revealed that week 1 (day 1) had a noticeably higher peak speed than week 3 (day 1) in the 1v1 format (+3.0 km/h; $p = 0.031$; $d = 1.296$). Moreover, week 3 (day 2) had a significantly smaller peak speed than weeks one (–5.9 km/h; $p < 0.001$; $d = 1.686$) and two (–5.0 km/h; $p = 0.001$; $d = 1.639$).

Figure 3 presents the within-player variability of the peak speed over the observation period. The Mixed ANOVA (time*format) revealed no significant influence on the number of sprints of day one ($F = 0.272$; $p = 0.774$; = 0.015) and day 2 ($F = 1.497$; $p = 0.226$; = 0.077). No substantial differences were found in the

TABLE 2. Between- and within-player variability for peak speed and sprinting count in the 1v1 and 5v5 formats.

Outcome	Format	Overall (Mean ± SD)	Overall BPV (CV%)	Overall WPV (CV%)	Day 1 (Mean ± SD)	Day 1 BPV (CV%)	Day 1 WPV (CV%)	Day 2 (Mean ± SD)	Day 2 BPV (CV%)	Day 2 WPV (CV%)
Peak Speed (km/h)	1v1	21.1 ± 3.5	13.9	16.4	20.6 ± 3.1	13.2	15.1	21.7 ± 3.8	14.6	15.9
Peak Speed (km/h)	5v5	21.2 ± 3.1	10.9	14.0	20.2 ± 2.5	11.8	10.8	22.2 ± 3.3	10.0	15.0
Sprint (n)	1v1	5.4 ± 3.7	64.7	62.1	5.2 ± 2.8	52.9	47.7	5.7 ± 4.5	76.5	73.2
Sprint (n)	5v5	5.3 ± 3.8	65.5	65.7	4.6 ± 3.8	76.5	66.5	6.1 ± 3.7	54.2	57.8

BPV: between-player variability (represents the average of coefficient of variation within the format and session); WPV: within-player variability (represents the average of coefficient of variation of each player across the different days analyzed); SD: standard deviation

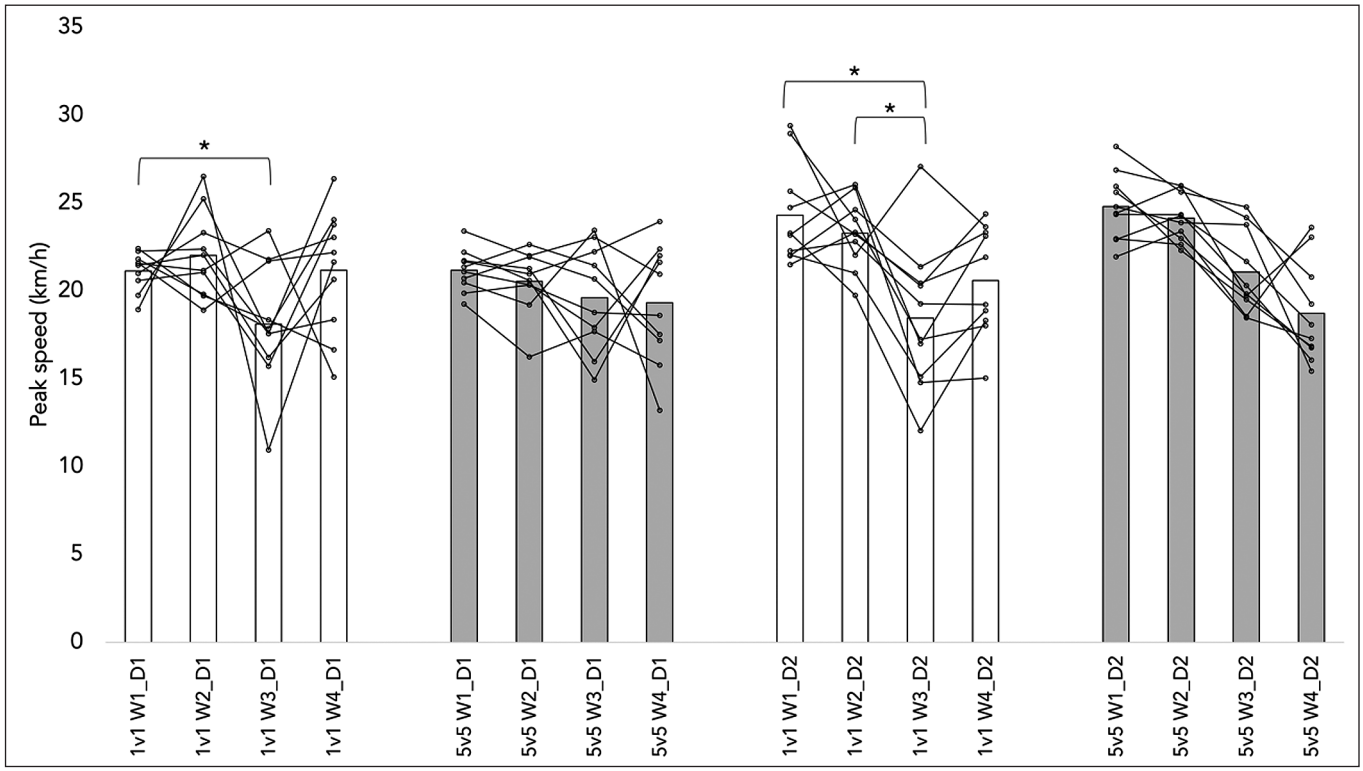


FIG. 2. Within-player variability of peak speed across different formats and sessions analyzed. Legend: W: week; D: day; *: significant difference ($p < 0.05$) in the within-format comparison.

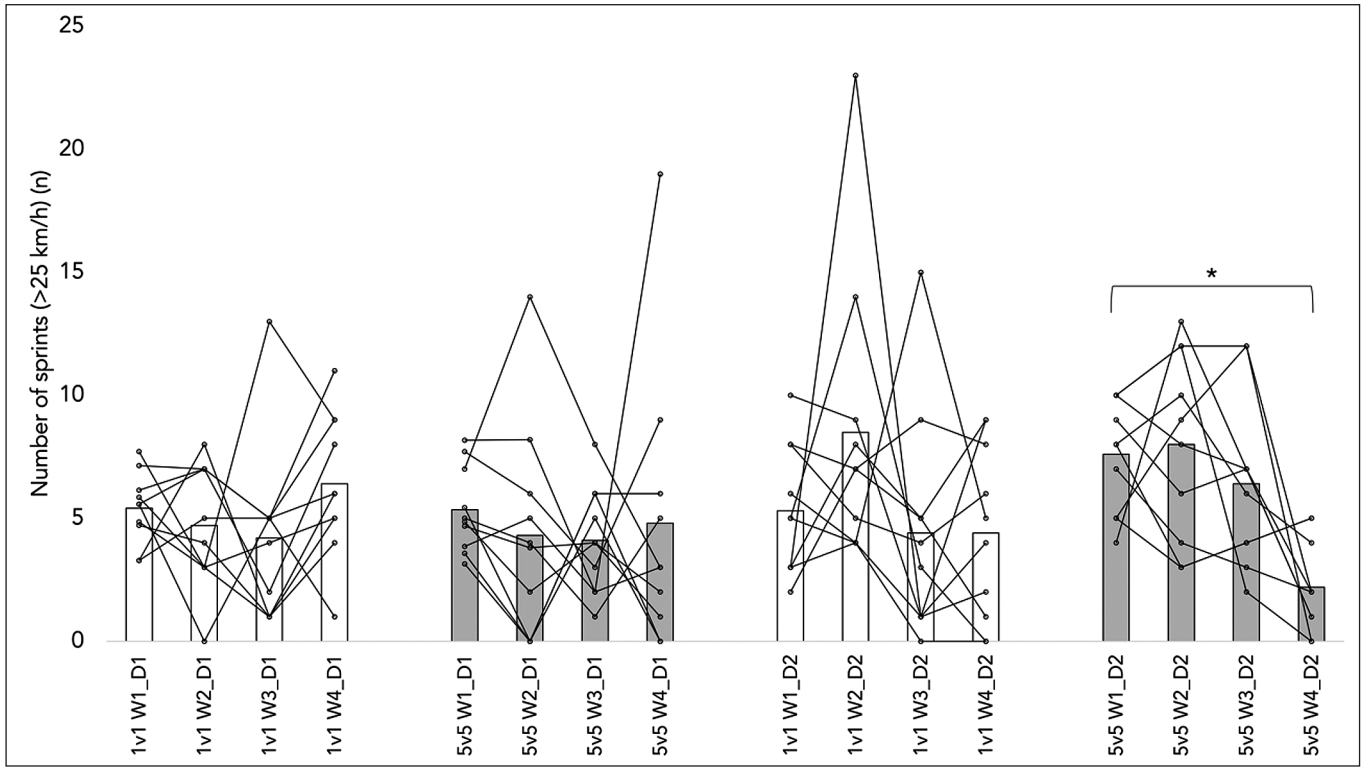


FIG. 3. Within-player variability of a number of sprints across different formats and sessions analyzed. Legend: W: week; D: day; *: significant difference ($p < 0.05$) in the within-format comparison.

number of sprints of day one between the 1 vs. 1 and 5 vs. 5 formats ($p = 0.556$) and day two ($p = 0.576$). The between-session analysis revealed no considerable differences in the number of sprints between the sessions on day one ($p > 0.05$). However, on day two, the number of sprints was significantly higher during week one than during week 4 in the 5v5 format (+5.40 n; $p = 0.002$; $d = 2.571$).

DISCUSSION

The current research revealed that the number of sprints presents higher between- and within-player variability. At the same time, the peak speed seems less variable in both play formats and across the repeated measures considered. Moreover, although considerable punctual differences were observed in the peak speed and the number of sprints between the weeks, most variations were insignificant. Finally, no substantial differences between the formats regarding the peak speed and the number of sprints were found.

Peak speed is one of the measures commonly inspected by sports scientists and coaches to identify a mechanical intensity level to which a player is exposed from a neuromuscular perspective [24, 25]. Peak speed is also a way to promote a mechanical stimulus to promote positive physical adaptation in soccer players [25, 26]. Since SSGs are common tasks coaches use to introduce a physical stimulus, it is important to understand how the between- and within-player variability can occur. The current research revealed that the peak speed presents the between-player variability around 11 and 14% (for the 5v5 and 1v1 formats, respectively) and the within-player variability around 14 and 16% (for the 5v5 and 1v1 formats, respectively). Although no comparative study has been reported, the variability of peak speed in small-sided games, the values registered are good since variability for high-speed running (as an example) usually varies between 45 and 146% [27]. Although the values attained were relatively low (~21 km/h), the variability within- and between players is not high, which is an exciting perspective for coaches. It is well-known that SSGs (notably smaller formats) do not allow a great velocity stimulus since fields are small and do not allow them to achieve high values of speed [28]. However, with the low between-player and within-player variability, it is more expectable for coaches to recognize the dose of stimulus that will be introduced. The fact that the 1 vs. 1 and 5 vs. 5 formats were used also weakened the hypothesis of high heterogeneity since a play is less structured than a bigger format, and players may play more similarly in a field.

The second main outcome analyzed in this research was the number of sprints. In this case, the variability was higher than the peak speed. The between-player variability fluctuated between 55 and 56% of the coefficient of variation, while within-player variability varied between 62 and 66%. Previous studies reported that sprints could vary between 50 and 140% [29]. Although GPS devices may be less accurate and generate greater errors in high-intensity demands, it is also important to mention that 10 Hz GPS is adequate to ensure the quality of the retrieved data [22]. One of the explanations for higher variability in the number of sprints can be the game dynamics which depends on contextual factors such as tactical behavior, match status, and opponent's skills [30]. Therefore, higher variability is expected since the game dynamics may influence exposure to high-demanding running activities. This is also observed in regular official matches [31]. One of the indications that should be disclosed is that coaches must monitor locomotor demands in SSGs to avoid situations of under or over-stimulus. When using SSGs, it is important to monitor and compensate players with less stimulus with additional sprint exposure [24].

The current research also tested repeated measure variations for each of the formats of a play. Although some significant differences were observed, most pairwise comparisons did not reveal considerable changes. This may suggest that the pooled data may have hidden within-player variability, which should be considered an alert for coaches. Looking into the mean may not reveal how the load is floating for each player. Thus it is vital to apply strategies of locomotor demands and monitor to identify the impact of the on each player.

This study presents some limitations. Because a crossover design was not used in the study, it is impossible to identify the effects of testing the same players with other formats. Moreover, the data have been collected from the same team, which does not allow a profound generalization of the findings. Future research should consider the extension of the number of teams included and the identification of how other SSG constraints may play a role in variability. It is also recommended that future research may combine information from situational factors and tactical-technical variables while combining them with variations in locomotor responses. That will open the view for the characterization of the processes that may justify the variability.

However, despite the limitations, the study is one of the few centering research on the peak speed and the number of sprints variability in SSGs, which may help coaches to identify how the exposure of soccer players to this type of event can vary. It is recommended to monitor players during SSGs and to apply compensating strategies to stabilize the stimulus in players that require such attention.

CONCLUSIONS

This study revealed that peak speed presents lower between- and within-player variability than the number of sprints in the 1v1 and 5v5 formats. Moreover, despite some differences in repeated measures over four weeks, most pairwise comparisons did not reveal significant changes in the exposure to the peak speed and the number of sprints. It is recommended that coaches should consider an individual monitoring process during SSGs and stay attentive to the variability of high-intensity demands, such as the number of sprints, to avoid under or over-stimulus for this important indicator.

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REFERENCES

1. Gonçalves L, Camões M, Lima R, Bezerra P, Nikolaidis PT, Rosemann T, et al. Characterization of external load in different types of exercise in professional soccer. Hum Mov. 2022; 23(1):89.95.
2. Clemente FM, Afonso J, Sarmento H. Small-sided games: An umbrella review of systematic reviews and meta-analyses. Boullosa D, editor. PLoS One. 2021; 16(2):e0247067.
3. Woods CT, McKeown I, O'Sullivan M, Robertson S, Davids K. Theory to Practice: Performance Preparation Models in Contemporary High-Level Sport Guided by an Ecological Dynamics Framework. Sports Med Open. 2020; 6(1):1–11.
4. Praça GM, Andrade AGP, Bredt S da GT, Moura FA, Moreira PED. Progression to the target vs. regular rules in Soccer small-sided Games. Sci Med Football. 2021; 6(1):66–71.
5. Clemente F. The Threats of Small-Sided Soccer Games: A Discussion About Their Differences With the Match External Load Demands and Their Variability Levels. Strength Cond J. 2019; 42(3):100–105.
6. Akyildiz Z, Nobari H, González-Fernández FTT, Praça GM, Sarmento H, Guler AH, et al. Variations in the physical demands and technical performance of professional soccer teams over three consecutive seasons. Sci Reports. 2022; 12(1):1–24.
7. Li Z, Mao L, Krustrup P, Randers MB. Internal and external load during 8 v 8, 5 v 5 and 3 v 3 in Chinese elite youth male football players. Biol Sport. 2022; 39(4):1065–71.
8. Clemente FM, Aquino R, Praça GM, Rico-González M, Oliveira R, Silva AF, et al. Variability of internal and external loads and technical / tactical outcomes during small-sided soccer games: a systematic review. Biol Sport. 2022; 39(3):647–72.
9. Custódio IJ de O, Praça GM, Paula LV de, Bredt S da GT, Nakamura FY, Chagas MH. Intersession reliability of GPS-based and accelerometer-based physical variables in small-sided games with and without the offside rule. Proc Inst Mech Eng P J Sport Eng Technol. 2022; 236(2):134–142.
10. Riboli A, Esposito F, Coratella G. Technical and locomotor demands in elite soccer: manipulating area per player during small-sided games to replicate official match demands. Biol Sport. 2023; 40(3):639–47.
11. Bredt, Sarah; Praça, Gibson; Figueiredo, Lucas; Paula, Leandro; Silva, Patrick; Andrade, André; Chagas M. Reliability of physical, physiological and tactical measures in small-sided soccer games with numerical equality and numerical superiority. Rev Bras Cinean Hum. 2016; 18(5):602–10.
12. Hill-Haas S, Coutts A, Rowsell G, Dawson B, Coutts A, Dawson B. Variability of acute physiological responses and performance profiles of youth soccer players in small-sided games. J Sci Med Sport. 2008; 11(5):487–90.
13. Praça GM, Chagas MH, Bredt SGT, Andrade AGP, Custódio IJO, Rochael M. The influence of the offside rule on players' positional dynamics in soccer small-sided games. Sci Med Football. 2021; 5(2):144–9.
14. Clemente FM, Chen YS, Bezerra JP, Guiomar J, Lima R. Between-format differences and variability of technical actions during small-sided soccer games played by young players. Hum Mov. 2018; 19(5):114–20.
15. Clemente FM, Praca GM, Teles Bredt S da G, van der Linden I CM, Serra-Olivares J. External load variations between medium- and large-sided soccer games: ball possession games vs regular games with small goals. J Hum Kinet. 2019; 70(1):191–8.
16. Praça GM, Chagas MH, Bredt SDGT, Andrade AGP de. Small-Sided Soccer Games with Larger Relative Areas Result in Higher Physical and Physiological Responses: a Systematic and Meta-Analytical Review. J Hum Kinet. 2022; 81(1):163–76.
17. Caso S, van der Kamp J. Variability and creativity in small-sided conditioned games among elite soccer players. Psychol Sport Exerc. 2020; 48:101645.
18. Praça GM, Barbosa GF, Moreira PED, Sousa RBE, Bredt SGT, Chagas MH, et al. Changes in tactical behavior during small-sided and conditioned games performed within a training session. Rev Bras Cinean Hum. 2020; 22:1–11.
19. Halouani J, Chtourou H, Gabbett T, Chaouachi A, Chamari K, Halouani, Jamel; Chtourou, Hamdi; Gabbett, Tim; Chaouachi, Anis; Chamari K. Small-sided games in team sports training: a brief review. J Strength Cond Res. 2014; 28(12):3594–618.
20. Hammami A, Gabbett TJ, Slimani M, Bouhlel E. Does small-sided games training improve physical-fitness and specific skills for team sports? A systematic review with meta-analysis. J Sports Med Phys Fitness. 2018; 58(10):1446–55.
21. Bizzini M, Impellizzeri FM, Dvorak J, Bortolan L, Schena F, Modena R, et al. Physiological and performance responses to the "FIFA 11+" (part 1): is it an appropriate warm-up? J Sports Sci. 2013; 31(13):1481–90.
22. Akyildiz Z, Yildiz M, Clemente FM. The reliability and accuracy of Polar Team Pro GPS units. Proc Inst Mech Eng P J Sport Eng Technol. 2022; 236(2):83–89.
23. Sagiroglu İ, Akyildiz Z, Yildiz M, Clemente FM. Validity and reliability of Polar Team Pro GPS units for assessing maximum sprint speed in soccer players. Proc Inst Mech Eng P J Sport Eng Technol. ahead-of-print.
24. Buchheit M, Simpson BM, Hader K, Lacome M. Occurrences of near-to-maximal speed-running bouts in elite soccer: insights for training prescription and injury mitigation. Sci Med Football. 2021; 5(2):105–10.
25. Thoseby B, D. Govus A, C. Clarke A, J. Middleton K, J. Dascombe B. Between-match variation of peak match running intensities in elite football. Biol Sport. 2022; 39(4):833–8.
26. Beato M, Drust B, Iacono A dello. Implementing High-speed Running and Sprinting Training in Professional Soccer. Int J Sports Med. 2021; 42(4):295–299.
27. Clemente FM, Aquino R, Praça G, Rico-González M, Oliveira R, Silva AF, et al. Variability of internal and external loads and technical/tactical outcomes during small-sided soccer games: a systematic review. Biol Sport. 2021; 3(39):647–72.
28. Castagna C, Francini L, Póvoas SCA, D'Ottavio S. Long-Sprint Abilities in Soccer: Ball Versus Running Drills. Int J Sports Physiol Perform. 2017; 12(9):1256–63.
29. Hill-Haas S, Coutts A, Rowsell G, Dawson B, Coutts A, Dawson B, et al. Variability of acute physiological responses and performance profiles of youth soccer players in small-sided games. J Sci Med Sport. 2008; 11(5):487–90.
30. Buchheit M, Simpson BM. Player-Tracking Technology: Half-Full or Half-Empty Glass? Int J Sports Physiol Perform. 2017; 12(Suppl 2):S2–35–S2–41.
31. Carling C, Bradley P, McCall A, Dupont G. Match-to-match variability in high-speed running activity in a professional soccer team. J Sports Sci. 2016; 34(24):2215–23.

Effective playing time affects physical match performance in soccer: An analysis according to playing position

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ABSTRACT: This study aimed to analyse the influence of effective playing time on physical match performance according to playing position in professional soccer. Official match data from 267 matches (3,731 single observations) during the 2018/2019 season of the German Bundesliga were used and the effective playing time (duration of play after subtracting the time taken up by stoppages, substitutions, injuries, and goals) was captured for each match. The physical match performance parameters total distance, high-intensity distance, sprinting distance, maximum velocity, and accelerations were analysed. Players were categorized as central defender, wide defender, central defensive midfielder, central offensive midfielder, wide midfielder, and forward. Effective playing time influenced physical match performance, with total distance and accelerations ($r = 0.48–0.61$) being the most and high-intensity distance, sprinting distance, and maximum velocity ($r = -0.17–0.03$) the least affected parameters. Players covered on average 10% more total distance and performed 13% more accelerations, while sprinting 7–10% less in matches with long (> 65 min) compared to short (< 50 min) effective playing times. The influence of effective playing time was rather similar between playing positions. Still, physical performance of wide midfielders and forwards partly deviated from the pattern observed in the other positions. Coaches and practitioners should be aware that effective playing time influences physical match performance in the German Bundesliga, while special attention should be given to wide midfielders and forwards. Effective playing time and its general and position-specific effects should be taken into account when interpreting physical match performance, thereby facilitating load management practices and training design.

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INTRODUCTION

The physical match performance of professional soccer players based on parameters such as running at different velocities, sprinting, accelerating, and decelerating has been investigated in a plethora of studies [1, 2]. While an official match lasts for 90 min plus additional time, several interruptions due to substitutions, fouls, injuries, goals, or the ball being out of play commonly occur over the course of a match [3, 4]. Taking these interruptions into account, the net playing time or effective playing time decreases to 52–55 min [5–7]. In this regard, studies have shown that physical match performance (e.g., running distances in different velocity zones per minute) is higher during the effective playing time compared to when the ball is out of play or to total playing time [8–10]. Moreover, considering effective playing time also sheds some light on the typically observed reduction in physical performance during the second half of a match, which has traditionally been linked to fatigue [11]. Here, studies revealed that lower performance in the second half could be explained in large part by the number and length of game interruptions [4] or even that performance was maintained when accounting for these interruptions or effective playing time [7, 12]. However, these results differ according to playing position; e.g., in contrast to other playing positions, forwards seem to reduce their match performance in the second half despite reductions in effective playing being considered [7].

While effective playing time accounts for 62% of total playing time on average, it might range between 49% and 72%, thereby demonstrating considerable variability [3]. Therefore, it seems plausible that physical match performance might differ according to effective playing time. Nevertheless, to date, there is no study investigating this potential association.

Therefore, the aim of this short communication was to analyse the influence of effective playing time on physical match performance in soccer according to playing position based on a full season in a European top league. We hypothesized that physical match performance would be influenced by effective playing time [4, 12] and that there emerged positional differences in the way players adapt to alterations in effective playing time [7, 13]. The results of this

study could facilitate the interpretation of physical match performance in relation to effective playing time, and consequently improve load management practices and training design in professional soccer.

MATERIALS AND METHODS

Study Design

In the present study, official match data from 267 matches during the 2018/2019 season of the German Bundesliga were used to determine the influence of effective playing time on physical match performance according to playing position.

Subjects

A total of 267 out of 306 matches were analysed, as matches including a player dismissal were not considered. Only outfield players who participated in the whole game time (i.e., the full 90 min) of the respective match were included. This led to a maximum of 20 outfield players per match and a total of 474 players and 3,731 separate observations (i.e., a single match performance of one player) that were analysed. All players were distinguished into six different playing positions as follows [14, 15]: central defender (1,130 observations), wide defender (833 observations), central defensive midfielder (563 observations), central offensive midfielder (390 observations), wide midfielder (400 observations), forward (415 observations).

The study was conducted according to the guidelines of the Declaration of Helsinki and was approved by the local ethics committee.

Procedures

All data used in this study are based on match analysis data of the German Bundesliga (DFL Observed Tracking-Data, Bundesliga 2018/2019, Deltatre, Turin, Italy). The data were captured using a Multi-Camera-Tracking System (TRACAB, Chyron Hego, Melville, NY, USA), which has recently been validated for obtaining game analysis data [16]. To assess the physical performance of the players, the parameters total distance [km], high-intensity distance [km], sprinting distance [km], maximum velocity [km/h], and number of accelerations [quantity] were analysed. As with previous studies [17–19], high-intensity distance was defined as 17.00–23.99 km/h and sprinting distance as ≥ 24.00 km/h. The maximum velocity reflects the highest velocity reached throughout a game. One acceleration was counted, when there were positive acceleration values in each frame for ≥ 1.5 s. All definitions are based on the catalogue of the German soccer league [20]. Lastly, the effective playing time of each match was captured, defined as the duration of play after subtracting the time taken up by stoppages, substitutions, injuries, and goals [7, 12].

Statistical Analysis

The data were analysed using SPSS statistical software version 28.0 (IBM SPSS, IBM Corporation, Armonk, NY). Mean values and standard deviations (SD) for physical match performance were calculated at the team level and for each playing position separately.

Pearson's product-moment correlations (r) and 95% confidence intervals were used to determine the association between effective playing time and physical match performance. According to Hopkins [21], the magnitude of the correlation coefficient was considered as trivial ($r < 0.1$), small ($0.1 \leq r < 0.3$), moderate ($0.3 \leq r < 0.5$), large ($0.5 \leq r < 0.7$), very large ($0.7 \leq r < 0.9$), and nearly perfect ($r \geq 0.9$). Lastly, possible differences in physical match performance between effective playing time categories (< 50 min, 50–55 min, 56–60 min, 61–65 min, > 65 min) were analysed using one-way analysis of variance and subsequent Bonferroni post-hoc comparisons.

TABLE 1. Descriptive data for the physical match performance parameters total distance, high-intensity distance, sprinting distance, maximum velocity, and number of accelerations for the total sample and separated by playing position. Results are presented as mean values ± SD.

	Total distance [km]	High-intensity distance [km]	Sprinting distance [km]	Maximum velocity [km/h]	Number of accelerations
Total sample (n = 3,731)	10.94 ± 0.88	1.35 ± 0.37	0.28 ± 0.14	31.02 ± 1.63	495 ± 41
CD (n = 1,130)	10.24 ± 0.64	1.00 ± 0.22	0.19 ± 0.09	30.71 ± 1.68	480 ± 36
WD (n = 833)	10.90 ± 0.66	1.42 ± 0.27	0.36 ± 0.13	31.56 ± 1.47	503 ± 37
CDM (n = 563)	11.60 ± 0.68	1.49 ± 0.33	0.22 ± 0.10	30.22 ± 1.58	518 ± 38
COM (n = 390)	11.72 ± 0.70	1.67 ± 0.29	0.32 ± 0.13	30.92 ± 1.52	507 ± 42
WM (n = 400)	11.34 ± 0.74	1.61 ± 0.28	0.40 ± 0.15	31.72 ± 1.43	499 ± 39
FW (n = 415)	10.86 ± 0.83	1.44 ± 0.32	0.34 ± 0.12	31.28 ± 1.47	469 ± 41

SD – Standard deviation; n = Number of single observations; CD – Central defender; WD – Wide defender; CDM – Central defensive midfielder; COM – Central offensive midfielder; WM – Wide midfielder; FW – Forward.

For the applied statistical procedures, the assumption of a normal distribution was made. The significance level for all statistical tests was set a priori to 0.05.

RESULTS

Descriptive values for each physical match performance parameter according to playing position can be found in Table 1. Effective playing time was 57.45 ± 4.31 min, with a minimum of 47.00 min and a maximum of 70.58 min.

At the team level, moderate to large positive relationships with effective playing time were found for total distance and accelerations, trivial negative relationships for sprinting distance and maximum velocity, and a trivial positive relationship for high-intensity distance. Exemplarily, results for total distance and sprinting distance at the team level are displayed in Figures 1–2.

Wide midfielders demonstrated the smallest positive relationships for total distance and accelerations, as well as the smallest negative relationships for maximum velocity and alongside central offensive midfielders for sprinting distance as compared to the other playing positions. By contrast, forwards were the playing position that showed the largest negative relationships for sprinting distance and maximum velocity (Table 2).

Differences in physical match performance between effective playing time categories were found for all parameters (ANOVA $p < 0.01$) except high-intensity distance (ANOVA $p = 0.43$). Exemplarily, results for total distance and sprinting distance at the team level are displayed in Figures 3–4. Cohen's d effect sizes ranged between 0.52 and 3.18 for total distance, and between 0.00 and 0.50 for sprinting distance.

DISCUSSION

The aim of this short communication was to analyse the influence of effective playing time on physical match performance according to playing position in professional soccer.

TABLE 2. Pearson's r, 95% CI and p-values for correlations between the effective playing time and the physical match performance parameters total distance, high-intensity distance, sprinting distance, maximum velocity, and number of accelerations on a team level and separated by playing position.

		Total distance	High-intensity distance	Sprinting distance	Maximum velocity	Number of accelerations
Whole team	Pearson's r	0.48	0.03	-0.17	-0.13	0.61
(n* = 267)	95% CI	0.41–0.55	-0.06–0.11	-0.25– -0.09	-0.21– -0.04	0.55–0.66
	p-value	< 0.01	0.51	< 0.01	< 0.01	< 0.01
CD	Pearson's r	0.35	-0.02	-0.12	-0.05	0.54
(n = 1,130)	95% CI	0.30–0.40	-0.08–0.3	-0.17– -0.62	-0.11–0.01	0.49–0.57
	p-value	< 0.01	0.45	< 0.01	0.09	< 0.01
WD	Pearson's r	0.32	-0.03	-0.12	-0.06	0.49
(n = 833)	95% CI	0.26–0.38	-0.10–0.04	-0.20– -0.05	-0.13–0.02	0.44–0.53
	p-value	< 0.01	0.45	< 0.01	0.10	< 0.01
CDM	Pearson's r	0.39	-0.02	-0.10	-0.09	0.35
(n = 563)	95% CI	0.32–0.46	-0.11–0.06	-0.18– -0.02	-0.17– -0.01	0.28–0.42
	p-value	< 0.01	0.59	0.02	0.03	< 0.01
COM	Pearson's r	0.34	0.05	-0.03	-0.02	0.42
(n = 390)	95% CI	0.25–0.43	-0.05–0.15	-0.13–0.07	-0.12–0.08	0.33–0.49
	p-value	< 0.01	0.33	0.61	0.66	< 0.01
WM	Pearson's r	0.20	0.01	-0.04	< 0.01	0.34
(n = 400)	95% CI	0.11–0.30	-0.09–0.11	-0.14–0.06	-0.10–0.10	0.25–0.42
	p-value	< 0.01	0.88	0.43	0.99	< 0.01
FW	Pearson's r	0.31	0.09	-0.21	-0.15	0.48
(n = 415)	95% CI	0.22–0.40	-0.01–0.18	-0.30– -0.12	-0.24– -0.05	0.40–0.55
	p-value	< 0.01	0.08	< 0.01	< 0.01	< 0.01

95% CI – 95% Confidence interval; n* = Number of matches; n = Number of single observations; CD – Central defender; WD – Wide defender; CDM – Central defensive midfielder; COM – Central offensive midfielder; WM – Wide midfielder; FW – Forward.

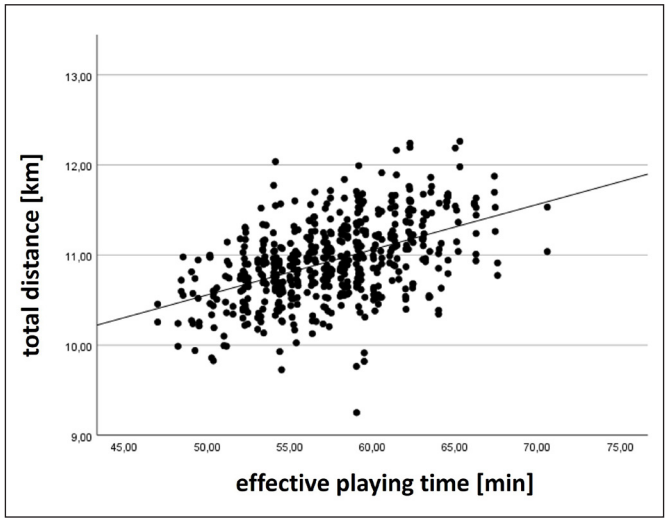


FIG. 1. Relationship between total distance at the team level and effective playing time.

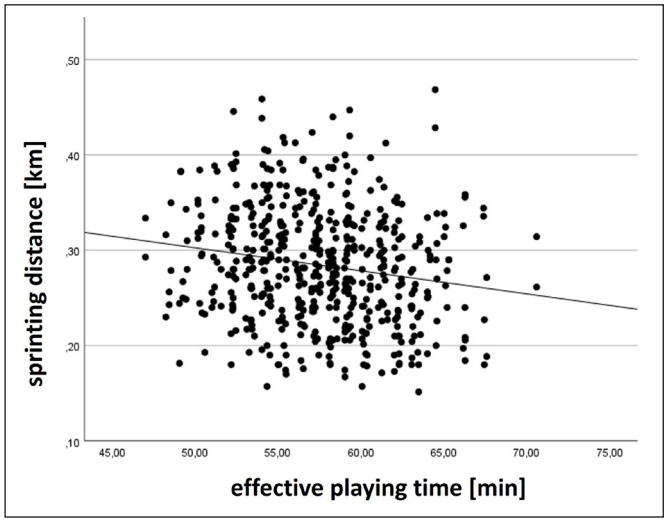


FIG. 2. Relationship between sprinting distance at the team level and effective playing time.

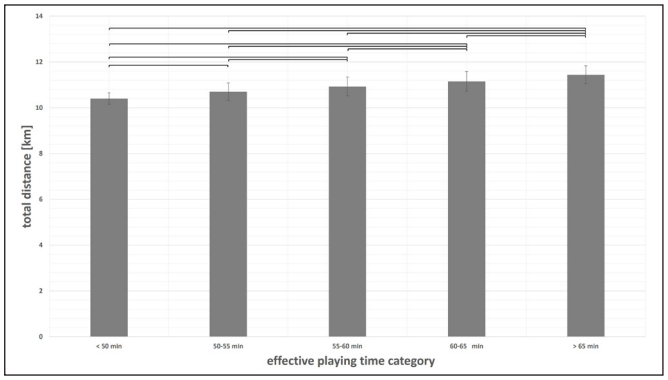


FIG. 3. Total distance at the team level according to effective playing time category presented as mean values ± SD. Braces indicate significant differences between effective playing time categories.

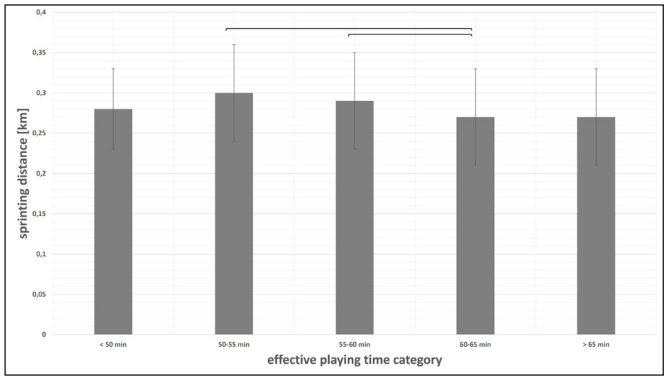


FIG. 4. Sprinting distance at the team level according to effective playing time category presented as mean values ± SD. Braces indicate significant differences between effective playing time categories.

Our main finding was that effective playing time influenced physical match performance, with total distance and accelerations being the most and high-intensity distance, sprinting distance, and maximum velocity the least affected parameters. Therefore, our first hypothesis addressing the general influence of effective playing time can be confirmed. At the positional level, the influence of effective playing time was rather similar between playing positions. Nevertheless, physical match performance of wide midfielders and forwards partly deviated from the pattern observed in the other positions. While wide midfielders typically adjust their total distance and number of accelerations less in order to maintain their sprinting distance and maximum velocity when effective playing time is increased, forwards display the largest losses in sprinting distance and maximum velocity during such scenarios. Hence, our second hypothesis postulating differences between playing positions can only be partially confirmed.

Our findings on physical match performance according to playing position generally support previous studies from other professional European leagues [13, 17, 22–25]. For instance, both central defensive and offensive midfielders as well as wide midfielders covered the greatest total and high-intensity distance [13, 17, 25]. In addition, wide midfielders followed by wide defenders and forwards achieved the greatest sprinting distance, while central defensive midfielders and central defenders covered the shortest distances while sprinting [13, 17, 22, 23]. Deviations in the absolute distances between the present and previous studies might be explained by different definitions of parameters such as high-speed running and sprinting.

The effective playing time during the 2018/2019 season in the German Bundesliga was 57.45 ± 4.31 min on average, which is somewhat longer than what was reported for the Spanish La Liga 2018/2019 (52.3 ± 4.7 min) [7], Italian Serie A 2018/2019 (54 ± 11 min) [6], UEFA EURO 2008 (54.4 ± 4 minutes) [12], and FIFA World Cup 2014 (55.12 ± 5.37 min) [26]. Moreover, effective playing time showed high levels of variability, ranging from a minimum of 47.00 min to a maximum of 70.58 min. This result is well in line with previous evidence from Siegle et al. [3], who reported a range of 49% to 72% of total playing time in the 2009/2010 German Bundesliga season.

Our results further revealed that total distance and number of accelerations increased with increasing effective playing time independently of the playing position. Typically, outfield players cover around 1 km (10%) more total distance and perform 66 (13%) more accelerations in matches with long (> 65 min) compared to short (< 50 min) effective playing times. By contrast, actions executed at higher velocities seem to be less influenced by effective playing time. While there was only a non-significant trivial positive relationship regarding high-intensity distance, statistically significant trivial negative relationships were revealed for sprinting distance and maximum velocity. For example, sprinting distance was on average decreased by 20–30 m (7–10%) during matches with the highest effective playing time. In summary, while players increase their total distance and number of accelerations during matches with a longer effective playing time, high-intensity parameters remain rather stable or even slightly decrease.

One possible explanation for the latter finding might be that matches with shorter effective playing time are characterized by many breaks, allowing the players to recover and subsequently perform more sprints compared to matches with longer effective playing time and fewer breaks to recover. However, without additional data about the match context and the physical capabilities of the players, it remains unclear if this might be due to the players not being able to perform more actions of high intensity or if the typical match context when effective playing time is increased does not pressure them to do so.

When looking at each playing position separately, a rather similar pattern as compared to the one at the team level was evident. Nevertheless, wide midfielders somewhat deviated from this pattern. More specifically, they typically increased their total distance and number of accelerations by a smaller extent with increasing effective playing time, while best maintaining their sprinting distance and maximal velocity output compared to other playing positions. This observation could be interpreted as a pacing strategy of wide midfielders. In matches with short effective playing time, there are many game interruptions that allow the players to recover from preceding high-intensity actions. By contrast, longer effective playing times lead to fewer recovery opportunities, and this might affect playing positions differently. The mentioned wide midfielders are commonly subject to the highest physical match demands of all playing positions, as evidenced by the present results as well as previous studies [7, 13, 17, 25]. As such players do not necessarily possess better physiological capacities (e.g., aerobic endurance) compared to other positions, they might already experience a heavy internal load during matches with conventional effective playing times [27]. During matches with long effective playing time, they therefore might increase total distance and number of accelerations to only small extents in order to save resources for maintaining sprinting distance and maximum velocity, which are of utmost importance for their tactical duties [28]. Such a pacing strategy could not be observed for other positions which mainly showed larger increases in total distance and number of accelerations, while slightly decreasing sprinting distance and maximum velocity. In addition, forwards displayed the largest decreases of all playing positions for sprinting distance and maximum velocity when effective playing time was increased. However, as forwards commonly possess a rather balanced profile in terms of physical match demands [17, 25], more contextual information is needed to explain this finding. Indeed, as the observed differences between playing positions were rather small, these findings should not be overinterpreted.

The main strengths of this investigation are that the analysis was carried out for all teams over a whole season in a top European soccer league and that different playing positions were distinguished, leading to more contextualized results as compared to team analyses only. Moreover, while matches with red cards and players who were not involved in the whole match were excluded from the analysis, thereby leading to high quality of the data in this regard, there are some limitations of this study that should be acknowledged. First, we only looked at the entire match as opposed to distinguishing between playing halves or shorter periods of play (e.g., 15-min sections) [4, 7, 12]. Second, neither contextual factors like venue, opposition quality, or scoreline [5, 29, 30] nor the fitness level of the players were considered [31]. Addressing both aspects seems promising for future studies in order to gain a deeper understanding of the time course of the players' adaptations to altered effective playing times as well as to contextual factors leading to such adaptations.

CONCLUSIONS

Coaches and practitioners should be aware that effective playing time influences physical match performance in the German Bundesliga, with total distance and accelerations being increased, and high-intensity distance, sprinting distance, and maximum velocity being maintained or slightly decreased during matches with long effective playing time. Special attention should be given to wide midfielders, who typically adjust their total distance and number of accelerations less in order to maintain their sprinting distance and maximum velocity when effective playing time is increased, as well as to forwards, who display the largest losses in sprinting distance and maximum velocity during such scenarios. From a practical perspective, effective playing time and its general and position-specific effects should be

taken into account when interpreting physical match performance of professional soccer players. Consequently, the information gained can facilitate load management practices and training design.

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Conflict of Interest

All contributing authors declare that they have no conflicts of interest relevant to the content of this study.

REFERENCES

1. Dolci F, Hart NH, Kilding AE, Chivers P, Piggott B, Spiteri T. Physical and Energetic Demand of Soccer. Strength Cond J. 2020;1. doi:10.1519/SSC.0000000000000533
2. Hands DE, Janse de Jonge X. Current time-motion analyses of professional football matches in top-level domestic leagues: a systematic review. Int J Perform Anal Sport. 2020;20(5):747–65. doi:10.1080/24748668.2020.1780872
3. Siegle M, Lames M. Game interruptions in elite soccer. J Sports Sci. 2012;30(7):619–24. doi:10.1080/02640414.2012.667877.
4. Linke D, Link D, Weber H, Lames M. Decline in Match Running Performance in Football is affected by an Increase in Game Interruptions. J Sports Sci Med. 2018;17(4):662–7.
5. Zhao Y, Zhang H. Effective playing time in the Chinese Super League. Int J Sports Sci Coach. 2021;16(2):398–406. doi:10.1177/1747954120965751
6. Riboli A, Semeria M, Coratella G, Esposito F. Effect of formation, ball in play and ball possession on peak demands in elite soccer. Biol Sport. 2021;38(2):195–205. doi:10.5114/biolsport.2020.98450
7. Rey E, Kalén A, Lorenzo-Martínez M, López-Del Campo R, Nevado-Garrosa F, Lago-Peñas C. Elite Soccer Players do Not Cover Less Distance in the Second Half of the Matches When Game Interruptions Are Considered. J Strength Cond Res. 2020;Publish Ahead of Print. doi:10.1519/JSC.0000000000003935
8. Mernagh D, Weldon A, Wass J, Phillips J, Parmar N, Waldron M, Turner A. A Comparison of Match Demands Using Ball-in-Play versus Whole Match Data in Professional Soccer Players of the English Championship. Sports. 2021;9(6):76. doi:10.3390/sports9060076
9. Wass J, Mernagh D, Pollard B, Stewart P, Fox W, Parmar N, Jones B, Kilduff L, Turner AN. A comparison of match demands using ball-in-play vs. whole match data in elite male youth soccer players. Sci Med Footb. 2020;4(2):142–7. doi:10.1080/24733938.2019.1682183
10. Castellano J, Blanco-Villaseñor A, Alvarez D. Contextual variables and time-motion analysis in soccer. Int J Sports Med. 2011;32(6):415–21. doi:10.1055/s-0031-1271771
11. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sports Sci. 2003;21(7):519–28. doi:10.1080/0264041031000071182
12. Lago-Penas C. The Influence of Effective Playing Time on Physical Demands of Elite Soccer Players. Open Sports Sci J. 2012;5(1):188–92. doi:10.2174/1875399X01205010188
13. Di Salvo V, Baron R, Tschan H, Bachl N, Pigozzi F. Performance characteristics according to playing position in elite soccer. Int J Sports Med. 2007;28(3):222–7. doi:10.1055/s-2006-924294
14. Arjol-Serrano JL, Lampre M, Díez A, Castillo D, Sanz-López F, Lozano D. The Influence of Playing Formation on Physical Demands and Technical-Tactical Actions According to Playing Positions in an Elite Soccer Team. Int J Environ Res Public Health. 2021;18(8). doi:10.3390/ijerph18084148
15. Dellal A, Chamari K, Wong DP, Ahmaidi S, Keller D, Barros R, Bisciotti GN, Carling C. Comparison of physical and technical performance in European soccer match-play: FA Premier League and La Liga. Eur J Sport Sci. 2011;11(1):51–9. doi:10.1080/17461391.2010.481334
16. Linke D, Link D, Lames M. Football-specific validity of TRACAB's optical video tracking systems. PLOS ONE. 2020;15(3):e0230179. doi:10.1371/journal.pone.0230179
17. Altmann S, Forcher L, Ruf L, Beavan A, Groß T, Lussi P, Woll A, Härtel S. Match-related physical performance in professional soccer: Position or player specific? PLOS ONE. 2021;16(9):e0256695. doi:10.1371/journal.pone.0256695
18. Forcher L, Forcher L, Jekauc D, Woll A, Gross T, Altmann S. Center backs work hardest when playing in a back three: The influence of tactical formation on physical and technical match performance in professional soccer. PLOS ONE. 2022;17(3):e0265501. doi:10.1371/journal.pone.0265501
19. Thron M, Härtel S, Woll A, Ruf L, Gross T, Altmann S. Physical match performance and injuries in professional soccer before and after the COVID-19 break. Sci Med Footb. 2021;5(sup1):31–4. doi:10.1080/24733938.2021.1955955
20. Deutsche Fußball Liga (DFL). Definitionskatalog Offizielle Spieldaten: [Definition Catalog Official Match Data]. Document Not Publicly Accessible.; 2019.
21. Hopkins W. A scale of magnitudes for effect statistics. A new view of statistics: Available at: http://www.sportsci.org/resource/stats/effectmag.html. 2002.
22. Radzimiński Ł, Lorenzo-Martinez M, Konefał M, Chmura P, Andrzejewski M, Jastrzębski Z, Padrón-Cabo A. Changes of physical match performance after the COVID-19 lockdown in professional soccer players according to their playing position. Biol Sport. 2022;39(4):1087–93. doi:10.5114/biolsport.2022.114281
23. Sarmento H, Marcelino R, Anguera MT, CampaniÇo J, Matos N, LeitÃo JC. Match analysis in football: a systematic review. J Sports Sci. 2014;32(20):1831–43. doi:10.1080/02640414.2014.898852
24. Oliva-Lozano JM, Muyor JM, Fortes V, McLaren SJ. Decomposing the variability of match physical performance in professional soccer: implications for monitoring individuals. Eur J Sport Sci. 2020;1–29. doi:10.1080/17461391.2020.1842513
25. Bush MD, Barnes C, Archer DT, Hogg B, Bradley PS. Evolution of match performance parameters for various playing positions in the English Premier League. Hum Mov Sci. 2015;391–11. doi:10.1016/j.humov.2014.10.003
26. Augste C, Cordes O. Game stoppages as a tactical means in soccer – a comparison of the FIFA World Cups™ 2006 and 2014. Int J Perform Anal Sport. 2016;16(3):1053–64. doi:10.1080/24748668.2016.11868947
27. Altmann S, Neumann R, Woll A, Härtel S. Endurance Capacities in Professional Soccer Players: Are Performance Profiles Position Specific? Front sports act living. 2020;2122. doi:10.3389/fspor.2020.549897
28. Ade J, Fitzpatrick J, Bradley PS. High-intensity efforts in elite soccer matches and associated movement

patterns, technical skills and tactical actions. Information for position-specific training drills. J Sports Sci. 2016;34(24):2205–14. doi:10.1080/02640414.2016.1217343
29. Paul DJ, Bradley PS, Nassis GP. Factors affecting match running performance of elite soccer players: shedding some light on the complexity. Int J Sports Physiol Perform. 2015;10(4):516–9. doi:10.1123/IJSPP.2015-0029
30. Trewin J, Meylan C, Varley MC, Cronin J. The influence of situational and environmental factors on match-running in soccer: a systematic review. Sci Med Footb. 2017;1(2):183–94. doi:10.1080/24733938.2017.1329589
31. Aquino R, Carling C, Maia J, Vieira LHP, Wilson RS, Smith N, Almeida R, Gonçalves LGC, Kalva-Filho CA, Garganta J, Puggina EF. Relationships between running demands in soccer match-play, anthropometric, and physical fitness characteristics: a systematic review. Int J Perform Anal Sport. 2020;20(3):534–55. doi:10.1080/24748668.2020.1746555.

Core training and performance: a systematic review with meta-analysis

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ABSTRACT: The purposes were to synthesize as much scientific evidence as possible to determine the effect of core training on balance, throwing/hitting velocity or distance, and jumping in healthy subjects, identify the possible differences between isolated and combined core training on performance and study training and sample variables related to performance. PRISMA guidelines were followed, and a systematic search was performed in the Scopus, Web of Science, Sports Discuss, and PubMed databases with no date restrictions until November 2022. The studies were considered for this meta-analysis following PICO; a) randomized control trials and randomized allocation studies with healthy subjects and > 12 years old b)isolated or combined core training programs with a minimum of 4 weeks in length; c) athletic performance outcomes for balance, throw/hit, and jump variables should be measured; d) sufficient data to calculate effect sizes. The Cochrane Collaboration Risk of Bias Tool and the Grading of Recommendations Assessment, Development, and Evaluation approach were used for assessing methodological quality. A total of 3223 studies were identified, 22 studies were included in the systematic review and 21 for the meta-analysis. We observed that core training improved balance outcomes (ES = 1.17; $p < 0.0001$), throwing/hitting velocity (ES = 0.30; $p = 0.14$), throwing/hitting distance (ES = 3.42; $p = 0.03$), vertical jumping (ES = 0.69; $p = 0.0003$), and horizontal jump (ES = 0.84; $p = 0.01$). Our findings indicate that core training improved different variables of performance such as balance, throw/hit, and vertical and horizontal jump.

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INTRODUCTION

The core represents the functional term of the trunk muscles, encompasses the back, abdominal, pelvic floor, diaphragm, hip, and gluteus muscles, and connects the upper and lower extremities. These muscles are responsible for providing stability to the spine and transferring forces from the proximal area to the most distal area of the body [1, 2]. Core research has focused on the study of core stability in injury prevention [3]. Several studies analyze the relationship between stability and core strength with anterior cruciate ligament injury [4], low back pain [5], and hip trochanteritis [6].

Furthermore, it explored how core training affects sports performance [7]. During the last decades, the focus of core study has been placed on performance and the influence of this musculature in actions such as balance, jumping, hitting or throwing, jumping, and running. Granacher et al. observed correlations between trunk muscle strength and balance variables and considered that core strength training is a feasible training program for seniors [8]. Prieske et al. concluded that core training has a small effect on balance and a medium effect on muscle power. Reed et al. concluded that performance in sports movements like a golf swing or running improves with core training and that there is little correlation between core stabilization and performance [9, 10]. However, this review did not focus on any specific indicator of sports performance; instead, the authors examined the effects on general performance, lower-extremity performance, and upper-extremity performance [9].

In addition, core training improves proximal stabilization, essential in sports requiring a high velocity of the distal segment, as in golf, tennis, baseball, handball, football, etc. [11–13]. In these sports, movement patterns are based on sequential kinetic chains and pursue a high final velocity of the distal segment. Via the kinetic chain, angular momentum is transferred from one segment to the other; thus, correct positioning of the pelvis and flexion and torsion movements of the trunk have confirmed the beneficial effects in baseball, handball, volleyball, and tennis [14–20].

A recent meta-analysis examines the effects of trunk muscle training on physical fitness and sport-specific performance in healthy competitive athletes. They found moderate effects on trunk muscle

endurance, linear sprint speed, and change of direction or agility, a large effect on local muscle endurance, small effects on maximal muscle strength, and, finally, moderate effects on sport-specific performance [21]. In addition, lower body muscle power was analyzed including the variable jump, and a small effect in favor of core training was found. However, this study did not take into account the type of jump, horizontal or vertical, to analyze the effect of core training on performance variables.

Even though numerous studies have shown the benefits of core training, whether performed in isolation or combined with lower-extremity exercises, upper-extremity exercises, or both [22–24], the impacts of core training on its own on an individual's performance have not yet been well established. There is great interest in knowing how the core strength acts in the improvement of different performance variables. However, at the moment, an answer to this question has not been obtained. Therefore, this meta-analysis aims to synthesize as much scientific evidence as possible to determine the effect of core training on balance, throwing/hitting velocity or distance and jumping in healthy subjects and identify the possible differences between isolated core training (ICT) and combined core training (CCT) on performance and study intervention and sample variables related to performance.

MATERIALS AND METHODS

A systematic revision was carried out on 7th September 2021 and updated on 22nd November 2022 to search the published scientific evidence and understand how the core training programs affect athletic performance. The protocol for this systematic review was registered on PROSPERO (Registration No: CRD42021281007). The reporting flow diagram of this systematic review was based on the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines [25] (Figure 1).

Search Strategy

Randomized control trials and randomized allocation studies were identified by searching the four electronic databases: Web of Science, SCOPUS, SportDiscuss, and PubMed. Before the bibliographic search, a scoping search was carried out to identify possible keywords. Identifying both Medical Subject Headings (MeSH) terms and the following keywords: "core muscle", trunk, "torso", abdominal, "endurance training," stability, "resistance training," "strength training", "plyometric exercise", "athletic performance", performance, and "physical test". These search terms were combined with two Boolean operators AND, and OR (Supplementary Table 1). The complete search phrase with the Boolean operators was (("core muscle" OR "torso" OR trunk OR abdominal) AND ("endurance training" OR stability OR "resistance training" OR "strength training" OR "plyometric exercise") AND ("athletic performance" OR "physical test")) to identify English or Spanish language original research studies. Also, the bibliographies of other previous related reviews and the selected studies were examined to search for new studies. Other possible scientific evidence related to the subject was identified by emailing the authors of the published articles.

Two independent reviewers (AR-P and WR-F) examined the title/summary of the articles found in the databases. After the initial selection, they analyzed each study with the inclusion criteria. Each criterion was evaluated as yes/no. In case of disagreement among researchers, the consensus approach was used. The authors were familiar with the existing literature and did not have a different bias toward any of the studies selected for inclusion in the review. A new search (n = 418) was performed on November 2022 to find relevant articles and two articles met the inclusion criteria.

Inclusion Criteria

Articles that met the following criteria were included in this review: a) only randomized control trials and randomized allocation studies with healthy subjects > 12 years old were considered for this meta-analysis; b) isolated or combined core training programs with a minimum of four weeks in length; c) athletic performance outcomes for balance, throw/hit, or jump variables should be measured; d) sufficient data to calculate effect sizes (ESs). The articles that met the inclusion criteria were identified, and their full-text versions were obtained.

Articles with one or more of these criteria were excluded: a) legal or illegal ergogenic aids or supplementation were used during interventions; and b) cohort or narrative reviews.

Data Collection Process

All calculations were conducted using Microsoft Excel (Microsoft, Redmond, WA, USA) spreadsheet containing data extracted from each publication. For studies that only reported their data in charts, WebPlotDigitizer version 4.4 was used to obtain the athletic performance values [26]. Review Manager (RevMan) version 5.4.5 was used for all statistical analyses of forest plots. The Cochran Q statistic [27] was used to assess heterogeneity between studies. Heterogeneity is a measure of the differences in main effects between studies. Also, I^2 statistics were used to evaluate heterogeneity ($I^2 > 50\%$).

Core training program effects on athletic performance were calculated for each included study following both groups' coding of post-interventions means and standard deviations (SDs). The standardized mean difference (SMD) was calculated by obtaining the post-intervention means and standard deviations of athletic performance values. Studies were grouped into different subgroups according to moderating variables to determine the effect of these variables on the overall effect size (type of core training, intervention-related variables, and sample-related variables). Data were required to take these forms: a) mean and SDs (pre-and post-intervention); b) 95% confidence interval (CI) data for post-intervention change for each group; or when this was unavailable, c) actual p values for post-intervention change for each group; or if only the level of statistical significance was available, d) default p values (e.g., $p < 0.05$ becomes $p < 0.049$, $p < 0.01$ becomes $p < 0.0099$, and p when not significant becomes

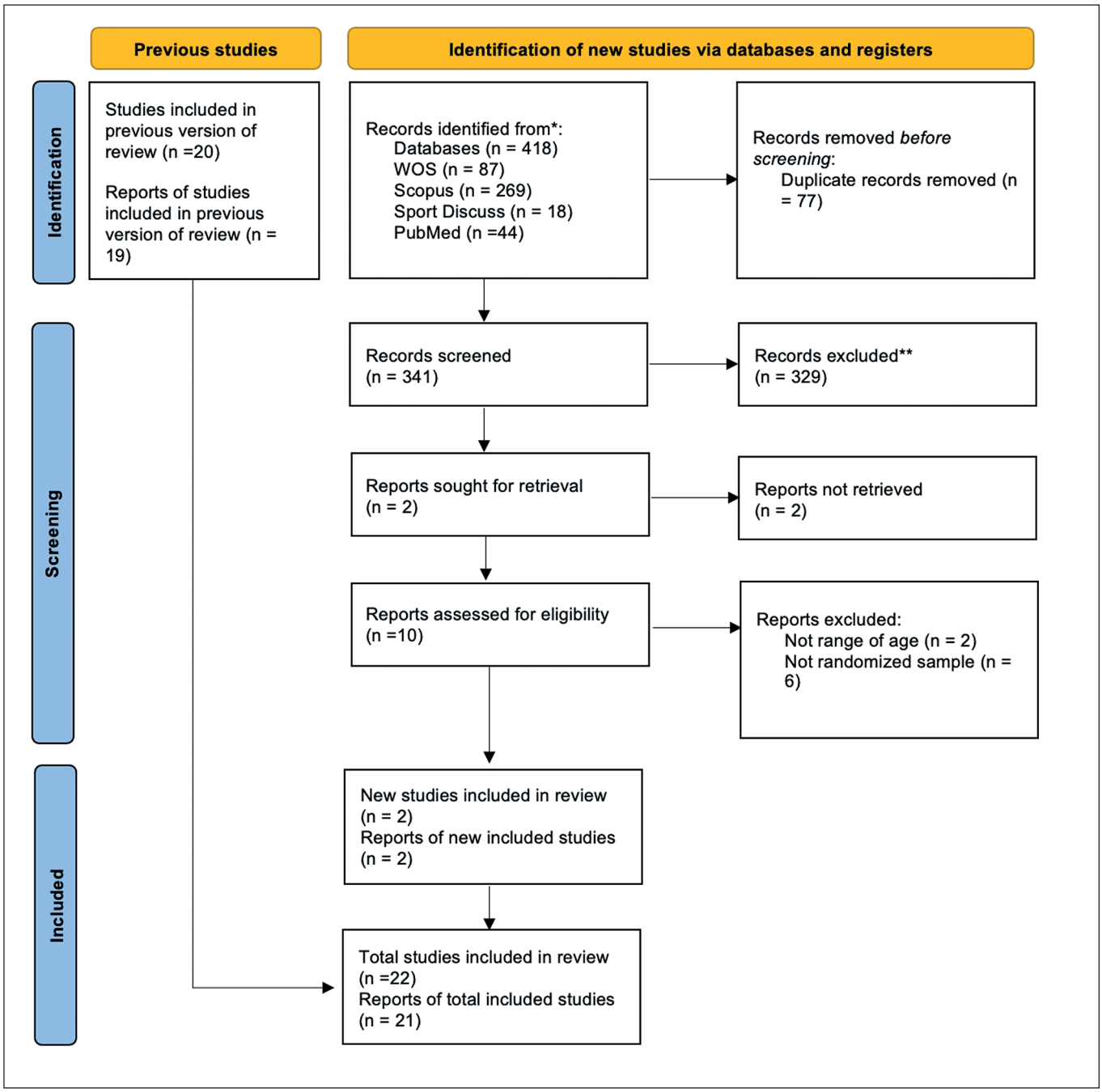


FIG. 1. PRISMA flow diagram for updated systematic reviews.

$p > 0.05$). A random-effects inverse variance (IV) was used to calculate de Standardized Mean Difference (SMD).

The analysis of ES was conducted with a random-effects model estimated using the DerSimonian and Laird method [28]; a random-effects model is incorporated when the assumption is that the effect across studies is randomly situated about a central value. Forest plots were generated to demonstrate the study-specific post-training performance differences and ESs within the respective 95% CIs. Combining estimates then allowed for the assessment of a pooled effect. The reciprocal sums of two variances were accounted for, including the estimated variance associated with the study and the estimated variance component due to the variation between studies. Risk of Bias (RoB) and Grading of Recommendations Assessment, Development and Evaluation approach (GRADE) analysis were conducted to identify the presence of highly influential studies that might have biased the analysis.

The study-specific weight was derived as the inverse of the square of the respective standard errors. The ESs of ≤ 0.2, ≤ 0.5, ≤ 0.8, and ≥ 0.8 were considered trivial, small, moderate, and large, respectively [29].

RESULTS

The flow diagram of this article's search and selection is depicted in Figure 1 with the updated search and the original search (Supplementary Figure 1), from "potentially relevant" to "finally included."

Study Selection

The preliminary search yielded 1929 relevant abstracts and citations. The full text of 53 articles was deemed to meet the inclusion criteria. Of these, 36 studies were rejected for this meta-analysis due to the reasons seen in figure 1, and three studies were included through manual search. Finally, a total of 20 studies met the inclusion criteria [30–49] for one or all athletic performance variables for the revision, and 19 studies met the inclusion criteria for meta-analysis. One article was not included in the meta-analysis because the sample size in the experimental and control groups was not specified [50]. The updated search was conducted in November 2022 and 418 articles were found with only 2 meetings the inclusion criteria [51, 52].

Demographic Characteristics

The studies included 172 participants in balance studies (51.74% male, 30.81% female, and 17.45% not reported), 280 participants in velocities or distance throwing/hitting studies (87.86% male and 12.14% female), and 483 participants in jump studies (54.24% male and 45.76% female). The study that did not report the data was the same study that could not be included in the meta-analysis because it did not indicate the sample size in the control and experimental groups. The age range varied between studies, ten studies evaluated youth (13 ≤ 18 years), and twelve studies evaluated adults (18–65 years). The sample comprises students and athletes who practice different sports such as volleyball, baseball, basketball, golf, tennis, handball, soccer, karate, and gymnastic, and the competitive level ranges from recreational to professional (Table 1).

In balance performance, females and males obtained a large effect (ES = 1.99; ES = 0.98) respectively in favor of core training. In throwing/hitting performance at velocity or distance males had a large effect (ES = 1.42), however, in females only one study analyzed the effect of core training, obtaining a small effect (ES = 0.24) in favor of training. And for jumping performance, females and males obtained a large effect (ES = 0.96; ES = 1.13) respectively in favor of core training. Furthermore, age affected performance, with adults having a large effect on all performance variables (ES > 0.80) except to jump performance (ES = 0.67) and youth having a large effect on balance (ES = 1.00), a small effect on throwing/hitting performance at velocity or distance (ES = 0.35) and a moderate effect on jumping (ES = 0.79) with non-significant differences ($p > 0.05$) (Table 4).

Measures

The three performance variables (balance, throwing/hitting, and jumping) were evaluated with different tests and instruments (Table 1). The most widely used device for measuring velocity or distance throwing/hitting was radar [30, 37, 39, 40, 46]. Three studies used other measurement devices: a motion capture system [15], a portable launch monitor [42], and a photocell array system [44]. The Star Excursion Balance Test (SEBT) was the most used on balance performance, and two studies used the de Y-Balance test [34, 48]. Jump performance was divided into a vertical jump and a horizontal jump, and there were various tests to measure this variable. The most used vertical jump was Counter Movement Jump (CMJ), Squat Jump (SJ), and Sargent Jump test, and to horizontal jump was the Standing Long Jump test (SLJ). The measuring instrument most used was a contact mat [35, 40, 41]. Other instruments used were an OptoJump System [47], a portable force plate [48], takei-brand jump meter [51], and a meter [36].

Training

The training intervention was core strength or core stability exercises, and the control group continued with the standard sports training in most of the studies. In some studies, ICT has been performed [31, 33, 35–38, 40, 42–45], and in others, CCT with plyometric training or lower or upper extremity training [30, 32, 34, 39, 41, 42, 46–48]. The most used implements for this type of training are the swiss ball or medicine ball. The duration of the programs ranged between 4 and 12 weeks, being the most frequent program duration of 6–8 weeks with 2–3 sessions per week. Regarding the training sessions, the time of each session was only specified in 13 articles; in these, it ranged from seven to 60 minutes. Finally, 14 studies were carried out in a period of competition or a rest period (off-season or pre-season), while this timing was not specified in the other cases (Table 2).

Risk of Bias

The risk of bias (RoB) assessment was performed using the Cochrane RoB tool [53]. This tool assesses the RoB according to the following seven domains: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and other sources of bias (Figure 2). Each domain could be considered as "low," "unclear," or "high" RoB. Data extraction and quality assessment were independently performed by two reviewers (AR-P and WR-F). In addition, a third researcher was consulted for the case in which a consensus could not be reached (DM-G).

Rating the quality of evidence

The quality of the evidence was rated using the GRADE approach [54]. GRADE offers four levels of evidence: High, moderate, low, and very low. The GRADE pro system (https://www.gradepro.org) was used for each outcome from the meta-analysis to create a summary of the findings table.

TABLE 1. Demographics characteristic of included studies

Authors	Sample	Sex	Age (years)	Sports	Performance variable
Anant et al., 2020	N = 55 EG = 30 CG = 25	M	EG = 25.3 ± 1.52 CG = 26.4 ± 1.63	Volleyball, basketball, kabaddi, handball, kho-kho and football	Standing Broad Jump Test
Arslan et al., 2021	N = 38 EG = 20 CG = 18	M	EG = 16.30 ± 0.47 CG = 16.5 ± 0.59	Soccer	CMJ, SJ and Y-Balance Test
Bashir et al., 2019	N = 30	-	EG = 15.20 ± 0.41 CG = 15.53 ± 1.06	Tennis	SEBT
Benis et al., 2016	N = 28 EG = 14 CG = 14	F	EG = 20 ± 2 CG = 20 ± 1	Basketball	Y-Balance Test
Dello Iacono et al., 2014	N = 20 EG = 10 CG = 10	M	EG = 18.7 ± 0.67 CG = 19 ± 0.63	Soccer	SEBT
Fadhil et al., 2013	N = 25 EG = 13 CG = 12	M	13.28 ± 0.45	Soccer	SLJ and sargent jump test
Fernandez-Fernandez et al., 2013	N = 30 EG = 15 CG = 15	M	EG = 13.2 ± 0.6 CG = 13.2 ± 0.5	Tennis	Serve velocity
Filipa et al., 2010	N = 16 EG = 9 CG = 7	F	EG = 15.4 ± 1.5 CG = 14.7 ± 0.8	Soccer	SEBT
Kabadayi et al., 2022	N = 29 EG = 16 CG = 13	M-F	EG = 12.75 ± 0.77 CG = 13.00 ± 0.91	Karate	CMJ and SLJ
Karagianni et al., 2020	N = 23 EG = 12 CG = 11	F	EG = 13.2 ± 1.3 CG = 12.3 ± 1.3	Gymnastic	CMJ and DJ
Kuhn et al., 2019	N = 20 EG = 10 CG = 10	F	EG = 24.1 ± 3.8 CG = 23.7 ± 5.2	Handball	Throwing velocity
Lu et al., 2022	N = 183 EG = 92 CG = 91	M-F	EG = 14.59 ± 1.00 CG = 14.46 ± 1.78	Students	Long jump
Manchado et al., 2017	N = 30 EG = 15 CG = 15	M	EG = 18.5 ± 3.0 CG = 18.9 ± 3.8	Handball	Throwing velocity
McCurdy et al., 2014	N = 35 EG = 17 CG = 18	M-F	23.43 ± 5.2 (F) and 27.95 ± 7.5 (M)	Tennis	Serve velocity
Mills et al., 2005	N = 20 EG = 10 CG = 10	F	EG = 20.3 ± 2.0 CG = 19.4 ± 1.7	Basketball and voleyball	Sargent jump test
Mills et al., 2005	N = 20 EG = 10 CG = 10	F	EG = 18.9 ± 1.1 CG = 19.4 ± 1.7	Basketball and voleyball	Sargent jump test
Ozmen et al., 2020	N = 20 EG = 10 CG = 10	M	EG = 14.90 ± 0.31 CG = 14.90 ± 0.56	Handball	Throwing velocity, SEBT and SJ
Sato et al., 2009	N = 20 EG = 12 CG = 8	M-F	EG = 37.75 ± 10.63 CG = 39.25 ± 10.81	-	SEBT
Sharma et al., 2012	N = 40 EG = 20 CG = 20	M-F	EG = 21.8 ± 1.8 CG = 22.4 ± 1.8	Voleyball	CMJ and SJ
Sung et al., 2016	N = 40 EG = 20 CG = 20	M	EG = 23.05 ± 0.5 CG = 24.0 ± 1.0	Golfers	Drive distance
Sung et al., 2016	N = 40 EG = 20 CG = 20	M	EG = 23.2 ± 0.6 CG = 24.0 ± 1.0	Golfers	Drive distance
Szymanski et al., 2007	N = 49 EG = 25 CG = 24	M	EG = 15.3 ± 1.2 CG = 15.4 ± 1.1	Baseball	Bat swing and medicine ball hitter's throw
Taskin 2016	N = 40 EG = 20 CG = 20	F	EG = 19.05 ± 1.15 CG = 18.55 ± 0.76	Soccer	Vertical jump and SLJ
Weston et al., 2013	N = 36 EG = 18 CG = 18	M	47 ± 12	Golfers	Club-head speed

EG = experimental group; CG = control group; M = male; F = female; CMJ = countermovement jump; SJ = squat jump; SLJ = standing long jump; SEBT = Star Excursion Balance Test; DJ = drop jump

TABLE 2. Details of core intervention protocols of included studies.

Study		Training						Core test
Authors	**Design**	**Type of intervention**	**Implements**	**Duration**	**Time (min)**	**Frecuency (days/week)**	**Period of training**	**Measure of core strength**
Anant et al., 2020	RAN	Core muscle strength training	Swiss ball	8 weeks	10–15	5	-	Lateral trunk endurance Curl-up test
Arslan et al., 2021	RAN	Core strength training + small sized games	Without implements	6 weeks	-	3	Off-season	No
Bashir et al., 2019	RAN	Core training program	Swiss ball	5 weeks	-	3	-	No
Benis et al., 2016	RAN	Core stability and plyometrics	Without implements	8 weeks	30	2	-	No
Dello Iacono et al., 2014	RAN	Core stability	Unstable planes	4 weeks	-	5	Season	No
Fadhil et al., 2013	RAN	Core stability, balance, plyometrics and strength	Without implements	12 weeks	20–25	5	Season	Prone Hold Test
Fernandez-Fernandez et al., 2013	RAN	Core training exercises, elastic tubing and medicine ball	Elastic tubing and medicine ball	6 weeks	50	3	Season	No
Filipa et al., 2010	RAN	Core stability and lower extremity	Swiss ball, bosu and airex pads	8 weeks	45	2	Season	No
Kabadayi et al., 2022	RCT	Core strength training program and Sport-specific program	Without implements	8 weeks	30–35	3	Off-season	Flexor, back and lateral endurance test
Karagianni et al., 2020	RAN	Strength training (core + upper limb + lower limbs) and plyometrics	Kettlebell, medicine ball and resistance band	10 weeks	7–9	3	Pre-season	No
Kuhn et al., 2019	RCT	Core stability	Swiss ball	6 weeks	45	2	Season	Swiss Olympic Medical center core performance test battery.
Lu etl al., 2022	RCT	Core strength training + bobby jump	Without implements	12 weeks	7–10	3	-	Core endurance
Manchado et al., 2017	RAN	Strengthening lumbopelvic region	Swiss ball	10 weeks	10–25	3	Season	No
McCurdy et al., 2014	RAN	Core strength and muscular endurance	Medicine ball	8 weeks	15	2	Season	Plank assessment
Mills et al., 2005	RCT	Lumbopelvic stability	Without implements	10 weeks	-	4	-	Lumbopelvic stability
Ozmen et al., 2020	RAN	Core strengthening exercise	Physioball and medicine ball	6 weeks	-	2	Season	No
Sato et al., 2009	RAN	Core strength training	Stability ball	6 weeks	-	4	Season	No
Sharma et al., 2012	RAN	Core strengthening exercise	Without implements	9 weeks	30–40	5	-	Modified double straight leg lowering test
Sung et al., 2016	RAN	Combined strengthening and core exercise	Dumbeell	8 weeks	60	6	Season	Flexion and extension trunk isokinetic strength
Szymanski et al., 2007	RAN	Rotational and full body medicine ball exercise	Medicine ball	12 weeks	-	3	Off-season	Torso rotational strength with isokinetic machine
Taskin 2016	RAN	core training program	Without implements	8 weeks	-	3	-	No
Weston et al., 2013	RAN	Isolated core training	Without implements	8 weeks	-	3	-	Isometric flexor endurance

RAN = randomized allocation; RCT = randomized controlled trial; min = minutes.



FIG. 2. Risk of bias graph and summary.

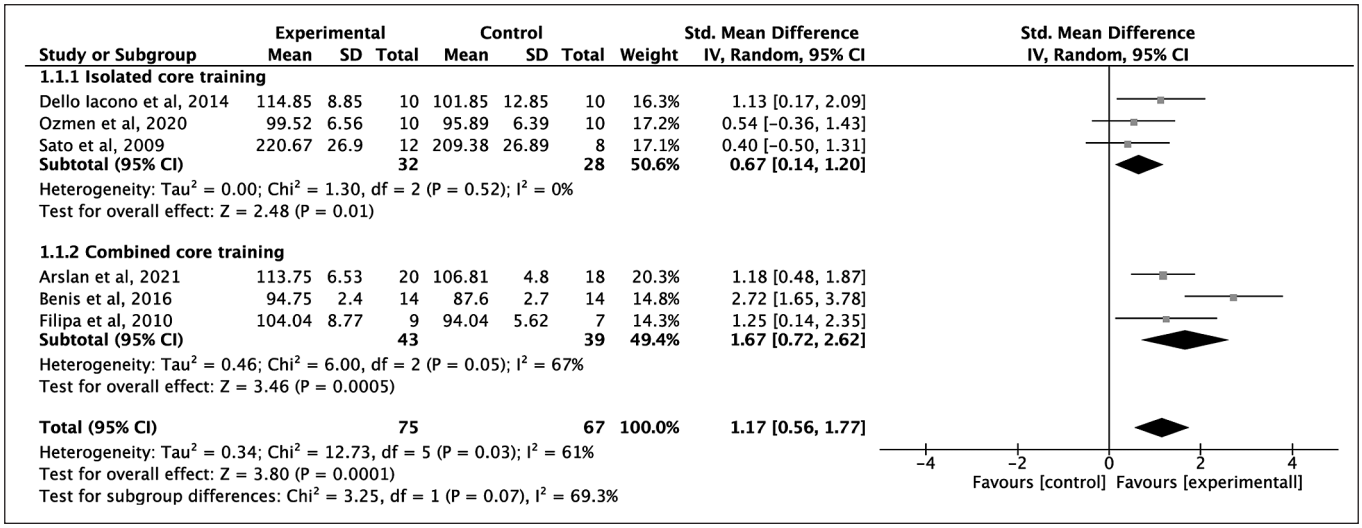


FIG. 3. Forest plot of comparison of balance for isolated core training and combined core training vs control group.

Effects of Core Training Programs on Balance Performance

Between groups, performance differences were assessed via meta-analysis for six included studies. All six studies showed a positive effect of core training on balance and moderate quality of evidence according to the GRADE rating (Table 3). The SMD 1.17 points ($p < 0.001$; $I^2 = 61\%$) indicated large effects in favor of core training with a significant difference (Figure 3). The pooled mean ES estimated balance comprised six treatment groups from 6 studies [31–34, 40, 48] (Table 1).

Six studies, comprising two intervention groups, were included in the analyses to determine the effects of ICT or CCT on balance. The weighted mean SMD of 0.67 ($p = 0.01$; $I^2 = 0\%$) indicated a moderate and significant effect in favor of ICT and the weighted mean SMD of 1.67 ($p < 0.0001$; $I^2 = 61\%$) indicated a large and significant effect in favor of CCT (Figure 3). In terms of intervention-related variables, no significant differences were found between studies ($p > 0.05$) (Table 4).

Effects of Core Training Programs on Throwing/Hitting Performance

Throwing and hitting performance (velocity and distance outcomes) were combined into different subgroup analyses due to potential heterogeneity in results. Seven studies were included to analyze the effects of core training on throwing/hitting velocity with an SMD of

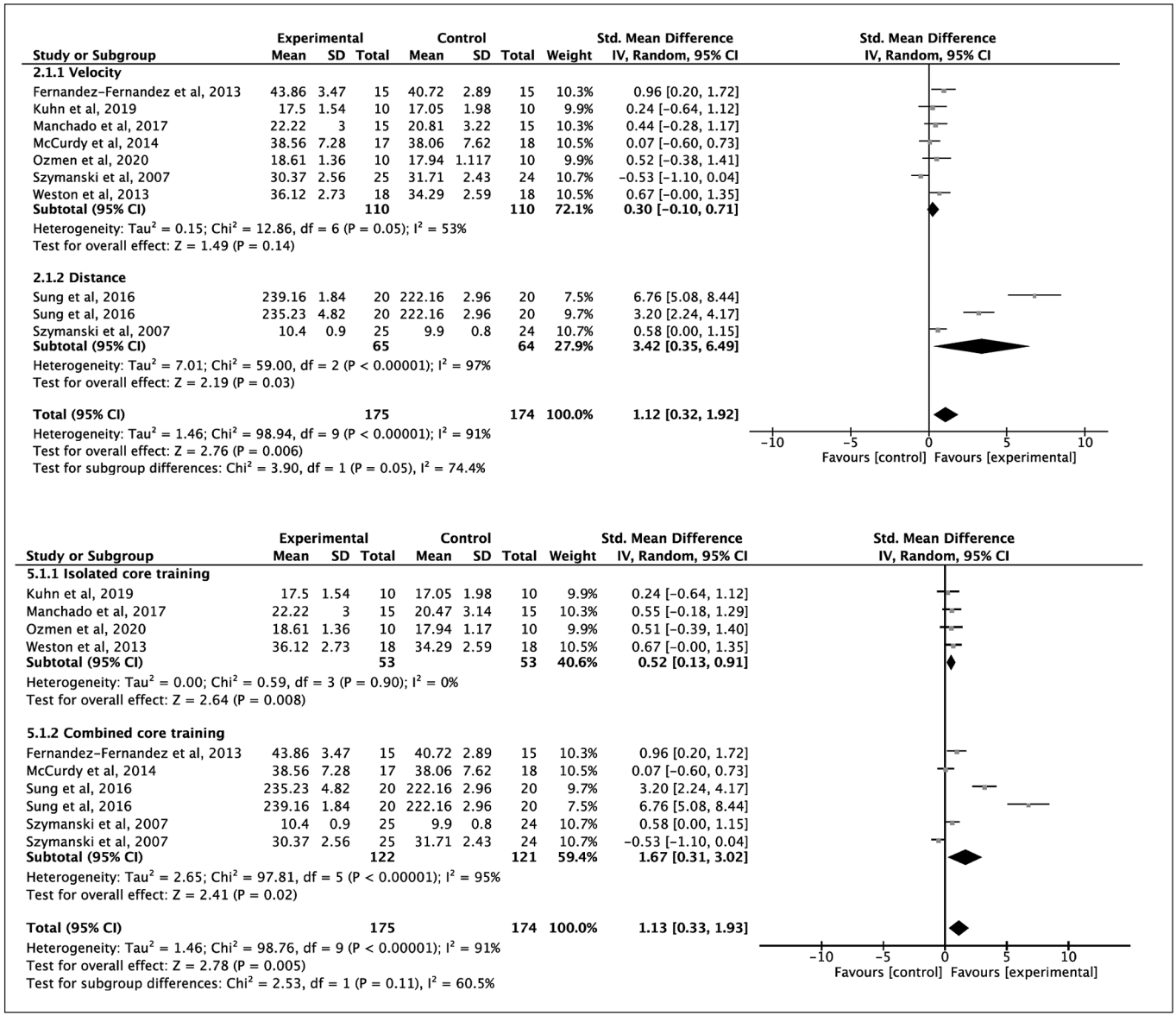


FIG. 4. Forest plot of comparison of throw/hit velocity for core training vs control group and forest plot of comparison of throw/hit distance for core training vs control group (upper figure) and forest plot of comparison of isolated core training vs control group and forest plot of comparison of combined core training vs control group (down figure).

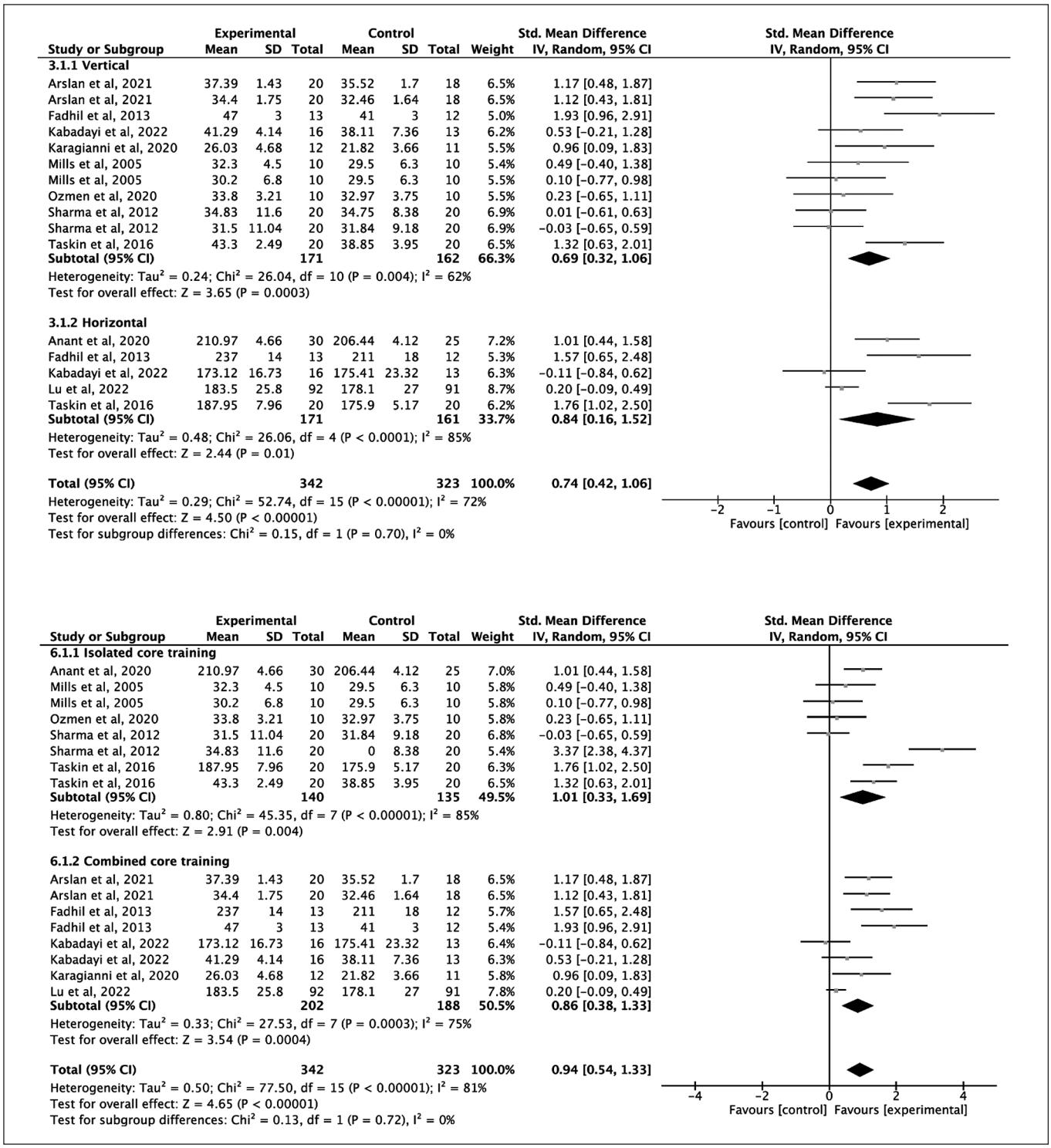


FIG. 5. Forest plot of comparison of vertical jump for core training vs control group and forest plot of comparison of horizontal jump for core training vs control group and (upper figure) and forest plot of comparison of isolated core training vs control group and forest plot of comparison of combined core training vs control group (down figure).

0.30 (p = 0.14; I^2 = 53%) indicating a small but non-significant effect in favor of core training [30, 37, 39, 40, 42, 44, 49]. Two studies analyzed the effect of core on throwing/hitting distance indicating a large and significant effect in favor of core training with SMD of 3.42 points (p = 0.03; I^2 = 97%) [15, 46]. All studies had a positive effect on the core training group except one study [49] (Figure 4 upper). The level of evidence according to the GRADE rating was low (Table 3).

When analyzed by the subgroup of ICT and CCT, four studies performed ICT with a SMD of 0.52 (p = 0.008; I^2 = 0%) indicating a moderate and significant effect in favor of ICT on throwing/hitting performance. Four studies were included in the CCT subgroup with an SMD of 1.67 (p = 0.02; I^2 = 95%) indicating a large and significant effect in favor of CCT for throwing/hitting performance (Figure 4 down).

In terms of intervention-related variables, large and significant effects were obtained with a frequency greater than two days per week (ES = 1.55), greater than 30 minutes (ES = 2.68), and a total volume greater than 16 weeks (ES = 1.55).

Effects of Core Training Programs on Jumping Performance

The jumping performance was divided into two subgroups (vertical and horizontal jumping) for the analysis due to the heterogeneity of the results. Eight studies were analyzed for the vertical jump variable with an SMD of 0.69 points (p = 0.0003; I^2 = 62%) indicating a moderate and significant effect in favor of core training with a [35, 36, 38, 40, 41, 47, 48, 51]. All studies included showed positive effects of core training on vertical jump except for one of the intervention groups in the study by Sharma et al., 2012. For the analysis of horizontal jumping 5 studies were assessed, with the SMD of 0.84 (p = 0.01; I^2 = 85%) indicating a large and significant effect size in favor of core training [36, 41, 43, 51, 52] (Figure 5 upper). The level of evidence according to the GRADE rating was moderate and low quality of evidence, respectively (Table 3).

Furthermore, the effect of ICT and CCT on jumping performance was studied. A SMD of 1.01 (p = 0.004; I^2 = 85%) indicates a large and significant effect in favor of ICT for jumping performance and an SMD of 0.86 (p < 0.001; I^2 = 75%) indicating a large and significant effect size in favor of CCT for jumping performance (Figure 5 down). In terms of intervention-related variables a large and significant effect to equal to or less than 30 minutes per session (ES = 1.05) (Table 4).

TABLE 3. Summary of findings (SoF) and quality of evidence (GRADE) for core training.

Certainty assessment							№ of patients		Effect			
№ of studies	Study design	Risk of bias	Inconsistency	Indirectness	Imprecision	Other considerations	core training	CG	Relative (95% CI)	Absolute (95% CI)	Certainty	Importance
Balance												
6	randomised trials	not serious	serious[a]	not serious	not serious	none	75	67	-	SMD 1.17 SD higher (0.56 higher to 1.77 higher)	⊕⊕⊕◯ Moderate	IMPORTANT
Vertical Jump												
11	randomised trials	not serious	serious[b]	not serious	not serious	none	171	162	-	SMD 0.69 SD higher (0.32 higher to 1.06 higher)	⊕⊕⊕◯ Moderate	IMPORTANT
Horizontal jump												
5	randomised trials	not serious	very serious[c]	not serious	not serious	none	171	161	-	SMD 0.84 SD higher (0.16 higher to 1.52 higher)	⊕⊕◯◯ Low	IMPORTANT
Velocity throw												
7	randomised trials	not serious	serious[d]	not serious	serious[e]	none	110	110	-	SMD 0.3 SD higher (0.1 lower to 0.71 higher)	⊕⊕◯◯ Low	IMPORTANT
Distance throw												
3	randomised trials	not serious	very serious[f]	not serious	not serious[g]	none	65	64	-	SMD 3.42 SD higher (0.35 higher to 6.49 higher)	⊕⊕◯◯ Low	IMPORTANT

CI: confidence interval; SMD: standardised mean difference. Explanations: a. The heterogeneity between studies was substantial (I^2 = 61%); b. The heterogeneity between studies was substantial (I^2 = 62%); c. The heterogeneity between studies was considerable (I^2 = 85%); d. The heterogeneity between studies was substantial (I^2 = 53%); e. Requires a total sample size of approximately 220; f. The heterogeneity between studies was considerable (I^2 = 97%); g. The confidence interval are large (0.35–6.49)

TABLE 4. Effects of intervention-related variables and sample-related variables on performance.

		Balance		Throwing/hitting velocity or distance			Jumping	
Intervention variables	**S**	**ES (p-value)**	**I^2(%)**	**S (EG)**	**ES (p-value)**	**I^2(%)**	**S (EG)**	**ES (p-value)**	**I^2(%)**
Frecuency									
≤ 2 d/w	3	1.48 (0.02)	79	3	0.23 (0.32)	0	1	0.23 (0.61)	NA
> 2 d/w	3	0.95 (0.0001)	0	5(7)	1.55 (0.007)	94	9(15)	0.98 (<0.0001)	82
		p = 0.45			p = 0.03				
Duration									
≤ 6 weeks	4	0.86 (0.0001)	0	3	0.61 (0.01)	0	2(3)	0.90 (0.001)	37
> 6 weeks	2	1.99 (0.007)	72	5(7)	1.41 (0.01)	94	8(13)	0.71 (0.0002)	74
		p = 0.14			p = 0.20			p = 0.57	
Implements									
With implements	4	0.78 (0.001)	0	7(9)	1.21 (0.009)	92	3	0.81 (0.0005)	12
Without implements	2	1.89 (0.01)	82	1	0.45 (0.05)	NA	7(13)	0.74 (0.0001)	76
		p = 0.17						p = 0.81	
Session duration									
≤ 30 minutes	1	2.72 (< 0.0001)	NA	2	0.24 (0.34)	0	4(5)	1.05 (0.002)	81
> 30 minutes	1	1.25 (0.03)	NA	3(4)	2.68 (0.02)	95	2(4)	0.08 (0.65)	0
					p = 0.03			p = 0.01	
Total volume									
≤ 16 sessions	3	1.48 (0.02)	79	3	0.23 (0.32)	0	1	0.23 (0.61)	NA
> 16 sessions	3	0.95 (0.0001)	0	5(7)	1.55 (0.007)	94	9(15)	0.77 (< 0.0001)	73
Sample		p = 0.45			p = 0.03				
Sex									
Female	2	1.99(0.007)	72	1	0.24 (0.59)	NA	3(5)	0.96 (0.001)	61
Male	3	0.98(0.0001)	0	5(7)	1.42 (0.005)	93	4(6)	1.13 (< 0.0001)	35
		p = 0.19						p = 0.63	
Mixed	1	0.40 (0.38)	NA	1	0.07 (0.85)	NA	3(5)	0.72 (0.10)	90
Age									
Youth (12 ≤ 18 years)	3	1.00(0.0001)	0	3(4)	0.35 (0.32)	75	6(9)	0.79 (0.0003)	71
Adults (18–65 years)	3	1.39 (0.04)	81	5(6)	1.74 (0.01)	94	4(7)	0.67 (0.01)	75
		p = 0.58			p = 0.07			p = 0.73	

ES = effect size; S (EG) = number of studies (EG = experimental groups); NA = not applicable; d/w = days per week;

DISCUSSION

This meta-analysis aimed to synthesize as much scientific evidence as possible to determine the effect of core training on balance, throwing/hitting velocity, or distance and jumping in healthy subjects, identify the possible differences between isolated and combined core training on performance and study training, and sample variables related to performance. The main novelty of this meta-analysis was to analyze each performance variable separately. The current results show small to large effects, with significant differences in balance performance, throwing distance, and vertical and horizontal jump, and a small but non-significant effect on throwing velocity, in favor of core training. In addition, ICT and CCT with other types of training (jumps, upper or lower body training) have a moderate to large and significant effect on all performance variables analyzed.

Previous reviews and meta-analyses have focused on trunk muscle training and other performance variables like trunk and local muscle endurance, linear sprint speed and change of direction (COD) or agility, lower limb muscle power, maximal muscle strength, and sport-specific performance. However, when the sports performance variables have been evaluated, they have not been studied independently. Still, different performance variables from various sports such as swimming (time in the 50 m freestyle, time in the flight phase and recovering), handball (throwing velocity), golf (drive distance), athlete (running economy), and soccer (ball shooting speed) have been joined [10, 21]. Therefore, they concluded that the role of core training is more negligible in these variables; although, if these variables are analyzed separately, as has been done in this meta-analysis, core training improves performance.

Moreover, core strength training has been shown to have a small to medium effect on physical fitness and athletic performance measures in trained individuals [10]. In addition, age seems to be a variable that does not affect sports performance, except for COD and agility [21]. Similar results were found in our study, with no significant differences between youth and adults even though the effect sizes were larger for adults in throwing/hitting velocity or distance performance. Neither were significant differences in performance found according to gender. As Reed noted in his 2012 study, not all articles measure core strength or stability before and after intervention [9]. For example, only eleven of the 22 studies included in this review evaluated core strength or stability. In addition, of the studies that analyzed this, only two used the gold standard (isokinetic devices) [46, 49].

Balance

Balance describes the dynamics of the body trying not to fall; therefore, it is crucial for daily life activities and sports [55]. The results of this meta-analysis show a large effect (ES = 1.17; p = 0.0001) in favor of core training groups. In the meta-analysis of Prieske et al., [10], the only balance test taken was the SEBT, and three studies were analyzed, although one of these studies did not perform the SEBT [38]. The results obtained do not agree with our studies, obtaining a small effect size in favor of core strength training. However, in our study, we added balance variables analyzed with the SEBT and the Y-balance test, and a large effect size was obtained in favor of core training.

Since the core muscles surround the center of mass in the lumbopelvic region [56], it should not be surprising that core training improves balance, i.e., improves the ability to keep the center of gravity stable within the base of support. The relationship between balance and injury risk has been previously established [57]. Indeed, the SEBT is considered a reliable measure and a valid dynamic test to predict the risk of lower extremity injury [58]. Recently, De la Motte et al. reported moderate evidence between poor balance test performance and increased risk of ankle injury [59]. Given the large effect of core training on balance, it is essential to consider the need to incorporate core training in sports in which balance plays a predominant role or has a higher incidence of lower extremity injury.

Furthermore, the results indicate that ICT and CCT have a moderate-large and significant effect on balance. Although there are no significant differences between the groups, the effect size of CCT (ES = 1.67) was larger than ICT (ES = 0.67). Therefore, greater improvements in balance will be obtained by training the core in combination with small-sized games, plyometrics, or lower limb training. The greatest effect of core training was found in combination with plyometrics, with an SMD of 2.72 points.

The methodology used to train the core was very varied, from 4 weeks to 8 weeks and with a frequency of 2 days a week to 5 days a week. It is essential to consider that none of the six studies included specifying the intensity at which the training was performed. Neither did they measure if core training produced differences in pre- and post-intervention strength, so we cannot be sure that the improvement in balance is due to core strengthening. Despite the varied training methodology, no significant differences were found for any of the variables related to the intervention. When observing the effect sizes, it could be concluded that improvement is greater with a frequency of 2 days a week, with a duration of more than 6 weeks, without the use of implements and a total volume equal to or less than 16 sessions, however, due to the high heterogeneity of the studies, it is not possible to obtain concluding data.

Future research should use implements that allow us to evaluate strength, such as functional dynamometers, and determine the training intensity, thus establishing whether the program corresponds to strength training [60, 61].

Throwing/hitting velocity and distance

Results of our meta-analysis provide small effects in throwing/hitting velocity performance (ES = 0.30; p = 0.14); however, the results provide a large and significant effect of training core training on distance performance (ES = 3.42; p = 0.03). High heterogeneity was found in the data, and study quality was low. The high heterogeneity of the data could be because seven studies of 4 different sports (tennis, handball, baseball, and golf) were included in the study of throwing/hitting velocity performance. Only two studies were included in the distance performance, one measuring drive distance in golf and another medicine ball hitter's throw in baseball players.

Throwing velocity or hitting velocity are determining variables in match performance [62], considered the most important in the offensive action in handball [63]. In tennis, the serve velocity is significantly related to winning the point [64, 65] and the position in the ranking [66]. In two studies, an isolated training core was found to have beneficial effects on throwing velocity [13, 24]. Similar results were found in our study, with a significant and moderate effect size in favor of isolated core training, although, when core exercise was combined, a large and significant effect size was obtained. However, Dahl et al. found no significant correlation between throwing velocity and core strength variables [22] and McCurdy et al., observed no significant effects of core intervention on tennis players' performance [30]. The data obtained in our metanalysis cannot be compared with previous meta-analyses because they did not study athletic performance variables independently [10, 21].

The core training methodology used to improve throwing/hitting velocity performance was similar. In most studies, training time was 6 to 8 weeks with a frequency of 2/3 days a week. In the distance performance, since there are only two studies, data cannot be extracted from the training methodology since very few studies have analyzed these variables. However, both studies measured core strength before and after the intervention with the gold standard. In the statistical analysis of the variables related to training, better throwing/hitting velocity or distance performance is obtained when

training sessions are carried out with a frequency greater than two days, a duration greater than 6 weeks and a session duration greater than 30 minutes.

Jump

The jump ability is a requirement for success in several sports. This meta-analysis shows a moderate and significant effect on jumping performance with core training (ES 0.74; $p < 0.00001$). In addition, the relationship between trunk musculature and limb function has been extensively described [67, 68]; in particular, we have known that a trunk contraction is necessary prior to lower limb movement [69].

Previous reviews report a small and moderate effect of core training on vertical jumping [10, 21]. The data from this metanalysis show a moderate effect in favor of core training (ES 0.69; $p = 0.0003$). Butcher et al. reported an increase in take-off velocity in the vertical jump following nine weeks of core training [70]. In addition, there is a positive correlation between drop jump and isokinetic trunk extensor strength [71] and a strong correlation between isokinetic and isometric strength and CMJ [72]. Thus, core training could improve jumping by stabilizing the spine and pelvis, allowing a better transfer of force from the lower and upper extremities, and optimizing force production in activities such as jumping.

Concerning horizontal jump, the results of this meta-analysis show a large effect in favor of core training (ES = 0.84; $p = 0.01$). Performance in this test is 90% dependent on the flight distance, which is determined by the center of mass velocity at the take-off [73]. Furthermore, Takahashi et al. determined that the trunk muscles of long jumpers have a greater cross-sectional area than untrained individuals [74]. Besides, the size of the rectus abdominis and iliacus is associated with jumping performance. Thus, core training could be a strategy to increase horizontal jump performance. In addition, ICT had a larger effect size on vertical and horizontal jump performance than CCT despite not having a significant difference. As with the variable of throwing/hitting performance, the results obtained in this meta-analysis cannot be compared with previous meta-analyses because they analyze lower body muscle power, including power output, jumps, accelerations, and 3RM squat [10, 21].

The core training methodology used to improve vertical jump performance was very varied, from 6 weeks to 12 weeks and with a frequency of 2 days a week to 5 days a week. Only three studies assess core strength in pre-and-post-intervention [36, 40, 41]; however, none used the gold standard. In horizontal jump performance, two of the three included studies trained for eight weeks (three and five times a week) [40, 45], and one during 12 weeks with a frequency of 5 days a week [41]. In addition, two of the included studies measured core pre-and post-intervention. Anant et al. and Fadhil et al. found significant differences in lateral trunk strength and abdominal muscle endurance [41, 43]; however, none used the gold standard. In the statistical analysis of the variables related to training, the only significant variable is the duration of the session, obtaining improvements in sessions equal to or less than 30 minutes of core training.

Limitations

This meta-analysis is not exempt from limitations, such as the use of only four databases, which may have limited the number of articles retrieved. In addition, the very different core training methodology may be a result of the high heterogeneity of studies in balance and vertical jump performance ($I^2 \approx 60\%$) and distance ($I^2 = 97\%$). Publication bias was not performed in this analysis because it requires a minimum of 10 studies according to the Cochrane handbook [75]. Most studies included reported unclear randomization generation and allocation concealment. In articles with training to improve performance, it is challenging to blind the participants, so the risk of bias is high. It does not occur in other studies where a placebo can be used. However, we consider it a strength of this review to incorporate youth and adult populations from randomized studies. In contrast to other meta-analyses, this review analyzed specific performance variables and was not pooled as general categories.

CONCLUSIONS

In conclusion, this systematic review and meta-analysis demonstrated that core training should be included in training sessions to improve athletic performance. Based on these findings, ICT and CCT have moderate and large effects on athletic performance, with no significant differences, although CCT performed better in balance and throwing/hitting and ICT in jumping performance. Therefore, for coaches of different sports in which one of these variables affects sports performance, training recommendations for balance improvement are inconclusive as there are no significant differences between the variables. However, if we consider the effect sizes, it is recommended to train 2 times a week with a duration of 6 weeks or less, without implements and a total volume equal to or less than 16 weeks. In the case of throwing/hitting performance, it is recommended to train more frequently than 2 days a week with sessions of more than 30 minutes and a total volume of more than 16 sessions and in jump performance, the recommendation would be to have sessions equal to or less than 30 minutes of core training.

No significant differences were found for age and gender for any of the performance variables analyzed.

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Conflicts of interest

All the authors declare that they have no conflicts of interest.

REFERENCES

1. Behm DG, Drinkwater EJ, Willardson JM, Cowley PM. The use of instability to train the core musculature. Appl Physiol Nutr Metab. 2010; 35(1):91–108. doi:10.1139/H09-127.
2. Kibler W Ben, Press J, Sciascia A. The Role of Core Stability in Athletic Function. Sports Med. 2006; 36(3):189–198. doi:10.2165/00007256-200636030-00001.
3. Huxel Bliven KC, Anderson BE. Core Stability Training for Injury Prevention. Sports Health. 2013; 5(6):514–522. doi:10.1177/1941738113481200.
4. Jeong J, Choi DH, Shin CS. Core Strength Training Can Alter Neuromuscular and Biomechanical Risk Factors for Anterior Cruciate Ligament Injury. Am J Sports Med. 2021; 49(1):183–192. doi:10.1177/0363546520972990.
5. Hlaing SS, Puntumetakul R, Khine EE, Boucaut R. Effects of core stabilization exercise and strengthening exercise on proprioception, balance, muscle thickness and pain related outcomes in patients with subacute nonspecific low back pain: a randomized controlled trial. BMC Musculoskelet Disord. 2021; 22(1). doi:10.1186/s12891-021-04858-6.
6. Miyasaki MR, Marcioli MAR, Cunha APRR da, et al. Greater trochanteric pain syndrome in women: Analysis of magnetic resonance, sagittal alignment, muscular strength and endurance of the hip and trunk. Int J Rheum Dis. 2021; 24(7):941–947. doi:10.1111/1756-185X.14149.
7. Zouita ABM, Salah FZ Ben, Dziri C, Beardsley C. Comparison of isokinetic trunk flexion and extension torques and powers between athletes and nonathletes. J Exerc Rehabil. 2018; 14(1):72–77. doi:10.12965/jer.1835126.563.
8. Granacher U, Gollhofer A, Hortobágyi T, Kressig RW, Muehlbauer T. The Importance of Trunk Muscle Strength for Balance, Functional Performance, and Fall Prevention in Seniors: A Systematic Review. Sports Med. 2013; 43(7):627–641. doi:10.1007/s40279-013-0041-1.
9. Reed CA, Ford KR, Myer GD, Hewett TE. The effects of isolated and integrated "core stability" training on athletic performance measures: a systematic review. Sports Med. 2012; 42(8):697–706. doi:10.2165/11633450-000000000-00000.
10. Prieske O, Muehlbauer T, Granacher U. The Role of Trunk Muscle Strength for Physical Fitness and Athletic Performance in Trained Individuals: A Systematic Review and Meta-Analysis. Sports Med. 2016; 46(3):401–419. doi:10.1007/s40279-015-0426-4.
11. Stodden DF, Campbell BM, Moyer TM. Comparison of trunk kinematics in trunk training exercises and throwing. J Strength Cond Res. 2008; 22(1):112–118. doi:10.1519/JSC.0b013e31815f2a1e.
12. Myers NL, Sciascia AD, Westgate PM, Kibler WB, Uhl TL. Increasing ball velocity in the overhead athlete: A meta-analysis of randomized controlled trials. J Strength Cond Res. 2015; 29(10):2964–2979. doi:10.1519/JSC.0000000000000931.
13. Saeterbakken AH, van den Tillaar R, Seiler S. Effect of Core Stability Training on Throwing Velocity in Female Handball Players. J Strength Cond Res. 2011; 25(3):712–718. doi:10.1519/JSC.0b013e3181cc227e.
14. Hong DA, Cheung TK, Roberts EM. A three-dimensional, six-segment chain analysis of forceful overarm throwing. J Electromyogr Kinesiol. 2001; 11(2):95–112.
15. Szymanski DJ, McIntyre JS, Szymanski JM, et al. Effect of torso rotational strength on angular hip, angular shoulder, and linear bat velocities of high school baseball players. J Strength Cond Res. 2007; 21(4):1117–1125. doi:10.1519/R-18255.1.
16. Wagner H, Buchecker M, von Duvillard SP, Müller E. Kinematic description of elite vs. low level players in team-handball jump throw. J Sports Sci Med. 2010; 9(1):15–23.
17. van den Tillaar R, Ettema G. Is there a proximal-to-distal sequence in overarm throwing in team handball? J Sports Sci. 2009; 27(9):949–955. doi:10.1080/02640410902960502.
18. Wagner H, Pfusterschmied J, Von Duvillard SP, Müller E. Skill-dependent proximal-to-distal sequence in team-handball throwing. J Sports Sci. 2012; 30(1):21–29. doi:10.1080/02640414.2011.617773.
19. Coleman SGS, Benham AS, Northcott SR. A three-dimensional cinematographical analysis of the volleyball spike. J Sports Sci. 1993; 11(4):295–302. doi:10.1080/02640419308729999.
20. Elliott BC, Marshall RN, Noffal GJ. Contributions of Upper Limb Segment Rotations during the Power Serve in Tennis. J Appl Biomech. 1995; 11(4):433–442. doi:10.1123/jab.11.4.433.
21. Saeterbakken AH, Stien N, Andersen V, et al. The Effects of Trunk Muscle Training on Physical Fitness and Sport-Specific Performance in Young and Adult Athletes: A Systematic Review and Meta-Analysis. Sports Med. 2022; 52(7):1599–1622. doi:10.1007/S40279-021-01637-0.
22. Dahl KS, Van Den Tillaar R. The Effect of Eight Weeks of Sling-Based Training with Rotational Core Exercises on Ball Velocity in Female Team Handball Players. J Hum Kinet. 2021; 77(1):261–272. doi:10.2478/hukin-2021-0024.
23. Lam NHK, Lau WM, Lau TL. Effects of a 6-week core stabilization training program on dynamic balance and trunk stabilization endurance of horse riders. Sport Sci Health. 2021; 17(3):655–664. doi:10.1007/s11332-020-00729-0.
24. Palmer T, Uhl TL, Howell D, Hewett TE, Viele K, Mattacola CG. Sport-specific training targeting the proximal segments and throwing velocity in collegiate throwing athletes. J Athl Train. 2015; 50(6):567–577. doi:10.4085/1062-6040-50.1.05.
25. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021; 372:n71. doi:10.1136/bmj.n71.
26. Drevon D, Fursa SR, Malcolm AL. Intercoder Reliability and Validity of WebPlotDigitizer in Extracting Graphed Data. Behav Modif. 2016; 41(2):323–339. doi:10.1177/0145445516673998.
27. Cochran WG. The combination of estimates from different experiments. Biometrics. 1954; 10(1):101–129.
28. DerSimonian R, Laird N. Meta-analysis in clinical trials. Control Clin Trials. 1986; 7(3):177–188.
29. Cohen J. Statistical Power Analysis for the Behavioral Sciences. 2nd ed. Lawrence Erlbaum Associates; 1988.
30. McCurdy K, Smart J, Pankey R, Walker J. The effect of core training in tennis serve velocity. J Aust Strength Cond. 2014; 22(4):24–30.
31. Sato K, Mokha M. Does core strength training influence running kinetics, lower-extremity stability, and 5000-M performance in runners? J Strength Cond Res. 2009; 23(1):133–140.
32. Filipa A, Byrnes R, Paterno M V, Myer GD, Hewett TE. Neuromuscular Training Improves Performance on the Star Excursion Balance Test in Young Female Athletes. J Orthop Sports Phys Ther. 2010; 40(9):551–558. doi:10.2519/jospt.2010.3325.
33. Dello Iacono A, Martone D, Alfieri A, Ayalon M, Buono P. Core Stability Training Program (CSTP) effects on static and dynamic balance abilities. Gazz Med Ital Arch Sci Med. 2014; 173(4):197–206.
34. Benis R, Bonato M, La Torre A. Elite female basketball players' body-weight neuromuscular training and performance on the Y-balance test. J Athl Train. 2016; 51(9):688–695. doi:10.4085/1062-6050-51.12.03.
35. Sharma A, Geovinson SG, Singh

Sandhu J. Effects of a nine-week core strengthening exercise program on vertical jump performances and static balance in volleyball players with trunk instability. J ORTHOP SPORT PHY***S.*** 2012; 52(6):606–615.
36. Taskin C. Effect of Core Training Program on Physical Functional Performance in Female Soccer Players. Int Educ Stud. 2016; 9(5). doi:10.5539/ies.v9n5p115.
37. Manchado C, García-Ruiz J, Cortell-Tormo JM, Tortosa-Martínez J. Effect of Core Training on Male Handball Players' Throwing Velocity. J Hum Kinet. 2017; 56(1):177–185. doi:10.1515/hukin-2017-0035.
38. Mills JD, Taunton JE, Mills WA. The effect of a 10-week training regimen on lumbo-pelvic stability and athletic performance in female athletes: A randomized-controlled trial. Phys Ther Sport. 2005; 6(2):60–66. doi:10.1016/j.ptsp.2005.02.006.
39. Fernandez-Fernandez J, Ellenbecker T, Sanz-Rivas D, Ulbricht A, Ferrautia A. Effects of a 6-week junior tennis conditioning program on service velocity. J Sports Sci Med. 2013; 12(2):232–239. PMID: 24149801.
40. Ozmen T, Aydogmus M, Yana M, Simsek A. Effect of core strength training on balance, vertical jump height and throwing velocity in adolescent male handball players. J Sports Med Phys Fit. 2020; 60(5):693–699. doi:10.23736/S0022-4707.20.10382-7.
41. Fadhil Farhan A, Justine M, Kamil Mahammed S. Effect of training program on physical performance in junior male Malaysian soccer players. J Phys Educ Sport. 2013; 13(2):238–243. doi:10.7752/jpes.2013.02039.
42. Weston M, Coleman NJ, Spears IR. The effect of isolated core training on selected measures of golf swing performance. Med Sci Sports Exerc. 2013; 45(12):2292–2297. doi:10.1249/MSS.0b013e31829bc7af.
43. Anant SK, Venugopal R. Effect of eight-week core muscles strength training on physical fitness and body composition variables in male players of team games. Rev Andal Med Deport. 2020; 14(1):17–33. doi:10.33155/J.RAMD.2020.06.001.
44. Kuhn L, WEBERRUß H, Horstmann T. Effects of core stability training on throwing velocity and core strength in female handball players. J Sports Med Phys Fit. 2019; 59(9):1479–1486. doi:10.23736/S0022-4707.18.09295-2.
45. Bashir SF, Nuhmani S, Dhall R, Muaidi QI. Effect of core training on dynamic balance and agility among Indian junior tennis players. J Back Musculoskelet Rehabil. 2019; 32(2):245–252. doi:10.3233/BMR-170853.
46. Sung DJ, Park SJ, Kim S, Kwon MS, Lim YT. Effects of core and non-dominant arm strength training on drive distance in elite golfers. J Sport Health Sci. 2016; 5(2):219–225. doi:10.1016/j.jshs.2014.12.006.
47. Karagianni K, Donti O, Katsikas C, Bogdanis GC. Effects of Supplementary Strength–Power Training on Neuromuscular Performance in Young Female Athletes. Sports. 2020; 8(8):1–12. doi:10.3390/sports8080104.
48. Arslan E, Soylu Y, Clemente FM, Hazir T, Isler AK, Kilit B. Short-term effects of on-field combined core strength and small-sided games training on physical performance in young soccer players. Biol Sport. 2021; 38(4):609–616. doi:10.5114/biolsport.2021.102865.
49. Szymanski DJ, Szymanski JM, Bradford TJ, Schade RL, Pascoe DD. Effect of twelve weeks of medicine ball training on high school baseball players. J Strength Cond Res. 2007; 21(3):894–901. doi:10.1519/R-18415.1.
50. Bashir SF, Nuhmani S, Dhall R, Muaidi QI. Effect of core training on dynamic balance and agility among Indian junior tennis players. J Back Musculoskelet Rehabil. 2019; 32(2):245–252. doi:10.3233/BMR-170853.
51. Kabadayı M, Karadeniz S, Yılmaz AK, et al. Effects of Core Training in Physical Fitness of Youth Karate Athletes: A Controlled Study Design. Int J Environ Res Public Health. 2022; 19(10). doi:10.3390/ijerph19105816.
52. Lu Y, Yu K, Gan X. Effects of a SMART Goal Setting and 12-Week Core Strength Training Intervention on Physical Fitness and Exercise Attitudes in Adolescents: A Randomized Controlled Trial. Int J Environ Res Public Health. 2022; 19(13). doi:10.3390/ijerph19137715.
53. Higgins JP, Altman DG, Sterne JA, Wiley J. Chapter 8: Assessing risk of bias in included studies. Published online 2017. Accessed January 21, 2022. www.wiley.com.
54. Santesso N, Glenton C, Dahm P, et al. GRADE guidelines 26: informative statements to communicate the findings of systematic reviews of interventions. J Clin Epidemiol. 2020; 119:126–135. doi:10.1016/j.jclinepi.2019.10.014.
55. Ringhof S, Stein T. Biomechanical assessment of dynamic balance: Specificity of different balance tests. Hum Mov Sci. 2018; 58(December 2017):140–147. doi:10.1016/j.humov.2018.02.004.
56. Akuthota V, Nadler SF. Core Strengthening. Arch Phys Med Rehabil. 2004; 85. doi:10.1053/j.apmr.2003.12.005.
57. Hrysomallis Con. Balance Ability and Athletic Performance. Sports Med. 2011; 41(3):221–232.
58. Gribble PA, Hertel J, Plisky P. Using the Star Excursion Balance Test to Assess Dynamic Postural-Control Deficits and Outcomes in Lower Extremity Injury: A Literature and Systematic Review. J Athl Train. 2012; 47(3):339–357. doi:10.4085/1062-6050-47.3.08.
59. De La Motte SJ, Lisman P, Gribbin TC, Murphy K, Deuster PA. Systematic Review of the Association Between Physical Fitness and Musculoskeletal Injury Risk: Part 3-Flexibility, Power, Speed, Balance, and Agility. J Strength Cond Res. 2019; 33(6):1723–1735. doi:10.1519/JSC.0000000000002382.
60. Dvir Z, Müller S. Multiple-Joint Isokinetic Dynamometry: A Critical Review. J Strength Cond Res. 2020; 34(2):587–601. doi:10.1519/JSC.0000000000002982.
61. Rodriguez-Perea A, Ríos LJC, Martinez-Garcia D, et al. Reliability of isometric and isokinetic trunk flexor strength using a functional electromechanical dynamometer. PeerJ. 2019; 2019(10). doi:10.7717/peerj.7883.
62. Nakata H, Nagami T, Higuchi T, Sakamoto K, Kanosue K. Relationship between performance variables and baseball ability in youth baseball players. J Strength Cond Res. 2013; 27(10):2887–2897. doi:10.1519/JSC.0b013e3182a1f58a.
63. Granados C, Izquierdo M, Ibàñez J, Ruesta M, Gorostiaga EM. Effects of an entire season on physical fitness in elite female handball players. Med Sci Sports Exerc. 2008; 40(2):351–361. doi:10.1249/mss.0b013e31815b4905.
64. Girard O, Millet GP. Physical determinants of tennis performance in competitive teenage players. J Strength Cond Res. 2009; 23(6):1867–1872. doi:10.1519/JSC.0B013E3181B3DF89.
65. Girard O, Micallef JP, Millet GP. Lower-limb activity during the power serve in tennis: Effects of performance level. Med Sci Sports Exerc. 2005; 37(6):1021–1029. doi:10.1249/01.MSS.0000171619.99391.BB.
66. Ulbricht A, Fernandez-Fernandez J, Mendez-Villanueva A, Ferrauti A. Impact of Fitness Characteristics on Tennis Performance in Elite Junior Tennis Players. J Strength Cond Res. 2016; 30(4):989–998. doi:10.1519/JSC.0000000000001267.
67. Saeterbakken AH, Stien N, Pedersen H, Andersen V. Core Muscle Activation in Three Lower Extremity Exercises With Different Stability Requirements. J Strength Cond Res. 2022; 36(2):304–309. doi:10.1519/jsc.0000000000003465.
68. Hibbs AE, Thompson KG, French D,

Wrigley A, Spears I. Optimizing performance by improving core stability and core strength. Sports Med. 2008; 38(12):995–1008.
69. Hodges PW, Richardson CA. Contraction of the Abdominal Muscles Associated With Movement of the Lower Limb. Phys Ther. 1997; 77(2):132–142. doi:10.1093/ptj/77.2.132.
70. Butcher SJ, Craven BR, Chilibeck PD, Spink KS, Grona SL, Sprigings EJ. The effect of trunk stability training on vertical takeoff velocity. J Orthop Sports Phys Ther. 2007; 37(5):223–231. doi:10.2519/jospt.2007.2331.
71. Prieske O, Muehlbauer T, Krueger T, Kibele A, Behm DG, Granacher U. Role of the trunk during drop jumps on stable and unstable surfaces. Eur J Appl Physiol. 2015; 115(1):139–146. doi:10.1007/S00421-014-3004-9/TABLES/3.
72. Guo L, Wu Y, Li L. Dynamic Core Flexion Strength is Important for Using Arm-Swing to Improve Countermovement Jump Height. Appl Sci. 2020; 10(21):7676. doi:10.3390/APP10217676.
73. Hay JG, Miller JA, Canterna RW. The techniques of elite male long jumpers. J Biomech. 1986; 19(10):855–866. doi:10.1016/0021-9290(86)90136-3.
74. Takahashi K, Wakahara T. Association between trunk and gluteus muscle size and long jump performance. PLoS One. 2019; 14(11):e0225413. doi:10.1371/JOURNAL.PONE.0225413.
75. Mavridis D, Salanti G. How to assess publication bias: funnel plot, trim-and-fill method and selection models. Evid Based Ment Health. 2014; 17(1):30–30. doi:10.1136/EB-2013-101699.

SUPPLEMENTARY

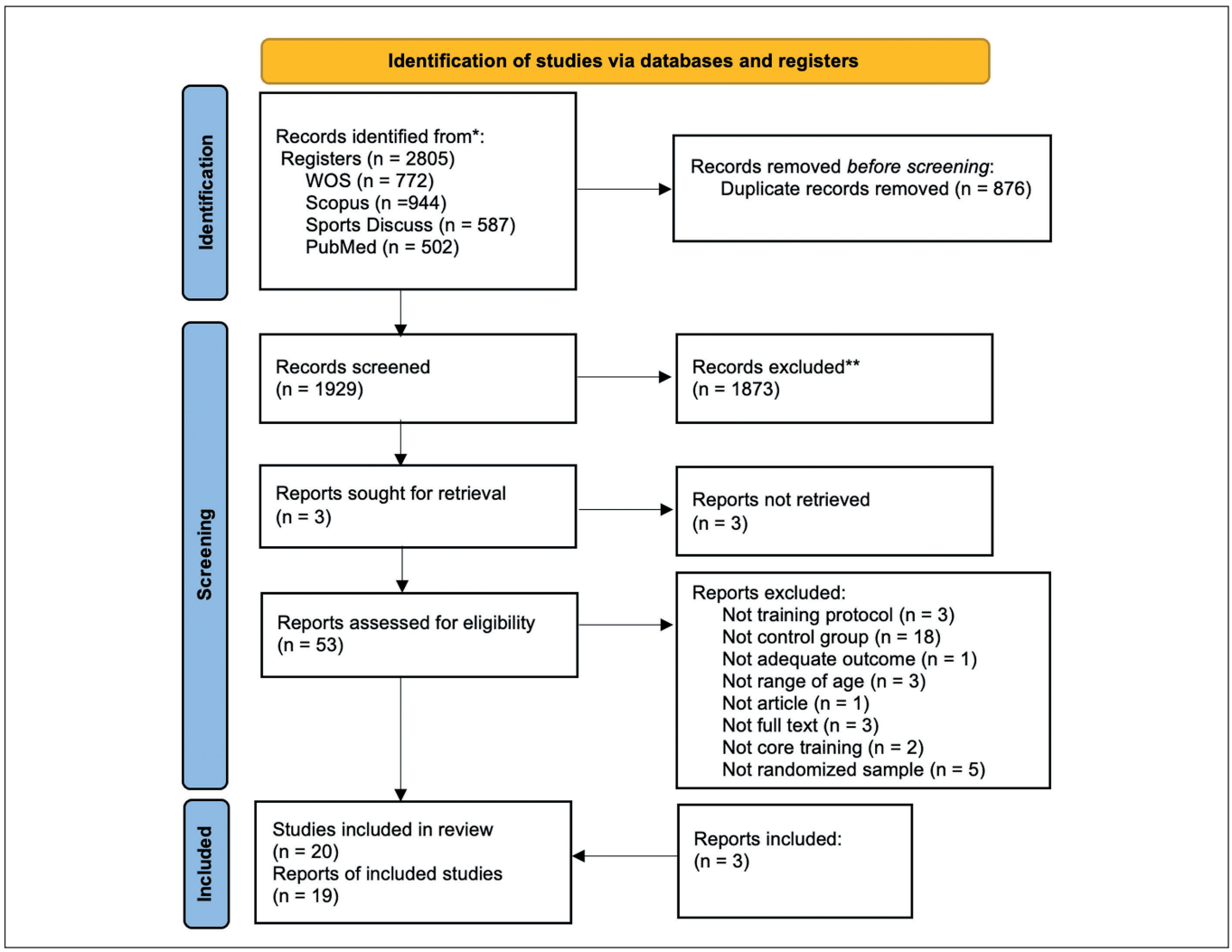


FIG. S1. PRISMA flow diagram for new systematic reviews.

TABLE S1. Search strategy

Steps	Stategy	WOS	Scopus	Sports Discuss	PubMed	Total
1	"core muscle"	401	584	232	292	1509
2	"torso"	9594	15035	3458	202731	230818
3	trunk	76311	112484	8122	259555	456472
4	abdominal	321307	619166	8201	477254	1425928
5	S1 OR S2 OR S3 OR S4	402299	735331	17060	616890	1771580
6	"endurance training"	6013	10639	4051	5196	25899
7	stability	1881252	2226181	17615	782176	4907224
8	"resistance training"	12504	23293	10648	15262	61707
9	"strength training"	7994	8602	11199	5836	33631
10	"plyometric exercise"	261	1003	221	798	2283
11	S6 OR S7 OR S8 OR S9 OR S10	1904791	2262590	40414	804990	5012785
12	"athletic performance"	5497	18670	4996	15050	44213
13	performance	5292466	6275769	212943	3697887	15479065
14	"physical test"	1070	4937	136	201	6344
15	S12 OR S13 OR S14	5293188	6279313	213015	3697971	15483487
16	S5 AND S11 AND S14	1579	1481	605	3874	7539
	With filter	772	944	587	502	2805
	After duplicates					1929

Sand and grass surfaces are equally effective in promoting positive adaptations in the sprint performance of elite young soccer players

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ABSTRACT: This study compared the effects of two sprint-jump training programmes, performed on either sand or grass surfaces, on the sprint and jump performance of elite young soccer players over an 8-week training period. Fifteen under-20 soccer players were randomly allocated to the sand (n = 7) or grass (n = 8) group. Athletes performed 12 training sessions, comprising vertical and horizontal jump exercises, and linear and change-of-direction (COD) sprint drills. Pre- and post-measurements were completed in the following order: vertical jump, sprint speed at 10 m and 17 m, curve sprint (CS), and modified Zigzag COD tests. Between-group differences were determined using a two-way ANOVA with repeated measures and effect sizes (ES). No improvements in jump performance were found in either group. Significant increases were observed in the sand group for acceleration in 0–10 m and for 10- and 17-m linear sprint velocity (ES = 1.15, 1.16, and 1.81, respectively; $P < 0.05$). In contrast, no significant differences were detected for acceleration and linear sprint velocity in the grass group, comparing pre- and post-tests (ES ranging from 0.01 to 0.47; $P > 0.05$). Both sand and grass groups revealed similar increases in the CS and COD velocities after the training period (ES ranging from 0.98 to 1.93; $P < 0.05$). In conclusion, sprint-jump training programmes performed on both grass and sand surfaces elicited significant improvements in CS and COD performances, whereas acceleration and linear sprint velocity increased only in the sand group, after a short-term training period. The sand training surface was proven to be a practical strategy to improve sprint performance in all its forms in soccer players, which is of great interest and importance for coaches and sport scientists working in elite soccer.

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INTRODUCTION

Soccer is an intermittent team sport characterized by short-duration, highly demanding activities interspaced with low- and moderate-intensity periods [1–3]. From a general perspective, the multiple physical tasks performed by soccer players during matches rely on aerobic metabolism and on high levels of speed and power [3]. Indeed, previous studies have already shown that sprinting and jumping are the most frequent actions preceding goal scoring situations and that, importantly, sprint distance and number of maximal sprints have increased substantially in professional soccer over the last few years [1, 2]. As a consequence, special attention has been paid to the proper and efficient development of neuromuscular qualities in elite soccer players [3–5].

Several training strategies have been proposed and used to improve speed and power capacities in team-sport athletes from different performance levels and age categories [3–5]. Recent surveys conducted with soccer practitioners working in national leagues from different countries revealed that "plyometrics" and "maximum speed sprinting" were the most frequently used training methods for increasing sprinting speed and power output in elite soccer players [4, 5]. In general, these training strategies are executed on "harder surfaces" (e.g., gym floor or grass) [6] based on the assumption that "softer surfaces" (e.g., sand) could dissipate a substantial amount of ground reaction forces (and elastic energy) during plyometric activities [7–10], thus affecting movement velocity, force, and power

production [6]. Therefore, soft surfaces might not be "optimal" to activate and potentiate the stretch-shortening cycle [7–10] and may contribute to higher energy expenditure when compared to sprint or jump tasks performed on harder surfaces at similar speeds or heights, which in turn may potentially impact the subjective perception of effort [6, 11, 12]. However, somewhat surprisingly, training on a sand surface has been proven to be as efficient as training on harder surfaces in terms of speed-power development (e.g., large effect sizes [> 1.0] and significant changes [$P < 0.05$] in jump and sprint performance) [6]. In fact, it has been observed that sand training may lead to higher motor unit recruitment in the muscle groups involved in some specific motor tasks (when compared to harder surfaces), which indicates that this training strategy might act as an "alternative way" to increase training load and thus promote positive changes in physical performance [6]. Despite these preliminary indications, the limited level of evidence regarding the effectiveness of this training method, specifically in highly trained athletes, precludes more robust conclusions on this issue.

Another crucial point to consider when implementing speed training strategies for soccer players is the importance of providing stimuli involving not only linear, but also other forms of sprinting (i.e., change-of-direction [COD], and curved sprints). A systematic review examining the number and nature of high-intensity activities executed during soccer matches revealed that each player performs between 7 and 61 linear sprints and > 300 directional changes with different cut angles, turns, and "swerves" (i.e., short and fast multidirectional movements) per match [13]. Moreover, a recent study reported that the vast majority of sprints (i.e., 80%) performed during soccer matches are curvilinear [14]. In this regard, it has been suggested that, to appropriately improve multidirectional speed qualities, mixed training approaches involving decelerations, accelerations and COD tasks should be implemented [4, 15, 16]. Nevertheless, the impact of implementing these mixed training strategies on the speed-related performance of team-sport athletes is still unknown, especially when considering the potential adaptations associated with different surface types (e.g., sand, or harder surfaces).

Developing practical training strategies able to maximize speed and power output in elite soccer players is unquestionably of great interest for practitioners [4, 5]. The use of plyometric drills combined with maximal sprint bouts, executed on either soft or hard surfaces, seems to be a very viable alternative. However, the current evidence [6] does not allow us to draw any firm conclusion regarding the superiority of one surface over the other. Therefore, the purpose of this study was to investigate and compare the effects of two different training programmes (i.e., mixed plyometric and sprint training strategies performed on sand or grass surfaces) on the jump and speed-related performance (assessed by linear, curvilinear, and COD speed tests) of elite young soccer players. Considering previous investigations [6, 8] on this topic, we hypothesized that both training strategies would be equally effective to elicit positive changes in the physical performance of the athletes.

MATERIALS AND METHODS

Participants

Eighteen elite young soccer players (18.5 ± 0.6 years; 71.7 ± 5.0 kg; 178.6 ± 7.5 cm) from the same club, playing in the 1st division of the under-20 Brazilian National Championship, participated in this study. Athletes were randomly allocated to two training groups, as follows: the "sand training group" (n = 9); and the "grass training group" (n = 9). Player names were entered in order of lowest to highest 17-m sprint times, by an independent researcher, in a customized spreadsheet, and grouped in pairs according to their baseline results. Subsequently, the group allocation of each pair was determined by tossing a coin. Three athletes did not complete all training sessions and were excluded from the analysis. Thus, the final dataset included 15 athletes (7 athletes in the sand group and 8 athletes in the grass group). The research was approved by the local Ethics Committee (registration number 5.200.656) and all participants and their legal guardians signed an informed consent form prior to participation in the study.

Study Design

This parallel, two-group, quasi-randomized study was designed to test the effects of two mixed-training programmes, performed on a sand or grass surface, on jump and sprint performances of elite young soccer players during an 8-week inter-season training period. Athletes were tested after the São Paulo Cup of Junior Soccer Players and before the Parana State Championship (under-20 category). The training content followed by the athletes during the intervention period is presented in Table 1. Except for the distinct training surfaces, players from both groups followed the same training routines throughout the study, which consisted of 12 sand or grass training workouts, 8 resistance training sessions, 28 technical and tactical training sessions, and 5 friendly matches. The training sessions were performed simultaneously by both groups at the soccer club's training facilities, with the sand and grass fields located next to each other. Table 2 shows the typical weekly training schedule of the players across the 8 weeks. All athletes were previously familiarized with the training and testing routines. The physical tests were conducted in the following order: squat and countermovement jump (SJ and CMJ), sprinting speed at 10 m and 17 m, curve sprint test (CS), and a modified Zigzag COD test. For the sake of consistency and to facilitate data interpretation, the distance of the linear and multidirectional sprint tests was standardized according to the previously validated CS test [17], which is performed on the "official arc of the soccer area" (i.e., 17 m). All tests were conducted at the same time of day, and the temperature (~20°C vs. ~18°C) and wind velocity (~3 $km \cdot h^{-1}$) were similar between pre- and post-assessments. Prior to measurements, a general and specific warm-up was performed involving light running (rating of perceived exertion [RPE] of 3–4 on a 1–10 scale [18]) for 10 min followed by 3 submaximal jumps, and 2 submaximal sprint trials (~70% of maximal sprint velocity) interspersed by 2 minutes of passive recovery. Finally, session-RPE

TABLE 1. Sprint and jump training program for both groups* during the period of the study.

	Sessions 1–4		Sessions 5–9		Sessions 10–12	
	Sets	Reps	Sets	Reps	Sets	Reps
Bilateral hurdle jumps	3	6	4	5	3	5
Unilateral horizontal jumps	3R 3L	6 6	4R 4L	5 5	3R 3L	5 5
Vertical drop jumps	4	6	4	6	4	4
Horizontal drop jumps	2	6	2	6	2	4
Linear sprint	6	1 × 10-m	6	1 × 15-m	3	1 × 10-m
90° COD sprint	2R 2L	1 × 10-m 1 × 10-m	2R 2L	1 × 15-m 1 × 15-m	1R 1L	1 × 10-m 1 × 10-m

*Both groups performed the same exercises on sand or grass surfaces. COD = change of direction; R = right side; L = left side; Reps = repetitions. Recovery time between repetitions and sets were 15–30 s and 1–3 min, respectively.

TABLE 2. Typical weekly training schedule of the soccer players during the 8 weeks of intervention.

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Resistance training (45-min) Small-sided games (60-min)	Technical-tactical training (50-min)	Sand or grass sprint-jump training (20–30-min) Offensive and defensive game situations (50-min)	Passing, shooting, and dribbling skills (40-min) Low demand (regenerative) activity (30-min)	Technical-tactical training (40-min)	Friendly match	Rest

Note: resistance training involved traditional strength exercises (e.g., bench press, half-squat, hip-thrust, and prone row) performed with moderate loads (e.g., 40–60% of one-repetition maximum).

(s-RPE) was assessed in every training session (45 sessions) across the 8 weeks.

Procedures

Vertical Jumping Tests

Vertical jump height was assessed using the SJ and CMJ. In the SJ, athletes were required to remain in a static position with a 90° knee flexion angle for ~2 s before jumping, without executing any preparatory movement. In the CMJ, athletes were instructed to execute a downward movement followed by complete extension of the legs and were free to determine the countermovement amplitude to avoid changes in jumping coordination [19]. All jumps were performed with the hands on the hips, with athletes being instructed to jump as high as possible. The jumps were performed on a contact platform (Elite Jump, S2 Sports, São Paulo, Brazil) and jump height was automatically calculated based on the flight time. A total of three attempts were allowed for each jump, interspersed by 15-s intervals. The best attempts for the SJ and CMJ were used for subsequent analyses.

Linear Sprinting Speed Test

Three pairs of photocells (Elite Speed, S2 Sports, São Paulo, Brazil) were positioned at the starting line and at the distances of 10 m and 17 m. Soccer players sprinted twice, starting from a standing position 0.5 m behind the starting line. The sprint tests were performed on an outdoor field of natural grass. Sprint velocity was calculated as the distance travelled over a measured time interval. The acceleration ability in the different distances (i.e., 0–10 m and 10–17 m) was calculated as the rate of change of velocity with respect to time. A 5-min rest interval was allowed between the two attempts and the fastest time was retained for analyses.

Curve Sprint Test

The CS test was performed as previously described [16]. The trajectory of the CS was the semi-circle of the goalkeeper area (of an official soccer field), which is standardized as follows: a 9.15-m radius (from the penalty spot); a 14.6-m distance from the initial to the final point in a straight line; an angle of 105.84° of amplitude from the penalty spot; a 17-m total distance (obtained from

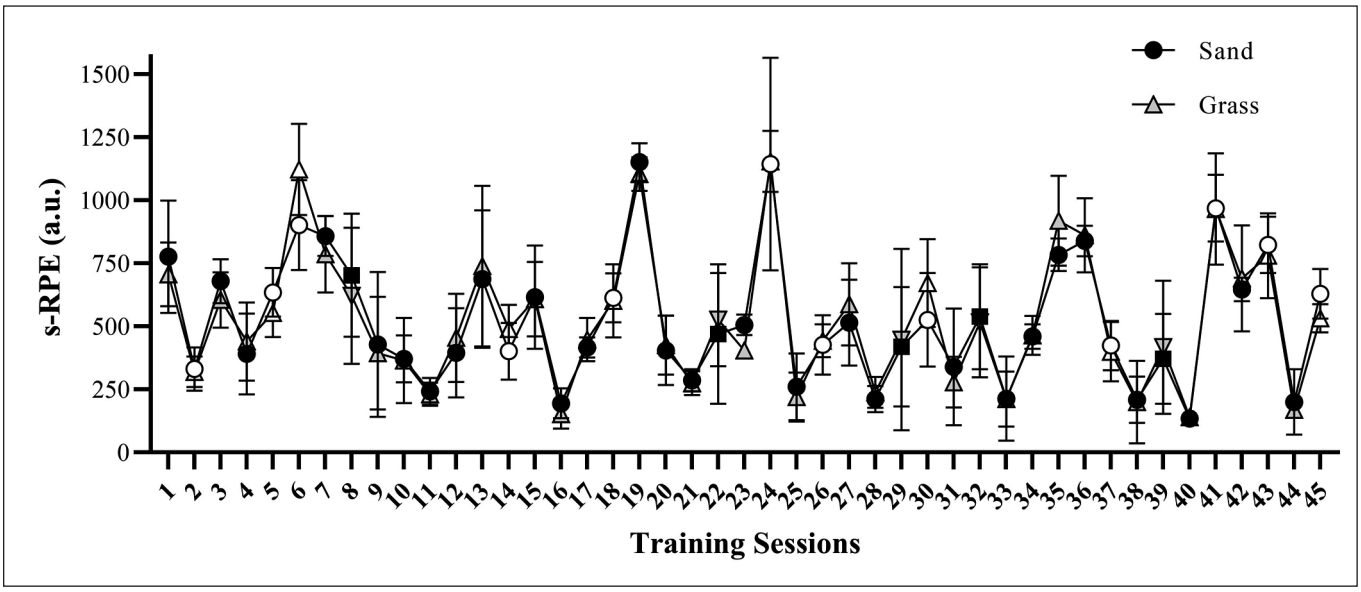


FIG. 1. Variations in the session-rating of perceived exertion (s-RPE) across the 45 sessions analysed during the 8-week training period. Black circles and grey triangles represent technical and tactical training sessions; white symbols correspond to sand and grass training sessions; squares and inverted triangles represent friendly matches.

TABLE 3. Comparisons of the vertical jump performances between pre- and post-assessments for both training groups.

	Groups	Pre	Post	ES (95% CI)	*P*-values	
					Pre *vs.* Post	Group*time interaction
SJ (cm)	Sand	37.5 ± 3.6	37.7 ± 4.3	0.08 (-0.66; 0.82)	0.995	0.661
	Grass	39.1 ± 3.6	38.8 ± 3.5	0.16 (-0.54; 0.86)	0.978	
CMJ (cm)	Sand	38.7 ± 4.1	40.0 ± 4.4	0.57 (-0.26; 1.35)	0.314	0.479
	Grass	41.5 ± 4.1	42.1 ± 4.4	0.39 (-0.35; 1.10)	0.823	

ES: effect size; CI: confidence intervals; SJ: squat jump; CMJ: countermovement jump.

a trigonometrical analysis). The test was completed outdoors, on natural turf. Two pairs of photocells (Elite Speed, S2 Sports, São Paulo, Brazil) were positioned at the beginning and at the end of the curved trajectory. Soccer players sprinted twice for each side, and the fastest times from the right and left sides were retained.

Modified Zigzag Change of Direction Speed Test

The modified Zigzag COD test consisted of four 4.25-m sections (total linear distance of 17 m, to match the linear sprint and curve sprint distances) marked with cones set at 100° angles [16], requiring the athletes to decelerate and accelerate as fast as possible around each cone. Two maximal attempts were performed, with a 5-min rest interval between attempts. Starting from a standing position 0.5 m behind the first pair of timing gates (Elite Speed, S2 Sports, São Paulo, Brazil), athletes were instructed to complete the test as quickly as possible, until crossing the second pair of timing gates, placed 17 m from the starting line. The measurement was performed on an outdoor field of natural grass. The fastest time from the two attempts was retained.

Session Rating of Perceived Exertion

The internal training load was recorded using the s-RPE method [18]. Approximately 30 min after completion of each training session, players were required to report the intensity of the whole session by means of a 10-point rating of perceived exertion scale [18]. This value was multiplied by the respective total duration of each training session. Daily s-RPE values for each group were used for the analyses.

Statistical Analyses

Data are presented as mean ± standard deviation (SD). Data normality was checked using the Shapiro-Wilk test. Absolute and relative reliability of the data were determined using the coefficient of

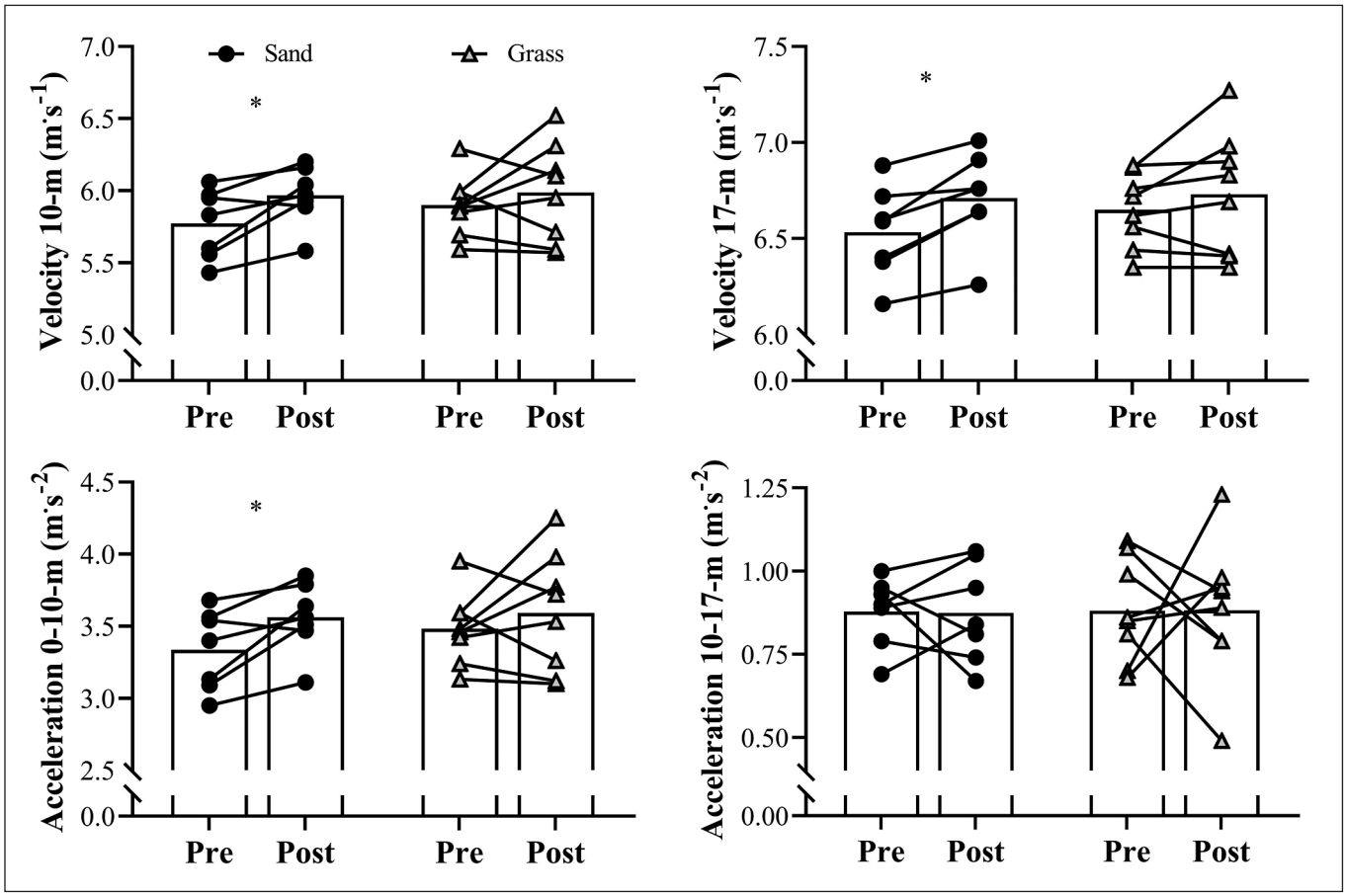


FIG. 2. Variations in the 10- and 17-m linear sprint velocities and in the 0–10- and 10–17-m acceleration capacities in the sand and grass groups during the 8-week training period. Symbols represent individual results and bars correspond to mean values. *Main effect of time ($P < 0.05$) in comparison to "Pre" assessments.

variation (CV) and a two-way random effects model intraclass correlation coefficient (ICC), based on the multiple attempts performed at pre-test. A two-way ANOVA with repeated measures (group*time interaction) followed by Tukey's post-hoc was used to examine pre- and post-test differences between groups. The statistical level of significance was set as $P < 0.05$. Additionally, to determine the magnitude of pre- and post-changes, effect sizes (ES) along with 95% confidence intervals (CI) were calculated and interpreted using the thresholds proposed by Rhea [20] for highly trained subjects, as follows: < 0.25, 0.25–0.50, 0.50–1.00, and > 1.00 for trivial, small, moderate, and large, respectively.

RESULTS

The CV values for all tests performed were < 5%. The ICC values for SJ, CMJ, 10-m and 17-m linear sprint, CS, and COD test were 0.98, 0.99, 0.88, 0.92, 0.84, and 0.82, respectively. No between-group significant differences were found for any variables tested in the baseline measures (P values ranging from 0.361 to 0.998). Figure 1 shows the variations in the s-RPE over the 8-week training period. Sand and grass groups showed similar changes in the s-RPE over the 45 sessions analysed ($P = 0.223$ for group*time interaction). Table 3 presents the comparisons of the vertical jump performances between pre- and post-assessments for both training groups. No significant changes were noted for SJ and CMJ height for both training groups (ES ranging from 0.16 to 0.57; $P > 0.05$).

Figure 2 depicts the changes in sprint velocity and acceleration ability across the 8 weeks, for both groups. Significant increases were observed for the sand group in 10-m ($P = 0.05$; ES [95% CI] = 1.16 [0.15; 2.11]) and 17-m ($P = 0.025$; ES [95% CI] = 1.81 [0.54; 3.03]) linear sprint velocity, and in 0–10-m acceleration ($P = 0.023$; ES [95% CI] = 1.15 [0.10; 2.10]) after the training intervention. Meanwhile, no significant change was noted in the 10–17-m acceleration for the sand group ($P = 0.963$; ES [95% CI] = 0.03 [-0.77; 0.71]). No significant differences were observed for 10-m ($P = 0.324$; ES [95% CI] = 0.30 [-0.42; 1.00]) and 17-m ($P = 0.405$; ES [95% CI] = 0.47 [-0.28; 1.19]) linear sprint velocities and acceleration abilities in 0–10 m ($P = 0.311$; ES [95% CI] = 0.31 [-0.41; 1.01]) and 10–17 m ($P = 0.989$;

ES [95% CI] = 0.01 [-0.69; 0.70]) in the grass group when comparing pre- and post-tests. No group*time interaction was detected for 10- and 17-m linear sprint performance (P = 0.548 and 0.21, respectively) and acceleration abilities in 0–10 m and 10–17 m (P = 0.453 and 0.966, respectively).

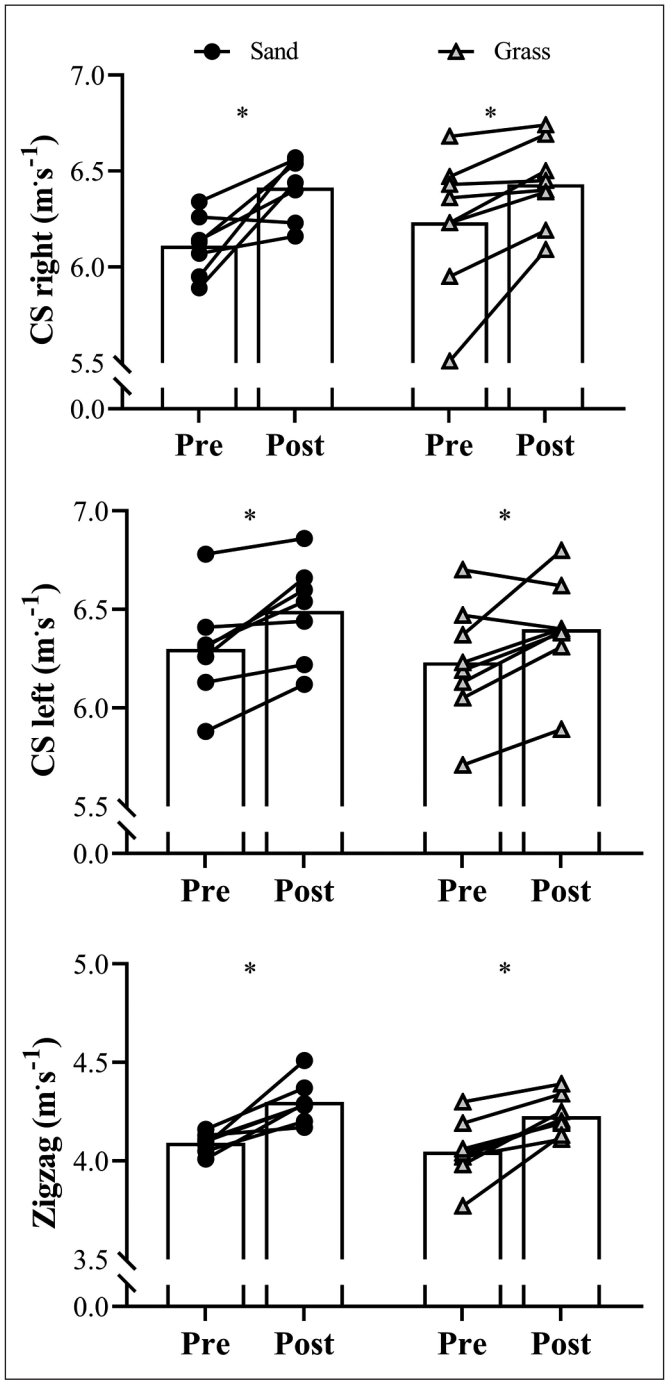


FIG. 3. Variations in the curve sprint for right and left sides, and Zigzag change of direction velocities in the sand and grass groups during the 8-week training period. Symbols represent individual results and bars correspond to mean values. *Main effect of time (P < 0.05) in comparison to "Pre" assessments.

Figure 3 shows the comparisons of CS and COD performances between pre- and post-assessments for both training groups. Both sand and grass groups revealed similar increases in the CS velocity for both right (P = 0.002; ES [95% CI] = 1.28 [0.23; 2.27]; P = 0.019; ES [95% CI] = 1.10 [0.18; 1.97], for sand and grass groups, respectively) and left sides (P = 0.006; ES [95% CI] = 1.46 [0.34; 2.53]; P = 0.009; ES [95% CI] = 0.98 [0.10; 1.81], for sand and grass groups, respectively) as well as for the COD velocity (P < 0.001; ES [95% CI] = 1.72 [0.49; 2.90]; P = 0.002; ES [95% CI] = 1.93 [0.71; 3.12], for sand and grass groups, respectively) after the 8-week training period. No group*time interaction was noted for CS and Zigzag COD velocities (P = 0.354 and 0.756 for right and left sides, respectively; and P = 0.615 for Zigzag).

DISCUSSION

This study examined and compared the effects of two different mixed training programmes (i.e., plyometric and sprint training strategies performed on sand or grass surfaces) on the jump- and speed-related performance of elite young soccer players across an 8-week interseason training period. Our main results revealed that: 1) similar training loads (i.e., assessed by s-RPE) were observed between both experimental groups during the 8 weeks; 2) no improvements in vertical jump performance were found in either of the groups; 3) linear sprint velocity and acceleration were significantly enhanced after sand training; 4) both training strategies significantly increased CS and COD speeds. These data confirm the effectiveness of mixed training strategies (i.e., sprint-jump training) performed on either sand or grass surfaces for inducing positive changes in speed-related performance. Nevertheless, the sand surface appears to be more efficient to simultaneously develop a range of different speed capacities (i.e., linear sprint, CS, and COD speed) in elite young soccer players.

The s-RPE values varied similarly in both groups over 45 training sessions. Considering that the s-RPE responses are influenced by distinct physical and physiological parameters (e.g., speed endurance and aerobic fitness) [21–23], this result suggests that the randomization process was well conducted and balanced, allocating players with similar fitness levels and demands to both groups. Importantly, the s-RPE values of both groups were similar for soccer training sessions and friendly matches, and when comparing sand and grass training sessions. The latter finding is especially relevant, since previous studies reported that training on sand is associated with greater metabolic energy cost [9] and lactate accumulation [24], compared to harder surfaces, which, theoretically, may result in higher perceived training loads. However, the high-speed impacts and high application of eccentric forces against hard surfaces may be more demanding for the soccer players, which, in turn, could equalize and balance the overall training stimulus, leading athletes from both groups to report similar perceived training loads after the sprint-jump training sessions. In fact, previous studies have shown that performing plyometrics on harder surfaces results in higher levels of

muscle soreness and indirect markers of muscle damage (e.g., creatine kinase activity) compared to sand surfaces [8, 10]. Therefore, the RPE after training sessions executed either on sand or hard surfaces may be influenced by different factors but result in similar RPE responses. Further studies are necessary to clarify the pathways and mechanisms behind these "similar perceptions" and responses to training.

Contrary to previous investigations [6, 8], we did not find significant improvements in vertical jumping ability after sand or grass interventions. To some extent, this result may be explained by two complementary factors: 1) twelve sprint-jump training sessions were completed over 8 weeks by both groups, which means that, across some weeks, only one plyometric/speed training session was performed; and 2) the total volume of jumps executed during the entire training phase was lower than that reported or indicated in previous studies (~110 jumps per week in 12 sessions vs > 140 jumps per week in > 14 sessions) [25, 26]. Indeed, during periods with high volumes of technical-tactical training and matches, higher frequencies and volumes of plyometric exercises seem to be necessary to substantially improve jumping performance [25–27]. For example, Ramirez-Campillo et al. [28] found only small increases in the CMJ height (4.3% versus 2.2% in the control group) of young soccer players, after examining the effects of a 7-week low-volume plyometric training (i.e., 60 drop jumps per session, twice a week) programme implemented during the in-season phase. It is worth noting that the regular training routine of these players (according to the authors) comprised "usual soccer sessions" with a much shorter duration than that described in our study (90 min vs. 134 min, on average, in our study). Unquestionably, this higher volume of soccer-specific training along with the inadequate time for optimizing power-related capabilities may further compromise the proper development of jumping ability. In this regard, soccer strength and conditioning coaches have already stated that the main challenges faced during the preparation of modern soccer players are associated with the difficulties imposed by the congested fixture [4] schedules, which hampers the balance between strength and conditioning practices (e.g., strength-power training) and soccer-specific training. In fact, when asked if they would change anything in their training routines, given unlimited time and resources, the most frequent responses of these practitioners were related to increases in the frequency and volume of neuromuscular training strategies [4, 5]. Of note, the plyometric programmes used in this study were defined in accordance with the technical staff of the club and were adequately implemented within a real training scenario. This should be considered in future interventions with soccer players, especially when improvements in vertical jump performance are expected.

Maximum acceleration capacity (i.e., 0–10 m) and linear sprint velocity improved only in the sand training group. Similar results were obtained by Impellizzeri et al. [8], who compared the effects of a 4-week plyometric training programme executed on sand or grass surfaces in amateur soccer players, in which linear sprint velocity increased significantly only in the sand group. Although the mechanisms underlying this result remain to be fully elucidated, it could be speculated that the use of sand exercises may provide a greater stimulus to muscle contractile properties (in comparison with grass drills) [6, 29, 30]. Indeed, to perform explosive drills on sand (e.g., maximal sprints and jumps), soccer players are forced to overcome the resistance naturally generated by this soft surface, which results in increased contraction time and greater displacement of the lower extremity joints and, consequently, in more work being done by the muscles [31, 32]. Likewise, during the initial phases of sprinting (i.e., acceleration phase), athletes have to accelerate rapidly to overcome the inertia of the body mass, and thus achieve higher velocities [33]. In practical terms, these movements tend to resemble those observed during sand training that rely heavily on the application of substantial amounts of force onto the ground, with a marked and prominent contribution of concentric muscle contractions [6, 8, 30]. At least in theory, the superior gains elicited by sand surfaces in both acceleration and linear sprint velocity may be related to these biomechanical and neuromuscular factors and similarities that can lead to a greater participation (and thus increase) of concentric strength during the initial phases of sprinting [6] (i.e., maximum acceleration phase). This hypothesis should be tested in future research, specifically designed to examine the neuromechanical adaptations to soft and hard surfaces.

After the 8-week training period, both groups presented significant (and similar) increases in CS velocity. This suggests that the mixed training programme used in our study, comprising unilateral and bilateral vertical and horizontal jumps of different types (e.g., drop jumps and hurdles jumps), short linear sprints, and 90º COD sprint drills, was effective to improve curvilinear sprint performance, irrespective of training surface (i.e., sand or grass). Curiously, unlike linear sprint velocity, which increased only in the sand training group, CS performance improved significantly in both groups. Although seemingly similar and largely correlated ($r \geq 0.74$ for linear and curvilinear sprints of equal distances, i.e., 17 m) [19], linear sprint and CS abilities exhibit some critical differences. In general, curvilinear running is associated with longer contact times and greater muscle activation in the gastrocnemius medialis, and lower muscle activation in the biceps femoris, compared to traditional sprints [17, 34]. In addition, over curved paths, the "inside leg" is usually more affected than the "outside leg", exhibiting higher activation of hip internal rotation muscles (i.e., semitendinosus and adductor) and longer foot contact times, whereas the outside leg displays higher activation of hip external rotation muscles (i.e., biceps femoris and gluteus medius) [17, 34]. Huge discrepancies in muscle activation and mechanical and technical aspects are also observed when comparing different jump types [35] and sprint stimuli [17]. Therefore, it can be speculated that the mixed training strategy (Table 1) proposed in our study contributed to promoting positive adaptations in certain mechanisms underpinning CS performance. However, we recognize that this is simply speculation, which should be further discussed and clarified.

Similarly to CS, COD sprint velocity increased as a result of both training interventions. This result agrees with previous research comparing the effects of sand and hard surface training interventions on the COD ability of team-sport athletes and supports our initial assumption that the combination of a range of different plyometric and (multi-directional) sprint activities would result in improved speed-related performance [36]. These beneficial effects may be explained, at least in part, by the reasons and mechanisms mentioned above, thus being a product of improvements in a series of neuromechanical factors directly related to COD performance (e.g., deceleration capacity, inter-limb muscle coordination, and motor-unit activation) [37–39]. Again, it should be emphasized that such improvements are commonly found after short-term training programmes (i.e., ≤ 8 weeks) involving sprint and/or jump drills [40–42], which reinforces our argument regarding their potential transference to COD performance.

In summary, we found that the mixed training strategy used in our study, comprising a variety of sprint and jump drills, was able to improve CS and COD speed performances, irrespective of training surface (i.e., sand or grass). Maximum acceleration capacity (i.e., 0–10 m) and linear sprint velocity (i.e., ≤ 17 m) increased only in the sand group, indicating the effectiveness of a sand surface to promote significant gains in short-sprint performance. The low volume of plyometric training (compared to the high volume of soccer-specific training) may potentially explain the lack of improvements reported for vertical jumping ability, for both groups. This study is limited by the small sample size and the lack of a pure control group of subjects who did not participate in any of the interventions, which is commonplace in studies involving elite team-sport players during the competitive season. Under this rationale, it is important to evaluate the extent to which the soccer-specific training content, and the other stimuli present in their weekly schedules (i.e., resistance training), could influence the physical performance of soccer players across the 8 weeks. Lastly, we did not assess the neuromuscular mechanisms and the biomechanical adjustments involved in the performance changes observed. Hence, it would be interesting to examine whether there are differences in neuromechanical adaptations after training programmes executed on different surfaces and compare the effects of sand training with those resulting from training strategies which also lead to acute decreases in sprint velocity by the addition of external resistance (e.g., sled towing).

CONCLUSIONS

We compared the effects of two different training surfaces across an 8-week training period in elite young soccer players. Our results reinforce the findings of a recent meta-analysis [6], supporting the use of a sand surface as an efficient and practical strategy to improve the speed-related performance of team-sport athletes. Moreover, sand training was not perceived as more intense than grass training, which may have important implications for training prescription, especially during congested match schedules and when carefully balanced. Overall, the mixed-training scheme implemented in our study, performed on both sand and grass surfaces, significantly improved (and to a similar extent) CS and COD speed performances. On the other hand, maximum acceleration capacity and linear sprint velocity increased only in the sand group. Bearing in mind the importance of acceleration and sprint capabilities in elite soccer [1–3], we consider that our results may be highly informative and practically relevant for soccer coaches and sport scientists.

Conflict of interest statement

The authors declare no conflict of interest.

REFERENCES

1. Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The evolution of physical and technical performance parameters in the English Premier League. Int J Sports Med. 2014; 35(13):1095–1100.
2. Faude O, Koch T, Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. J Sports Sci. 2012; 30(7):625–631.
3. Stølen T, Chamari K, Castagna C, Wisløff U. Physiology of soccer: an update. Sports Med. 2005; 35(6):501–536.
4. Loturco I, Freitas TT, Alcaraz PE, Kobal R, Nunes RFH, Weldon A, Pereira LA. Practices of strength and conditioning coaches in Brazilian elite soccer. Biol Sport. 2022; 39(3):779–791.
5. Weldon A, Duncan MJ, Turner A, Sampaio J, Noon M, Wong DP, Lai VW. Contemporary practices of strength and conditioning coaches in professional soccer. Biol Sport. 2021; 38(3):377–390.
6. Pereira LA, Freitas TT, Marín-Cascales E, Bishop C, McGuigan MR, Loturco I. Effects of training on sand or hard surfaces on sprint and jump performance of team-sport players: a systematic review with meta-analysis. Strength Cond J. 2021;43(3):56–66.
7. Giatsis G, Kollias I, Panoutsakopoulos V, Papaiakovou G. Biomechanical differences in elite beach-volleyball players in vertical squat jump on rigid and sand surface. Sports Biomech. 2004; 3(1):145–158.
8. Impellizzeri FM, Rampinini E, Castagna C, Martino F, Fiorini S, Wisloff U. Effect of plyometric training on sand versus grass on muscle soreness and jumping and sprinting ability in soccer players. Br J Sports Med. 2008; 42(1):42–46.
9. Lejeune TM, Willems PA, Heglund NC. Mechanics and energetics of human locomotion on sand. J Exp Biol. 1998; 201(Pt 13):2071–2080.
10. Miyama M, Nosaka K. Influence of surface on muscle damage and soreness induced by consecutive drop jumps. J Strength Cond Res. 2004; 18(2):206–211.
11. Binnie MJ, Dawson B, Pinnington H, Landers G, Peeling P. Part 2: effect of training surface on acute physiological responses after sport-specific training. J Strength Cond Res. 2013; 27(4):1057–1066.
12. Binnie MJ, Dawson B, Pinnington H, Landers G, Peeling P. Effect of training surface on acute physiological responses after interval training. J Strength Cond Res. 2013; 27(4):1047–1056.
13. Taylor JB, Wright AA, Dischiavi SL, Townsend MA, Marmon AR. Activity Demands During Multi-Directional Team Sports: A Systematic Review. Sports Med 2017; 47(12):2533–2551.
14. Caldbeck P. Contextual sprinting in Premier League football. Liverpool John Moores University; 2020.

15. Fernandes R, Bishop C, Turner AN, Chavda S, Maloney SJ. Train the Engine or the Brakes? Influence of Momentum on the Change of Direction Deficit. Int J Sports Physiol Perform. 2021; 16(1):90–96.
16. Freitas TT, Pereira LA, Reis VP, Fernandes V, Alcaraz PE, Azevedo P, Loturco I. Effects of a Congested Fixture Period on Speed and Power Performance of Elite Young Soccer Players. Int J Sports Physiol Perform. 2021; 16(8):1120–1126.
17. Filter A, Olivares-Jabalera J, Santalla A, Morente-Sánchez J, Robles-Rodríguez J, Requena B, Loturco I. Curve Sprinting in Soccer: Kinematic and Neuromuscular Analysis. Int J Sports Med. 2020; 41(11):744–750.
18. Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, Doleshal P, Dodge C. A new approach to monitoring exercise training. J Strength Cond Res. 2001; 15(1):109–115.
19. Loturco I, Pereira LA, Fílter A, Olivares-Jabalera J, Reis VP, Fernandes V, Freitas TT, Requena B. Curve sprinting in soccer: relationship with linear sprints and vertical jump performance. Biol Sport. 2020; 37(3):277–283.
20. Rhea MR. Determining the magnitude of treatment effects in strength training research through the use of the effect size. J Strength Cond Res. 2004; 18(4):918–920.
21. Milanez VF, Pedro RE, Moreira A, Boullosa DA, Salle-Neto F, Nakamura FY. The role of aerobic fitness on session rating of perceived exertion in futsal players. Int J Sports Physiol Perform. 2011; 6(3):358–366.
22. Nakamura FY, Pereira LA, Rabelo FN, Ramirez-Campillo R, Loturco I. Faster Futsal Players Perceive Higher Training Loads and Present Greater Decreases in Sprinting Speed During the Preseason. J Strength Cond Res. 2016; 30(6):1553–1562.
23. Pereira LA, Freitas TT, Zanetti V, Loturco I. Variations in Internal and External Training Load Measures and Neuromuscular Performance of Professional Soccer Players During a Preseason Training Period. J Hum Kinet. 2022; 81:149–162.
24. Pinnington HC, Dawson B. The energy cost of running on grass compared to soft dry beach sand. J Sci Med Sport. 2001; 4(4):416–430.
25. Ramirez-Campillo R, Castillo D, Raya-González J, Moran J, de Villarreal ES, Lloyd RS. Effects of Plyometric Jump Training on Jump and Sprint Performance in Young Male Soccer Players: A Systematic Review and Meta-analysis. Sports Med. 2020; 50(12):2125–2143.
26. Ramirez-Campillo R, Moran J, Oliver JL, Pedley JS, Lloyd RS, Granacher U. Programming Plyometric-Jump Training in Soccer: A Review. Sports (Basel). 2022; 10(6).
27. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. J Strength Cond Res. 2012; 26(8):2293–2307.
28. Ramírez-Campillo R, Meylan C, Alvarez C, Henríquez-Olguín C, Martínez C, Cañas-Jamett R, Andrade DC, Izquierdo M. Effects of in-season low-volume high-intensity plyometric training on explosive actions and endurance of young soccer players. J Strength Cond Res. 2014; 28(5):1335–1342.
29. Binnie MJ, Dawson B, Pinnington H, Landers G, Peeling P. Sand training: a review of current research and practical applications. J Sports Sci. 2014; 32(1):8–15.
30. Pinnington HC, Lloyd DG, Besier TF, Dawson B. Kinematic and electromyography analysis of submaximal differences running on a firm surface compared with soft, dry sand. Eur J Appl Physiol. 2005; 94(3):242–253.
31. Ahmadi M, Nobari H, Ramirez-Campillo R, Pérez-Gómez J, Ribeiro ALA, Martínez-Rodríguez A. Effects of Plyometric Jump Training in Sand or Rigid Surface on Jump-Related Biomechanical Variables and Physical Fitness in Female Volleyball Players. Int J Environ Res Public Health. 2021; 18(24).
32. Mirzaei B, Norasteh AA, Asadi A. Neuromuscular adaptations to plyometric training: depth jump vs. countermovement jump on sand. Sport Sci Health. 2013; 9(3):145–149.
33. Loturco I, Pereira LA, Kobal R, Zanetti V, Kitamura K, Abad CC, Nakamura FY. Transference effect of vertical and horizontal plyometrics on sprint performance of high-level U-20 soccer players. J Sports Sci. 2015; 33(20):2182–2191.
34. Pietraszewski P, Gołaś A, Krzysztofik M. Comparison of Muscle Activity During 200 m Indoor Curve and Straight Sprinting in Elite Female Sprinters. J Hum Kinet. 2021; 80:309–316.
35. Cappa DF, Behm DG. Neuromuscular characteristics of drop and hurdle jumps with different types of landings. J Strength Cond Res. 2013; 27(11):3011–3020.
36. Beato M, Bianchi M, Coratella G, Merlini M, Drust B. Effects of Plyometric and Directional Training on Speed and Jump Performance in Elite Youth Soccer Players. J Strength Cond Res. 2018; 32(2):289–296.
37. Asadi A, Arazi H, Ramirez-Campillo R, Moran J, Izquierdo M. Influence of Maturation Stage on Agility Performance Gains After Plyometric Training: A Systematic Review and Meta-analysis. J Strength Cond Res. 2017; 31(9):2609–2617.
38. Dos'Santos T, Thomas C, Comfort P, Jones PA. The Effect of Angle and Velocity on Change of Direction Biomechanics: An Angle-Velocity Trade-Off. Sports Med. 2018; 48(10):2235–2253.
39. McBurnie AJ, Dos' Santos T. Multidirectional Speed in Youth Soccer Players: Theoretical Underpinnings. Strength Cond J. 2022; 44(1):15–33.
40. Ross A, Leveritt M, Riek S. Neural influences on sprint running: training adaptations and acute responses. Sports Med. 2001; 31(6):409–425.
41. Markovic G, Mikulic P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. Sports Med. 2010; 40(10):859–895.
42. Ross A, Leveritt M. Long-term metabolic and skeletal muscle adaptations to short-sprint training: implications for sprint training and tapering. Sports Med. 2001; 31(15):1063–1082.

Core body temperature responses during competitive sporting events: A narrative review

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ABSTRACT: Due to the lack of research in real-world sports competitions, the International Olympic Committee, in 2012, called for data characterising athletes' sport and event-specific thermal profiles. Studies clearly demonstrate that elite athletes often attain a core body temperature (Tc) ≥ 40°C without heat-related medical issues during competition. However, practitioners, researchers and ethical review boards continue to cite a Tc ≥ 40°C (and lower) as a threshold where athlete health is impacted (an assumption from laboratory studies). Therefore, this narrative review aims to: (i) summarise and review published data on Tc responses during competitive sport and identify key considerations for practitioners; (ii) establish the incidence of athletes experiencing a Tc ≥ 40°C in competitive sport alongside the incidence of heat illness/heat stroke (EHI/EHS) symptoms; and (iii) discuss the evolution of Tc measurement during competition. The Tc response is primarily based on the physical demands of the sport, environmental conditions, competitive level, and athlete disability. In the reviewed research, 11.9% of athletes presented a Tc ≥ 40°C, with only 2.8% of these experiencing EHI/EHS symptoms, whilst a high Tc ≥ 40°C (n = 172; Tc range 40–41.5°C) occurred across a range of sports and environmental conditions (including some temperate environments). Endurance athletes experienced a Tc ≥ 40°C more than intermittent athletes, but EHI/EHS was similar. This review demonstrates that a Tc ≥ 40°C is not a consistently meaningful risk factor of EHI/EHS symptomology in this sample; therefore, Tc monitoring alongside secondary measures (i.e. general cognitive disturbance and gait disruption) should be incorporated to reduce heat-related injuries during competition.

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INTRODUCTION

An athlete's core body temperature (Tc) increases during strenuous physical activity [1, 2] as locomotion and associated metabolic pathways are thermally 'inefficient' at providing energy for muscular contractions [3]. Only ~20–25% of the energy used translates to movement, with the remaining released as heat [4]. The Tc rise is proportional to movement demands [3], and hence, athletes competing in short intermittent activities (e.g. repeated sprinting) or prolonged endurance events (e.g. long-distance running) can both experience a high Tc [3]. In environments where the air temperature and mean radiant temperature are lower than the athlete's skin temperature (i.e. negative heat gradient), thermoregulatory mechanisms (i.e. cutaneous vasodilation, peripheral blood flow and sweating) and changes in behaviour effectively dissipate excess heat to balance heat gain with heat loss [5]. These mechanisms transfer heat from the core towards the skin surface, where the heat dissipates into the environment via evaporation (predominately), convection, radiation, and conduction [5].

While thermoregulatory mechanisms effectively regulate Tc in cool environments (e.g. heat production does not overwhelm heat dissipation), athletes often compete in hot [6, 7] and/or humid conditions [8, 9], where the capacity for heat exchange decreases [3]. Consequently, if heat production exceeds the body's ability to dissipate it, an athlete's Tc will increase [10], often resulting in a reduction in pace or power output [11, 12]. This Tc rise can reduce performance, and in some scenarios, exertional heat illness/heat stroke (EHI/EHS) may ensue [13, 14]. Risk of EHI/EHS is an increasing concern [1], given major-sporting events are increasingly hosted in hot climates due to continued globalisation of sport alongside climate change [12].

In response to these concerns and the lack of research in competitive sport, the International Olympic Committee (IOC) called for research to better characterise sport and event-specific thermal profiles of Olympic and international level athletes competing in the heat [1, 15]. Recent advancements in ingestible telemetric sensor

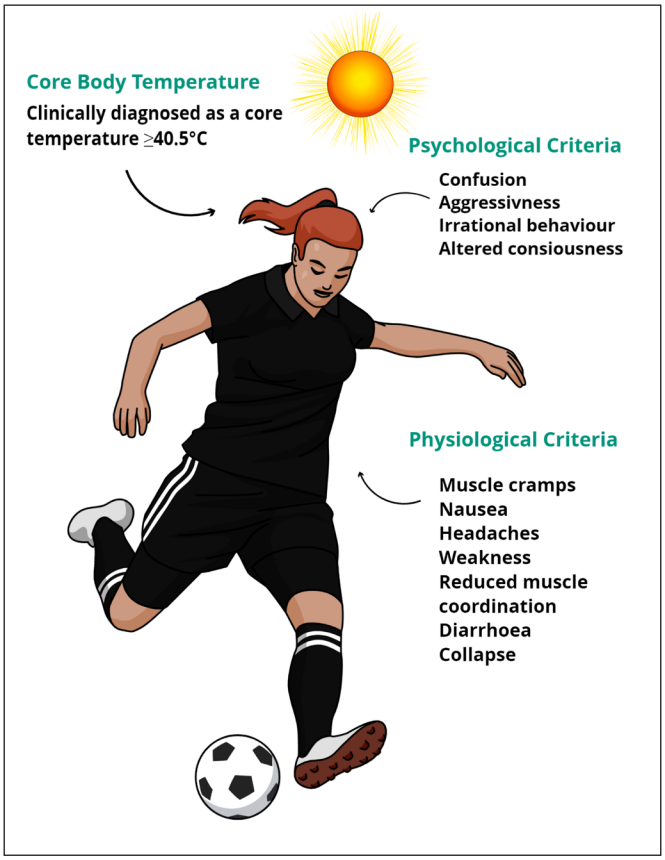


FIG. 1. Symptoms of Exertional Heat Illness/Heat Stroke. Note. The information illustrated in this figure was extracted from *Consensus Recommendations on Training and Competing in the Heat and National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses* [1,75].

technology allow continuous Tc measurements (with data logging) during an event without the need for any other equipment to be carried by the athlete [16, 17]. Harnessing these technological advancements and thus meeting the IOC call, data now demonstrates that elite athletes can and often attain a Tc ≥ 40°C (a recognised criterion in diagnosing heat illnesses; see Figure 1) without heat-related medical issues arising during competition.

Although the belief that a Tc ≥ 40°C results in health and performance impairments have been heavily criticised [18, 19], practitioners, researchers and ethical review boards continue to mistakenly cite a Tc ≥ 40°C (and lower) as a threshold where athlete health is negatively impacted, which is an assumption derived from laboratory studies [19]. Importantly, practitioners may have a concerning lack of knowledge in this area, as a recent study demonstrated that some practitioners believed a safe Tc was between 29–45°C [20], which is biologically implausible, thus highlighting a need for a resource characterising the Tc profiles of athletes in competitive sport. Nevertheless, studies measuring Tc responses during sports have not yet been collated into a single resource, which could assist practitioners in contextualising the Tc responses across various sports and environments to inform their athletes' physical preparation and performance plans for upcoming competitions.

Therefore, this narrative review aims to: (i) summarise and review the data published on Tc responses during competitive sport and identify key considerations for practitioners; (ii) establish the incidence of athletes experiencing a Tc ≥ 40°C in competitive sport alongside the incidence of EHI/EHS symptoms; and (iii) discuss the evolution of Tc measurement during athletic competition. A narrative review was chosen since this is a review of descriptive studies [21], with a focus on providing an accessible resource to benefit practitioners, athletes and scientists.

CORE BODY TEMPERATURE RESPONSES

Summary of the data

This review included studies that measured athletes' rectal or gastrointestinal Tc during a competitive sporting event, including events organised by researchers that followed the same regulations used in competition. Athletes competing in all environmental conditions were included (see Table 1). Articles were excluded if they measured Tc within a laboratory environment or during training sessions. Further, this review did not consider skin and tympanic temperatures valid measures of Tc [22]. A data extraction software tool (WebPlotDigitizer, California, USA) was used to retrieve core body temperature data from figures where necessary, and authors were also contacted to confirm these data if required.

A summary of 49 studies that measured the Tc response of athletes during competitive sports is presented in Table 1. The studies represent a sample of 1,450 athletes competing in a range of sports, categorised as intermittent (i.e. association football, Australian football, cricket, rugby sevens and tennis) or endurance sports (i.e. cycling, racewalking, running, triathlon, swimming, adventure racing and surf-skiing). The incidence of a Tc ≥ 40°C, EHI/EHS symptoms and sample demographics/study setting (i.e. competitive level, physical ability, sport type, and environmental risk categories) from the 49 studies appear in Table 2. These data will be used to provide further insight into Tc responses of athletes across the demographic/study settings.

Considerations for practitioners and athletes

Physical demands of the sport

Athletes competing in endurance sports had a higher incidence of a Tc ≥ 40°C (13.8%) than athletes in intermittent sports (4.4%). However, the prevalence of EHI/EHS symptoms was similar between both (2.8 vs. 2.7%). Notably, six endurance studies [12, 44, 52, 53, 58, 59] reported at least one symptom of EHI/EHS compared to two for intermittent sports (i.e. cricket and Rugby sevens) [6, 57], but it is unclear whether these symptoms occurred with the co-presence of a Tc ≥ 40°C in some studies.

Evidently, intermittent and endurance sports have different physical demands. Intermittent sports require repeated efforts (including

supra-maximal efforts) with short and often incomplete recovery periods [68], whilst endurance athletes typically work at submaximal intensities continuously for long durations with limited or no recovery [69]. Consequently, the contrasting demands drive differential Tc response kinetics [3], given that the rise in Tc is generally proportional to the oxygen consumption in temperate environments, which will vary with mechanical efficiency or movement economy [5]. Australian Football (AFL) athletes, for instance, experience peak Tc during the quarters (regardless of chronological order) with the highest number of maximal accelerations [23], whilst the Tc of endurance runners gradually increases throughout their event, likely due to the more stable exercise intensity and oxygen consumption [27]. Some endurance events have an intermittent component as well, such as road cycling, which involves periods of drafting and free-wheeling, which decreases power output, energy expenditure, heart rate and overall heat storage [54, 70] or conversely, attacks and stages with ascents can increase power output and heat storage [52]. An interesting comparison between road and time-trial cycling events demonstrated that cyclists experience higher Tc during a time-trial than road race event, despite similar environmental conditions and the road race having a far greater duration [7]. Hence, the higher Tc in the time-trial was caused by a higher mean power output (4.7 ± 0.3 W/kg) than in the road race (2.7 ± 0.4 W/kg) [7], which is evidence that the intensity of an activity is a bigger contributing factor to a Tc rise than duration.

Endurance athletes gradually accumulate heat, with peak Tc's in the latter stages of their events [26, 27, 46, 63]. For example, the Tc of race walkers [59], marathon [27, 44] and endurance runners [8, 24] and swimmers increased initially and then reached a relative plateau (although likely still increasing minimally when time-averaged) or increased at each measurement interval throughout their race [8, 39]. Endurance athletes typically, but not exclusively, perform a large duration of their events at constant intensities (albeit with periods of attacks and surges, including the well-discussed 'end spurt' phenomenon) [71]. This consistent locomotion liberates substantial heat, due to the inefficiencies outlined earlier. Whilst these Tc responses to endurance exercise in the heat are typical, there are exceptions. Triathlon, for example, is a sport where peak Tc was seen post-swim, decreasing thereafter in the cycling and running phases [8, 43]. The evaporative, convective, and radiative heat exchange potentials are more favourable during the run and cycle phases compared to the swim, especially when a wetsuit is worn. However, the Tc of swimmers in other studies initially increased [30, 40–42, 55] and then began to decrease approximately 20 minutes into their swim [55]. Interestingly, these swimmers presented a lower Tc at the end of their event, likely due to the cold-water temperatures these swimmers were competing in [30, 40–42, 55]. As such, the variation in Tc responses makes it difficult to simply define a Tc threshold that can affect endurance performance, but endurance athletes that maintain high intensities for a medium-long duration, without recovery opportunities, have an increased likelihood of experiencing a Tc ≥ 40°C.

Core body temperature does not necessarily accumulate across an intermittent event, due to the variability in the physical demands within and between these sports. Professional soccer players can perform 459–856 m of high-speed running within a match [72], and the variability of high-speed running appears to influence the Tc response. Indeed, the peak Tc of soccer players competing in the heat were similar after each half, despite a ~7% reduction in total distance and ~26% reduction in high-speed running in the second half [47]. The players likely adopted a pacing strategy to reduce the number of high speed-efforts in the second half to avoid excessive fatigue in the heat, which is a common strategy by professional soccer players (as observed during the 2014 FIFA World Cup) [73]. Rugby sevens is another intermittent sport played at very high intensities [74]. Yet only one Rugby sevens athlete experienced a Tc ≥ 40°C and presented at least one symptom of EHI/EHS [6] across 13 matches in a range of conditions (WBGT range 18.9°C-31.3°C) [34, 60] and ambient temperature ranges (26.0–31.3°C) [6]. Since a Rugby sevens match is considerably shorter than most sports (only 14-minutes), the short duration combined with breaks in play and substitutions may have precluded the athletes' Tc from exceeding 40°C. Based on the available research, cricket was the only intermittent sport where multiple athletes reported symptoms of EHI/EHS [57]. Cricket athletes (e.g. batters, close fielders and the wicket-keeper) wear extra protective clothing, which can hinder evaporative heat loss. The extra clothing, coupled with the high ambient temperatures, may explain the reported symptoms. It is also important to consider that the cricket athletes compete over consecutive days, and the risk of EHI/EHS increases the day after an athlete competes in an environment with a high WBGT [75], which may explain the symptoms reported.

Environmental risk categories

While athletes experienced a Tc ≥ 40°C in all environmental conditions, the highest incidence of a Tc ≥ 40°C was in the "high-very high risk" (18.4%), followed by the "moderate-high risk" (18.2%), "extreme risk" (8.8%), "low risk" (9.6%) and "low-moderate risk" (4.8%) conditions. Unsurprisingly, environmental condition thresholds incorporating an element of 'high-risk' (i.e., "high-very high risk" and "moderate-high risk") had the highest incidence of Tc ≥ 40°C since the thermal gradient between the skin and environment decreases in hot climates (further compounded by the co-presence of high ambient water vapour pressure), thereby compromising heat loss [3].

Direct comparisons between events in different environmental risk categories further demonstrated that athletes' Tc were generally greater in higher-risk categories. For example, 37.1% of Australian Football athletes in one study experienced a Tc ≥ 40°C during matches played in "high-very high risk" conditions compared to zero in low-moderate risk conditions [23]. Similarly, soccer [47] and tennis [51] athletes' experienced a significantly higher Tc during matches played in "extreme risk" conditions than in "low-moderate risk" environments. However, tennis athletes in another study did not present a significantly different peak Tc between matches played in

TABLE 1. Summary of Studies Investigating the Core Body Temperature Responses to Competitive Sport.

Investigation	Sample, Event	Conditions	Tc	Peak Tc	Tc ≥ 40°C	EHI symptoms	Tc Measurement method
Aughey et al. [23]	Elite males ($n = 35$), Australian Football	Hot T_a: 24–30°C; RH: 40–86% Cold T_a: 12–22°C; RH: 29–60%	Average: 37.3–39.4°C	40.5°C	13	0	CorTemp capsules, 60, 30 & 2 min prior & quarters.
Baillot and Hue [8]	Trained males ($n = 19$), Guade-loupe Half Ironman Triathlon	T_a: 27.2 ± 0.5°C RH: 80 ± 2% WBGT: 25.4 ± 1.0°C Water temp: 29.5°C	Average B (± SD): 37.1 ± 0.7°C Average 1 (± SD):37.8 ± 0.9°C Average 2 (± SD): 37.8 ± 1.0°C Average 3 (± SD): 38.4 ± 0.7°C	40.1°C	1	0	CorTemp capsules, Before & after swim, cycle, run phase
Baillot et al. [24]	Gender not reported ($n = 20$), Trail des Châteaux	T_a: 25.7 ± 0.6°C RH: 78% WBGT: 23.6 ± 0.9°C	Start mean (± SD): 37.4 ± 0.9°C 11 km mean (± SD): 38.5 ± 1.0°C End mean (± SD): 38.3 ± 0.9°C	39.9°C	0	0	CorTemp capsules, Start, 11th km, end
Bergeron et al. [25]	Youth Boys ($n = 8$), Tennis National Youth Championships	WB GT 30.3 ± 2.5°C	Singles average B (± SD): 37.3 ± 0.3°C Average 1 (± SD): 38.6 ± 0.3°C Average 2 (± SD): 38.6 ± 0.3°C Average 3 (± SD): 38.6 ± 0.2°C Doubles average B (± SD): 38.0 ± 0.4°C Average 1 (± SD): 38.3 ± 0.4°C Average 2 (± SD): 38.5 ± 0.5°C Average 3 (± SD): 38.3 ± 0.5°C	N/a	0	0	CorTemp capsules, Changeovers & after matches
Duffield et al. [31]	Elite males ($n = 10$), Australian Football	T_a: 29.5 ± 1.3°C RH: 64.9 ± 16.7% WBGT: 27.6 ± 2.3°C	Average B (± SD): 37.2 ± 0.4°C Average 1 (± SD): 37.8 ± 0.5°C Average 2 (± SD): 39.0 ± 0.8°C Average 3 (± SD): 39.1 ± 0.7°C Average 4 (± SD): 39.2 ± 0.9°C Average 5 (± SD): 39.2 ± 0.6°C	N/a	1	0	VitalSense capsules, Before match & quarter breaks

TABLE 1. Continued.

Investigation	Sample, Event	Conditions	Tc	Peak Tc	Tc ≥ 40°C	EHI symptoms	Tc Measurement method
Duffield et al. [9]	Elite males (n = 7), A-League Matches	T_a: 27 ± 2°C RH: 80 ± 10% WBGT: 26 ± 2°C	*Control Group Average (± SD)* 1: 38.5 ± 0.3°C 2: 39.9 ± 0.4°C 3: 39.1 ± 0.3°C 4: 39.7 ± 0.8°C *Cooling Group Average (± SD)* 1: 28.5 ± 0.2°C 2: 39.7 ± 0.4°C 3: 38.7 ± 0.3°C 4: 39.6 ± 0.6°C	N/a	0	0	VitalSense capsules, Before match, before & after half time
Edwards and Clark [32]	Recreational males (R; n = 8), Professional males (P; n = 7), Football (soccer)	R T_a:16°C; RH 47% P T_a :19°C; RH 53%	Average 1st R (± SD): 38.5 ± 0.6°C Average 1st P (± SD): 38.1 ± 0.5°C Average 2nd R (± SD): 39.3 ± 0.5°C Average 2nd P (± SD): 38.8 ± 0.5°C	N/a	0	0	CorTemp capsules, 10 min intervals
Fenemor et al. [6]	Elite males (n = 11), Oceania Rugby Sevens tournament	Game 1 Ta: 31.3°C RH 71%; Game 2 $Ta_.$ 29.0°C, RH: 73%; Game 3 T_a. 30.4°C RH: 73%; Game 4 T_a. 29.9°C, RH: 75%; Game 5 T_a. 26.0°C RH: 81%	N/a	N/a	1	1	e-Celsius capsules, 30 s intervals
Griggs et al. [33]	SCI (n = 10) and Non-SCI (n = 7), Wheelchair Rugby	T_a: 18.4–20.9°C RH: 31.1–45.1%	Average SCI (± SD): 37.6 ± 0.4–39.3 ± 0.5°C. Average non-SCI (± SD): 38.1 ± 0.3–38.8 ± 0.3°C	39.3°C	0	0	CorTemp capsules, End of quarters
Henderson et al. [34]	Elite females (n = 12) World Rugby 7's	G1 WBGT: 19.0–19.6°C, G2 WBGT: 18.9–20.0°C G3 WBGT: 18.9–20.1°C	Median (range) G1: 38.4 (37.7–39.1°C) G2: 38.7 (37.9–39.3°C) G3: 38.6 (38.2–39.6°C)	39.9°C	0	0	e-Celsius capsules, 30 s intervals
Hornery et al. [35]	Professional males (n = 6), Australian Tennis Circuits	Hard T_a: 32.0 ± 4.5°C Hard RH: 38.0 ± 14% Clay T_a: 25.4 ± 3.8°C; Clay RH: 32.0 ± 5%	Average hard (± SD): 38.9 ± 0.3°C Average clay (± SD): 38.5 ± 0.6°C	Hard: 39.3°C Clay: 39.5°C	0	0	Fitsense capsules, Breaks
Hue et al. [36]	Trained males (n = 8) Trained female (n = 1), Gwadarun	T_a: 30.0 ± 2.4°C RH: 82 ± 4%	Mean (± SD): 38.5 ± 0.2°C	38.3–38.7°C	0	0	CorTemp capsules, Before and finish
Hue et al. [37]	Elite subjects (n = 5), Surfski Ocean Ze Caribbean Race	T_a: 36.8 ± 2.4°C RH: 68 ± 3.0%	Before mean (± SD): 37.1 ± 0.4°C After mean (± SD): 38.5 ± 0.3°C	38.9°C	0	0	CorTemp capsules, Before and after
Hue et al., [38]	Elite subjects (n = 8), Surfski Ocean Racing World Cup	T_a: 35.9 ± 2.8°C RH: 64 ± 4.0%	Before mean (± SD): 36.7 ± 1.7°C After mean (± SD): 38.1 ± 1.1°C	40°C	1[1]	0	CorTemp capsules, Before and after

TABLE 1. Continued.

Investigation	Sample, Event	Conditions	Tc	Peak Tc	Tc ≥ 40°C	EHI symptoms	Tc Measurement method
Hue et al. [39]	Elite males ($n = 5$) Elite females ($n = 3$), Open Swimming French National Cup	WBGT: 30.0 ± 2.1°C Water temp: 28.1 ± 0.0°C	Mean (± SD): 38.3 ± 0.4°C	N/a	0	0	CorTemp capsules, At 2 km intervals
Høiseth et al. [40]	Trained Males ($n = 42$) Females ($n = 9$), Norseman Xtreme Triathlon	T_a = 8.6–15.6°C	Range 36.5–39.4°C	39.4	0	0	e-Celsius capsule, 2 min intervals
Knetchtle et al. [41]	Trained Male ($n = 1$), Ice Mile	Ta: 0°C WS: 2.19 km/h Water temp: 4.8°C	Start mean Tc (± SD) 37.7 ± 0.2°C Range: 36.9–38.3°C Finish mean Tc (± SD) 37.5°C ± 0.6°C Range: 35.9–38.5°C	38.6°C	0	0	Endotherm rectal thermometer,
Knetchle et al. [42]	Elite Males ($n = 2$), Ice swim	T_a: 0.8°C Humidity: 76% WS: 4 m/s Water temp: 4.3°C	Swimmer 1 start: 37.2°C Swimmer 1 finish: N/a Swimmer 2 start: 37.0°C Swimmer 2 finish: 32.0°C	N/a	0	0	Rectal thermometer, At the start and end of the race
Laursen et al. [43]	Trained males ($n = 10$), Ironman Triathlon	T_a: 23.3 ± 1.9°C (range: 19–26°C) RH: 60 ± 14% (range: 44–87%) Water temp: 19.5°C	Average (± SD): 38.1 ± 0.3°C	40.5°C	1	0	CorTemp capsules, Before, after swim, cycle, run finish
Lee et al. [44]	Male soldiers ($n = 31$), Singapore Half Army Marathon	Average (range) T_d: 26.4 (26.1–27.3°C) RH: 81% (79–82%) T_w 23.9 (23.7–24.4°C)	Peak average: 39.8 ± 0.5°C Range: 38.5–40.7°C	40.9°C	10	1	Vitalsense & CorTemp capsules,15 s intervals
Lucas et al. [45]	Males ($n = 7$) and females ($n = 5$), Southern Traverse Adventure Race	T_a Day 1: 5.2–22.3°C T_a Day 2: 11.5–22.2°C T_a Day 3: 7.1–11.4°C T_a Day 4: 4.4–13.0°C T_a Day 5: 2.6–16.8°C	Range: 36.0–39.2°C	N/a	0	0	CorTemp capsules, 1 min intervals
Maron et al. [46]	Trained males ($n = 2$), Santa Barbara Marathons	T_d: 17.9–21.7°C; T_w :13.2–17.4°C	Final Tc Athlete 1: 39.8–41.7°C Final Tc Athlete 2: 39.3–39.9°C	41.9°C	2	0	Rectal Thermometer, 9 min intervals
Mohr et al. [47]	Elite males ($n = 17$), Football (soccer)	T_a: 21°C, RH: 55% (mod) T_a: 43°C, RH: 12% (hot)	Average mod 1st (± SD): 38.7 ± 0.2°C, Average mod 2nd (± SD): 38.3°C ± 0.1 Average hot 1st (± SD): 39.6 ± 0.1°C Average hot 2nd (± SD): 39.6°C ± 0.1	N/a	0	0	Phillips rectal thermometer, Half time breaks
Morante and Brotherhood [48]	Males ($n = 19$) And females ($n = 6$), Semi-pro ($n = 13$), Recreational ($n = 12$), Tennis	T_a: 23.3 ± 7.1°C -26.9 ± 6.4°C WBGT: 20.9 ± 6.2°C -24.4 ± 4.9°C	Range male (± SD): 38.4 ± 0.4°C -38.5 ± 0.48°C Range female (± SD): 38.2 ± 0.3°C-38.4 ± 0.3°C	N/a	0	0	YSI rectal thermistor, 1 min intervals

TABLE 1. Continued.

Investigation	Sample, Event	Conditions	Tc	Peak Tc	Tc ≥ 40°C	EHI symptoms	Tc Measurement method
Morante and Brotherhood [49]	Males (n = 19) and females (n = 6), Tennis	T_a: 25 ± 5.4°C (range: 14.5–38.4°C); RH: 50.7 ± 14.3% (range: 21.8–73.7%) WBGT: 22.5 ± 4.3°C (range: 13.5–29.2)	Average (± SD): 38.45 ± 0.36°C Range: 37.43 to 39.98°C	N/a	0	0	YSI rectal thermistor, 1 min intervals
Özgünen et al. [50]	Semi-pro males (n = 11), Football (soccer)	G1 T_a: 34 ± 1°C; RH: 38 ± 2% G2 T_a: 36 ± 0°C; RH: 61 ± 1%	G1 range: 37.6 ± 0.3°C -39.1 ± 0.4°C G2 range: 37.7 ± 0.4°C -39.6 ± 0.3 1°C	40.2°C	2	0	VitalSense capsules, 10 min intervals
Périard et al. [51]	Males (n = 12), ITF Tennis	Cool T_a: 21.8 ± 0.1°C, Cool RH: 72.3 ± 3.2% Hot T_a: 36.8 ± 1.5°C, Hot RH: 36.1 ± 11.3%	Average cool (± SD): 38.7 ± 0.2°C Average hot (± SD): 39.4 ± 0.5°C	N/a	0	0	VitalSense capsules, Rest Breaks
Périard et al. [52]	Elite males (n = 14), Tour Down Under	T_d: 23–37°C RH: 19–72% WBGT: 21–29°C	Mean: 38.2–38.5°C	40.2	3	0	e-Celsius capsules, 30 s intervals
Pugh et al. [53]	Gender not reported (n = 77), Marathon	T_a: 22.0–23.5°C; RH: 52–58%; T_w: 15.5–17.5°C	Range: 36.7–41.1°C	41.1°C	7	4	Rectal thermometer, At the end of the race
Racinais et al. [7]	Elite males & females (n = 40), UCI Road World Championships	T_a: 36.9°C ± 2.8°C; RH: 24.6% ± 15.6% WBGT: 27.1 ± 2.4°C	Average male TTT (± SD): 39.2 ± 0.2°C Average male ITT (± SD): 39.8 ± 0.4°C Average male RR (± SD): 39.6 ± 0.2°C Average female TTT (± SD): 40.8 ± 0.7°C Average female ITT (± SD): 39.9 ± 0.5°C Average female RR (± SD): 39.1 ± 0.4°C	41.5°C	10	0	e-Celsius capsules, 30 s intervals
Racinais et al. [12]	Elite males (n = 39) and females (n = 17), IAAF World Athletics Championships	T_a: 29.3°C ± 0.5°C -32.7 ± 0.2°C; RH: 46.3% ± 1.0 -80.6% ± 1.1% WBGT: 23.5°C ± 0.5°C -30.6°C ± 0.3°C	Average pre (± SD): 37.7 ± 0.3°C Average peak post (± SD): 39.6 ± 0.6°C	41.1°C	16	9	e-Celsius capsules, 30 s intervals
Ross et al. [54]	Elite males' cyclists Tour of Gippsland (n = 5) Tour of Geelong (n = 5)	T_a :15.8°C ± 1.4°C RH: 54 ± 12% T_a:13.2°C ± 2.1°C RH: 80 ± 8%	Peak average (± SD): 38.9°C ± 0.7°C Peak average (± SD: 39.3°C ± 0.4°C	N/a	0	0	CorTemp capsules, 30 s intervals
Rüst et al. [55]	Trained Males (n = 1), Ice Mile Swim	Ta: 9.5 – 11.3°C Water: 9.8–1–10.0°C	Range: 36.0–38.1°C	38.1	0	0	Endotherm rectal thermometer,
Singh et al. [56]	Males (n = 5) Females (n = 7) Trail Run	Stage 1 T_a: 11.5–21.7°C, RH: 63–95%; Stage 2 T_a: 12.4–22.8°C, RH: 54–97%; Stage 3 T_a: 12.1–21.2°C, RH: 64–96%	Average (± SD): 38.2 ± 0.4°C	40.2°C	2	0	CorTemp capsules, Continuous

TABLE 1. Continued.

Investigation	Sample, Event	Conditions	Tc	Peak Tc	Tc ≥ 40°C	EHI symptoms	Tc Measurement method
Stay et al. [57]	Elite males ($n = 38$) Cricket	Batting T_a: range: 22.4–32.8°C RH range: 35.6–69.8% WBGT: 15.6–31.8°C Fielding T_a range: 20.9–34.5°C RH range: 34.9–61.3% WBGT: 17.0–31.4°C	Median Batting (IQR): 38.5°C (37.7 – 39.3°C) Median Fielding (IQR): 38.0°C (37.3–38.7°C)	*Batting* 39.3°C *Fielding* 38.7°C	0	8	CorTemp capsules, Rest breaks
Stephenson et al. [58]	Males ($n = 17$) and females ($n = 11$), Iseo-Franciacorta ITU, Paratriathlon World Cup	Event 1 T_a: 33°C RH: 41% Water temp: 27°C Event 2 T_a: 33°C RH: 35% Water temp: 25°C	Average acclimatised: 39.78 ± 0.55°C Average non-acclimatised: 39.22 ± 0.41°C Average wet suits: 38.45 ± 0.34°C Average no wet suits: 38.03 ± 0.35°C	N/a	8	16	e-Celsius capsules, 30 s intervals
Stevens et al. [59]	Elite/pre-elite males ($n = 5$) and females ($n = 9$), Commonwealth Games & International Athletics Association Federation Racewalking	R1 T_a: 25°C, RH: 74% R2 T_a: 19°C, RH: 34% R3 T_a: 29°C, RH: 47% R4 T_a: 23°C, RH: 72%	Average R1 (± SD): 39.70 ± 1.04°C Average R2 (± SD): 39.37 ± 0.67°C Average R3 (± SD): 39.31 ± 0.67°C Average R4 (± SD): 38.95 ± 0.56°C	41.2°C	12	2	e-Celsius capsules, 10 s intervals
Taylor et al. [60]	Elite males ($n = 17$), World Rugby 7's	Singapore WBGT range: 21.4–27.0°C London WBGT range: 13.8–22.3°C	Singapore G1 range: 36.80–39.10°C Singapore G2 range: 36.40–39.50°C Singapore G3 range: 37.30–38. 50°C London G1 range: 36.00–39.20°C London G2 range: 37.00–39.50°C	N/a	0	0	e-Celsius capsules, 30 s intervals
Tippet et al. [61]	Professional females ($n = 7$), Tennis	WBGT: 30.3 ± 2.3°C Range: 26.1 – 31.9°C	Average Tc (± SD): 38.65°C ± 0.20°C Average Peak (± SD): 39.13 ± 0.20°C	N/a	0	0	CorTemp capsules, 5 min prior, warmup, rests
Valentino et al. [62]	Males ($n = 23$) and females ($n = 7$), Western States Endurance Run	T_a 23.6 ± 6.3°C RH: 38.2 ± 16.0%	Average finishers (± SD): 38.2 ± 0.4°C Non-finishers (± SD): 38.2 ± 0.4°C	39.4°C	0	0	CorTemp capsules, 18, 90, 126 km
Veltmeijer et al. [63]	Males ($n = 111$) and Females ($n = 116$), Seven Hill Run	T_d: 10.5°C RH: 87% WBGT: 11°C	Average start (± SD): 37.8 ± 0.4°C Average finish (± SD): 39.2 ± 0.7°C	N/a	31	0	CorTemp capsules, 1 hour and 15 s before & after the event
Veltmeijer et al. [64]	Elite males ($n = 6$), Wheelchair Tennis	T_d: 21.2–24.8°C RH: 51.8–61.4% WBGT:17.9– 20.0°C	*Average Tc Increase* (± SD) Injured + 0.6 ± 0.11°C; Non-injured + 0.3 ± 0.1°C	N/a	0	0	CorTemp capsules, 20 s intervals
Wyndham and Strydom [65]	Males ($n = 31$), Sugar Marathons	Event 1 T_a: 14.8–17.0°C RH: 81–96% Event 2 T_a: 9.1–16.9°C RH: 29–82%	Peak event 1: 105.1°F (40.8°C) Peak event 2: 105.6°F (40.6°C)	105.6°F (40.8°C)	1	0	Rectal Thermometer, End of event

TABLE 1. Continued.

Investigation	Sample, Event	Conditions	Tc	Peak Tc	Tc ≥ 40°C	EHI symptoms	Tc Measurement method
Yeargin et al. [66]	Youth males ($n = 16$), American Football	Game 1 WBGT 22.0°C Game 2 WBGT: 31.0°C	Peak average game 1: 38.6°C Peak average game 2: 38.7°C	> 39.0°C	0	0	CorTemp capsules, Timeouts
Bongers et al. [26]	Trained males ($n = 195$) and females ($n = 180$), Seven Hills Run, Nijmegen	T_a 8–12°C RH: 80–95%	Average (± SD): 39.2°C ± 0.7°C	N/a	M:12% F: 10%	0	CorTemp capsules, Before & after the event
Byrne et al. [27]	Male soldiers ($n = 18$), Singapore Half Army Marathon	T_a: 27.2 ± 1.0°C RH: 87 ± 5% T_w: 25.9 ± 0.3°C WBGT: 26.0–29.2°C	Average (range) 30 min: 39.2 ± 0.3°C (38.7–39.8°C) Average (range) 60 min: 39.6 ± 0.6°C (38.5–40.6°C) Average (range) 90 min: 39.7 ± 0.7°C (38.3–41.3°C) Average (range) final 39.9 ± 0.8°C (38.3–41.7°C) Peak average (± SD): 40.1 ± 0.7°C	41.7°C	12	0	CorTemp capsules, 15 s intervals
Christensen and Ruhling [28]	Trained female ($n = 1$), Marathon	T_a: 12.7–27.9°C RH: unavailable	Tc remained between 37.5–40.0°C	40.0°C	1	0	Rectal thermometer, 10 min intervals
Del Coso et al. [29]	Trained males ($n = 30$) and females ($n = 4$), Ironman Triathlon	T_a: 29 ± 3°C (range: 24–30°C) RH: 73 ± 8% (range 65–85%) Water temp: 19 ± 1°C	Average start (± SD): 37.5 ± 0.6°C Average after (± SD): 38.8 ± 0.7°C	N/a	0	0	CorTemp capsules, Before & after the event
Diversi et al. [30]	Trained Males ($n = 6$) Females ($n = 3$), Six-hour swim	T_a: 15–25°C Water temp: 15–15.8°C	Mean (± SD) 36.49 ± 0.79	37.29°C	0	0	CorTemp capsules, interval N/a

"high-very high risk" and "low-moderate risk" conditions [35]. Athletes competing in the "high-very high risk" environmental conditions had significantly longer rest periods between points (25.1 ± 4.3 vs. 17.2 ± 3.3 seconds), which may have attenuated the rise in Tc [35]. Collectively, these studies indicate that athletes competing in higher risk environments can experience a high Tc, even in sports of an intermittent nature. This may introduce a problem for athletes expecting cool conditions at a sporting event but are surprised by hot conditions.

Athletes in "extreme risk" conditions had a lower incidence of a Tc ≥ 40°C than in other high risk environments (i.e. "high-very high risk" and "moderate-high risk" conditions [47, 50–52, 57, 61, 66]. Often amateur or recreational events are cancelled in "extreme risk" conditions, and as such, fewer athletes were competing in these conditions, which likely explains the low incidence of a Tc ≥ 40°C. Elite athletes competing in "extreme risk" environments can also change their behaviour to reduce thermal strain [12, 47, 51]. This was highlighted by research on soccer players, with a 26% decline in high-intensity running distances during a match played in "extreme risk" conditions than in a "low-moderate risk" environment [47]. Tennis athletes competing in "extreme risk" conditions also had a significantly lower effective playing percentage (i.e. time competing on the court) than in the cooler conditions [51]. Elite racewalkers at the 2019 Doha World Athletics Championships had 12% ± 7% slower event times compared to their personal bests [12], likely due to reductions in pace to alleviate thermal strain. Most sports in "extreme risk" conditions were intermittent, which likely provided athletes with rest periods and cooling opportunities (and some sports implement such changes when playing in these environments due to their heat policies). Endurance athletes in "extreme risk" conditions were elite race walkers, marathon runners, ski-surfers or simmers who were heat acclimatised and implemented mid-cooling strategies during their events, which may explain the low incidence of a Tc ≥ 40°C [8, 11, 12, 36–39]. Accordingly, changes in behaviour coupled with the intermittent nature and cooling strategies of the sports played in "extreme risk" conditions may explain the low incidence of a Tc ≥ 40°C. Despite this, 6.8% of cricket athletes competing in

these environments reported at least one symptom of EHI/EHS without a Tc ≥ 40°C [57]. This may be explained by cricket athletes wearing extra protective equipment, as mentioned previously.

An interesting finding was that athletes competing in "low risk" [26, 63, 65] and "low-moderate risk" [23, 43, 46, 53, 56] environments could also experience a Tc ≥ 40°C. In particular, 22% [26] and 15% [63] of athletes included in mass participation marathon events experienced a Tc ≥ 40°C in ambient temperatures < 12°C [26, 63]. This may be explained by conditions of high relative humidity (> 80%) that likely contributed to the high incidence of a Tc ≥ 40°C, since the water vapour gradient between the skin and environment reduces in humid climates, impeding the evaporative cooling capacity [3]. Collectively, these observations suggest that athletes can experience a remarkably high Tc in a range of environmental conditions, including climates categorised as "low risk", with high humidity; therefore, practitioners should be aware of not only the ambient temperature but also the relative humidity of the environment.

Competitive level

Elite and trained athletes had the highest incidence of a Tc ≥ 40°C (see Table 2). Interestingly, elite athletes had a higher prevalence of at least one symptom of EHI/EHS (8.8%) than trained athletes (0.1%). No amateur/recreational or youth athletes experienced a Tc ≥ 40°C or EHI/EHS symptom. Elite and trained athletes are more likely to be acclimatised to the heat, possessing heightened plasma volume expansion and earlier onset of sweating, resulting in enhanced thermoregulation (i.e. lower peak Tc) [76]. However, elite athletes are more likely to push themselves beyond their limits with very high motivation to perform well in their events and endure a high Tc, if necessary, despite their enhanced thermoregulatory capacity than their lesser-trained counterparts. Elite athletes also have a higher tolerance to heat sensation/pain than non-athletes [77], which may allow them to push themselves beyond their limits.

Several acclimatised endurance athletes commonly experienced a Tc ≥ 40°C [7, 46, 59]. For example, two elite female cyclists experienced a Tc > 41°C without experiencing any symptoms of EHI/EHS [7]. These cyclists participated in a 9-day heat acclimation programme before their event [7], suggesting that this training helped the athletes tolerate a high Tc. In a separate study, elite racewalkers with extensive heat acclimation training often presented a Tc ≥ 40°C, but two athletes reported at least one symptom of EHI/EHS after the event [59]. Racewalkers in another study also reported EHI/EHS symptoms, but the incidence of a Tc ≥ 40°C was low, likely due to the low radiant heat load imposed during the night races at the 2019 IAAF World Championships, reduction in pace and extensive use of mid-cooling strategies [11]. The race-walking competitions were at major sporting events, and hence the athletes were highly motivated to win and therefore tolerated the high Tc during competition.

Athletes who experienced a Tc ≥ 40°C were often the fastest competitors in their events [43, 46, 53] or medal recipients [7, 59]. It appears that elite athletes experiencing a Tc ≥ 40°C did not have impaired health or performance during real-world sporting competitions, likely due to being heat acclimatised from their training and their perceptual tolerance to the heat. This finding raises an ethical dilemma for medical practitioners monitoring real-time Tc during competition to reduce the risk of EHI/EHS, because it is uncertain whether the high Tc observed will result in health impairments. For example, if a marathon runner presents a Tc ≥ 40.5°C, with 1–2 km left, medical practitioners must decide whether to stop the athlete, which may deny them a chance of winning a medal or let them continue, potentially leading to EHI/EHS [16]. Indeed, as discussed throughout this review, athletes do not necessarily present EHI/EHS symptoms when experiencing a Tc ≥ 40°C, and therefore, it is unclear exactly what temperature might be used as a cut-off point in this situation. Instead, practitioners should ensure that they understand an athlete's thermal tolerance and know EHI/EHS symptoms during competition. Further, a recent paper by Muniz-Pardos et al. (2021) emphasises the importance of developing a system that allows real-time Tc monitoring but accompanied by a secondary measure such as cognitive/biomechanical assessments (i.e. general cognitive disturbance, gait disruption) to protect athletes from EHI/EHS.

Athlete disability

Para-athletes presented a greater incidence of a Tc ≥ 40°C and prevalence of at least one symptom of EHI/EHS compared to able-bodied athletes (see Table 2). Athletes with a spinal cord injury often have neural impairments that alter physiological responses that affect thermoregulation [78]. One study highlighted this, where 47.1% of the athletes reported at least one symptom of EHI/EHS while competing in a para-triathlon under "high-very high risk" environmental conditions [58]. Ten athletes also competed in wetsuits [58], which can provide a competitive advantage in the water, but are also designed to prevent heat loss [79]. Consequently, a combination of impaired thermoregulation, high-risk conditions and wetsuit use may have increased the athletes' thermal stress. Two studies comparing the rise in Tc between spinal cord-injured and non-injured athletes reported spinal cord-injured competitors with a greater Tc rise among spinal-cord injured athletes in wheelchair rugby [33] and tennis matches [64]. Based on these studies, it appears that spinal cord injured athletes, especially when competing in higher-risk conditions for long durations, are at increased risk of EHI/EHS. Therefore, practitioners should ensure such athletes are prepared for these conditions and consider using cooling strategies to attenuate thermal stress caused by impaired thermoregulation.

EVOLUTION OF CORE BODY TEMPERATURE MEASUREMENT

The measurement of Tc in thermoregulation research during competitive sports has evolved over the last 50 years [80]. Traditionally, researchers would collect Tc using rectal probes when performing stationary exercises or before and after an event (see Table 1) because these probes require a wired connection to a data logging

TABLE 2. Summary of the Sample Demographics and Study Setting

Sample Demographics	*n* (%)	Tc ≥ 40°C (%)	EHI/Heatstroke (%)
Sport Types			
Intermittent sports	295 (20.3)	4.4	2.7
American football	16 (1.1)	0	0
Association football (soccer)	50 (3.4)	6.0	0
Australian football	45 (3.1)	20.0	0
Cricket	38 (2.6)	0	21.1
Rugby union	57 (3.9)	1.8	1.8
Tennis	89 (6.1)	0	0
Endurance sports	1155 (79.7)	13.8	2.8
Adventure racing	24 (1.7)	8.3	0
Cycling	64 (4.4)	20.3	0
Racewalking	53 (3.7)	47.2	3.8
Running	838 (57.8)	16.6	0.6
Swimming	21 (0.9)	0	0
Surf Skiing	13 (0.9)	7.7	0
Triathlon	142 (9.8)	7.0	11.3
Environmental Risk Categories			
Extreme-risk	170 (11.7)	8.8	7.3
High-very high risk	201 (13.9)	18.4	8.0
Moderate-high risk	220 (15.2)	18.2	1.8
Low risk	757 (52.2)	9.6	0
Low-moderate risk	249 (17.2)	4.8	1.6
Competitive Level			
Amateur/recreational	20 (1.4)	0	0
Elite	411 (28.3)	15.3	8.8
Trained	901 (62.1)	11.3	0.1
Unknown	102 (7.0)	6.9	3.9
Youth	16 (1.1)	0	0
Physical Ability			
Able-bodied athletes	1,399 (96.5)	11.7	1.8
Para-athletes	51 (3.5)	15.7	31.4

Note. The WBGT risk categories included; low (WBGT < 20°C), moderate-high (WBGT 21–25°C), high-very high (WBGT 26–29°C) and extreme (WBGT ≥ 30°C) [67]. While the ambient condition risk categories included; low (Ta 15–20°C), low-moderate (Ta 21–25°C; relative humidity [RH] > 70%), moderate-high (Ta 26–29°C; RH > 60%), high-very high (Ta 31–35°C; RH > 50%) and extreme (Ta ≥ 36°C; RH > 30%) [67]. The competitive level was based on how the authors reported participants in the original investigations. *Key. n* (participant number), Tc ≥ 40°C (incidence of core body temperature ≥ 40°C) and EHI/EHS (number of individuals reported with at least one symptom of exertional heat illness/heatstroke).

device. Alternatively, athletes would insert a rectal probe before an event, hide the cord within their clothes whilst competing and then connect to a data logger during breaks. The limited data collection opportunities and invasive nature of rectal probes have led researchers to use ingestible telemetric capsules, which wirelessly transmit Tc measurements to a data logger via telemetry [81]. Earlier systems (i.e. CorTemp and VitalSense systems) required athletes to carry a data logger on their person to visualise or store the data. However, this limits data collection opportunities, as the data-logger could add unwanted weight to the athlete, interfere with their technique, and increase the injury risk for athletes in contact sports (plus, carrying data loggers during competition in contact sports is often prohibited for obvious reasons). As a result, researchers could still only collect Tc data during break periods in

many events, meaning that the athletes' peak Tc could not be deduced from the limited data collected. More recently, advancements to ingestible telemetric capsule technology have produced a solution, whereby data can be stored within the capsule itself and transmitted wirelessly to a portable receiver at a later time (i.e. e-Celsius) [80]. This technology has enabled researchers to collect continuous Tc data in situations where the individual is not permitted to carry a data logger with them (i.e. in team-sports and elite competitions/events). Indeed, Tc measurement during competition via telemetry has been performed since 2006 (see Table 1), specifically in situations where a data logger could be attached on an athlete or when Tc measurements could be taken at intervals/breaks in play. To our knowledge, the first published study using the e-Celsius technology during sports competition included in this review was in 2019 [60], and since this time, nine studies have used this to contextualise the thermal demands across different sports [6, 7, 12, 34, 40, 52, 58–60].

LIMITATIONS

Athletes and practitioners should be aware of the following limitations of this review. First, there was likely a higher incidence of athletes experiencing a Tc ≥ 40°C across the literature, since the limitations of the available technology described above meant that continuous Tc measurements could not be recorded in many of the cited studies. Furthermore, the Tc measurement frequency was inconsistent across the studies, with researchers sampling Tc from anywhere between 10 seconds to 10 minutes or only during breaks in play. Studies with more frequent sampling better profile Tc changes during competition, and studies with less frequent sampling may not capture important fluctuations in Tc between measurements. Therefore, future research should aim to continuously measure Tc throughout the event with a sampling frequency of at least every 1 minute. Additionally, the Tc data presentation across the studies was also inconsistent, with researchers reporting the average, median or Tc range, and the peak Tc was often not clear. Researchers are encouraged to present full data traces of the mean Tc across the event to increase the utility of the work.

Researchers have recommended consuming these capsules at least six hours before the first measurement, allowing them to transit through the stomach and into the intestinal tract to avoid coming into direct contact with ingested liquids [80, 81]. However, in some situations, athletes were unable to ingest a capsule within this timeframe; for example, cricket athletes in one study ingested telemetric capsules three hours before the first session each day, and as such, the initial Tc measurements on each day of the study may be inaccurate [57]. Researchers can instruct athletes to ingest a capsule the night before [82], although the capsules can pass with the first bowel movement the next morning, which was highlighted in a recent cycling study [52], resulting in limited data. One solution to overcome these issues is to insert the capsule into the rectum to measure rectal Tc instead of gastrointestinal Tc, as successfully performed in one of the studies [59].

Finally, several limitations likely exist in reporting EHI/EHS symptoms. Athletes may not have accurately reported EHI/EHS symptoms due to fears that the coaching staff may reduce their playing time. Alternatively, athletes may not have been provided with enough opportunity (or any opportunity) to report these symptoms. Indeed, many studies did not explicitly state that they measured the occurrence of such symptoms. Further, the Tc of the athletes' that reported EHI/EHS symptoms could not be determined from the reviewed studies.

CONCLUSIONS

After collating the Tc responses from various sports and environmental conditions, it is evident that athletes commonly experience a Tc ≥ 40°C during real-world competitive events. It appears that the physical demands of the sport, environmental conditions, competitive level, and athlete disability are contributing factors to a high Tc. Despite athletes commonly experiencing a Tc ≥ 40°C, the prevalence of EHI/EHS symptoms was low. Practitioners should also be aware that athletes competing in all environmental conditions can experience a Tc ≥ 40°C, particularly in climates categorised as "high-very high risk" and "moderate-high risk". When the competitive level was compared, elite and trained athletes commonly had a Tc ≥ 40°C, with elite athletes presenting the highest prevalence of EHI/EHS symptoms. Nevertheless, spinal-cord injured athletes experienced the greatest occurrence of EHI/EHS symptoms due to neurological and physiological impairments that impact thermoregulatory pathways. Collectively, these findings suggest that a Tc ≥ 40°C is not a consistently meaningful risk factor of EHI/EHS in this sample; therefore, Tc measurement alongside secondary measures should be incorporated to safeguard athletes during competition.

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Gurpreet Singh, Kyle. J.M. Bennett, Lee Taylor and Christopher. J. Stevens declare that they have no conflicts of interest in relevance to this review.

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REFERENCES

1. Racinais S, Alonso JM, Coutts AJ, Flouris AD, Girard O, González-Alonso J, et al. Consensus recommendations on training and competing in the heat. Br J Sports Med. 2015; 49:1164.
2. Tyler CJ, Reeve T, Hodges GJ, Cheung SS. The effects of heat adaptation on physiology, perception and exercise performance in the heat: A meta-analysis. Sports Med. 2016; 46:1699–724.
3. Périard JD, Eijsvogels TMH, Daanen HAM. Exercise under heat stress: Thermoregulation, hydration, performance implications, and mitigation strategies. Physiol Rev. 2021; 101:1873–979.
4. Sawka MN, Young AJ, Francesconi RP, Muza SR, Pandolf KB. Thermoregulatory and blood responses during exercise at graded hypohydration levels. J Appl Physiol Bethesda Md 1985. 1985; 59:1394–401.
5. Cramer MN, Jay O. Biophysical aspects of human thermoregulation during heat stress. Auton Neurosci. 2016; 196:3–13.
6. Fenemor SP, Gill ND, Driller MW, Mills B, Casadio JR, Beaven CM. The relationship between physiological and performance variables during a hot/humid international rugby sevens tournament. Eur J Sport Sci. Routledge; 2021; 0:1–9.
7. Racinais S, Moussay S, Nichols D, Travers G, Belfekih T, Schumacher YO, et al. Core temperature up to 41.5ºC during the UCI Road Cycling World Championships in the heat. Br J Sports Med. BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine; 2019; 53:426–9.
8. Baillot M, Hue O. Hydration and Thermoregulation during a half-ironman performed in tropical climate. J Sports Sci Med. 2015; 14.
9. Duffield R, Coutts A, McCall A, Burgess D. Pre-cooling for football training and competition in hot and humid conditions. Eur J Sport Sci. 2013; 13:58–67.
10. Cramer MN, Jay O. Partitional calorimetry. J Appl Physiol 1985. 2019; 126:267–77.
11. Racinais S, Ihsan M, Taylor L, Cardinale M, Adami PE, Alonso JM, et al. Hydration and cooling in elite athletes: relationship with performance, body mass loss and body temperatures during the Doha 2019 IAAF World Athletics Championships. Br J Sports Med. BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine; 2021; 55:1335–41.
12. Racinais S, Havenith G, Aylwin P, Ihsan M, Taylor L, Adami PE, et al. Association between thermal responses, medical events, performance, heat acclimation and health status in male and female elite athletes during the 2019 Doha World Athletics Championships. Br J Sports Med. 2022; 56:439–45.
13. Rodgers J, Slota P, Zamboni B. Exertional heat illness among secondary school athletes: Statewide policy implications. J Sch Nurs Off Publ Natl Assoc Sch Nurses. 2018; 34:156–64.
14. Westwood CS, Fallowfield JL, Delves SK, Nunns M, Ogden HB, Layden JD. Individual risk factors associated with exertional heat illness: A systematic review. Exp Physiol. 2021; 106:191–9.
15. Bergeron M, Bahr R, Bärtsch P, Bourdon L, Calbet J, Carlsen K, et al. International Olympic Comitee consensus statement on thermoregulatory and altitude challenges for high-level athletes. Br J Sports Med. 2012; 46:770–9.
16. Muniz-Pardos B, Angeloudis K, Guppy FM, Tanisawa K, Hosokawa Y, Ash GI, et al. Ethical dilemmas and validity issues related to the use of new cooling technologies and early recognition of exertional heat illness in sport. BMJ Open Sport Amp Exerc Med. 2021; 7:e001041.
17. Travers GJS, Nichols DS, Farooq A, Racinais S, Périard JD. Validation of an ingestible temperature data logging and telemetry system during exercise in the heat. Temperature. Taylor & Francis; 2016; 3:208–19.
18. Ely BR, Ely MR, Cheuvront SN, Kenefick RW, DeGroot DW, Montain SJ. Evidence against a 40°C core temperature threshold for fatigue in humans. J Appl Physiol. American Physiological Society; 2009; 107:1519–25.
19. Nybo L, González-Alonso J. Critical core temperature: A hypothesis too simplistic to explain hyperthermia-induced fatigue. Scand J Med Sci Sports. 2015; 25 Suppl 1:4–5.
20. Alabdulwahed S, Galán-López N, Hill T, James LJ, Chrismas BCR, Racinais S, et al. Heat adaptation and nutrition practices: Athlete and practitioner knowledge and use. Int J Sports Physiol Perform. 2022; 1–14.
21. Furley P, Goldschmied N. Systematic vs. narrative reviews in sport and exercise psychology: Is either approach superior to the other? Front Psychol. 2021; 12:685082.
22. Casa DJ, Becker SM, Ganio MS, Brown CM, Yeargin SW, Roti MW, et al. Validity of devices that assess body temperature during outdoor exercise in the heat. J Athl Train. 2007; 42:333–42.
23. Aughey RJ, Goodman CA, McKenna MJ. Greater chance of high core temperatures with modified pacing strategy during team sport in the heat. J Sci Med Sport. 2014; 17:113–8.
24. Baillot M, Le Bris S, Hue O. Fluid Replacement Strategy during a 27-km Trail Run in Hot and Humid Conditions. Int J Sports Med. 2013; 35:147–52.
25. Bergeron MF, McLeod KS, Coyle JF. Core body temperature during competition in the heat: National boys' 14 s junior tennis championships. Br J Sports Med. British Association of Sport and Excercise Medicine; 2007; 41:779–83.
26. Bongers CCWG, Ten Haaf DSM, Ravanelli N, Eijsvogels TMH, Hopman MTE. Core temperature and sweating in men and women during a 15-km race in cool conditions. Int J Sports Physiol Perform. 2020; 1–6.
27. Byrne C, Lee JKW, Chew SAN, Lim CL, Tan EYM. Continuous thermoregulatory responses to mass-participation distance running in heat. Med Sci Sports Exerc. 2006; 38:803–10.
28. Christensen CL, Ruhling RO. Thermoregulatory responses during a marathon. A case study of a woman runner. Br J Sports Med. 1980; 14:131–2.
29. Del Coso J, González C, Abian-Vicen J, Salinero Martín JJ, Soriano L, Areces F, et al. Relationship between physiological parameters and performance during a half-ironman triathlon in the heat. J Sports Sci. 2014; 32:1680–7.
30. Diversi T, Franks-Kardum V, Climstein M. The effect of cold water endurance swimming on core temperature in aspiring English Channel swimmers. Extreme Physiol Med. 2016; 5:3.
31. Duffield R, Coutts AJ, Quinn J. Core temperature responses and match running performance during intermittent-sprint exercise competition in warm conditions. J Strength Cond Res. 2009; 23:1238–44.
32. Edwards AM, Clark NA. Thermoregulatory observations in soccer match play: Professional and recreational level applications using an intestinal pill system to measure core temperature. Br J Sports Med. 2006; 40:133–8.
33. Griggs KE, Havenith G, Price MJ, Mason BS, Goosey-Tolfrey VL. thermoregulatory responses during competitive wheelchair rugby match play. Int J Sports Med. 2017; 38:177–83.
34. Henderson MJ, Chrismas BCR, Stevens CJ, Coutts AJ, Taylor L. Changes in core temperature during an elite female rugby sevens tournament. Int J Sports Physiol Perform. 2020; 1–10.
35. Hornery DJ, Farrow D, Mujika I, Young W. An integrated physiological and performance profile of professional tennis. Br J Sports Med. 2007; 41:531–6; discussion 536.
36. Hue O, Henri S, Baillot M, Sinnapah S, Uzel A-P. Thermoregulation, hydration and performance over 6 days of trail running in the tropics. Int J Sports Med. 2014; 35:906–11.
37. Hue O, Le Jeannic P, Chamari K. A pilot study on how do elite surfski padllers manage their effort and hydration pattern in the heat. Biol Sport. 2014; 31:283–8.

38. Hue O, Le Jeannic P, Chamari K. Self-hydration and thermoregulatory processes of average-level paddlers during international surfski events in a tropical climate. Biol Sport. 2015; 32:329–32.
39. Hue O, Monjo R, Riera F. Imposed cold-water ingestion during open water swimming in internationally ranked swimmers. Int J Sports Med. 2015; 36:941–6.
40. Høiseth LØ, Melau J, Bonnevie-Svendsen M, Nyborg C, Eijsvogels TMH, Hisdal J. Core temperature during cold-water triathlon swimming. Sports. Multidisciplinary Digital Publishing Institute; 2021; 9:87.
41. Knechtle B, Rosemann T, Rüst CA. Ice swimming and changes in body core temperature: a case study. SpringerPlus. 2015; 4:394.
42. Knechtle B, Christinger N, Kohler G, Knechtle P, Rosemann T. Swimming in ice cold water. Ir J Med Sci. 2009; 178:507.
43. Laursen PB, Suriano R, Quod MJ, Lee H, Abbiss CR, Nosaka K, et al. Core temperature and hydration status during an Ironman triathlon. Br J Sports Med. 2006; 40:320–5.
44. Lee JKW, Nio AQX, Lim CL, Teo EYN, Byrne C. Thermoregulation, pacing and fluid balance during mass participation distance running in a warm and humid environment. Eur J Appl Physiol. 2010; 109:887–98.
45. Lucas SJE, Anglem N, Roberts WS, Anson JG, Palmer CD, Walker RJ, et al. Intensity and physiological strain of competitive ultra-endurance exercise in humans. J Sports Sci. 2008; 26:477–89.
46. Maron B, Wagner A, Horvath SM. Thermoregulatory responses during competitive marathon running. 1977; 6.
47. Mohr M, Nybo L, Grantham J, Racinais S. Physiological responses and physical performance during football in the heat. PLOS ONE. Public Library of Science; 2012; 7:e39202.
48. Morante SM, Brotherhood JR. Air temperature and physiological and subjective responses during competitive singles tennis. Br J Sports Med. 2007; 41:773–8.
49. Morante SM, Brotherhood JR. Autonomic and behavioural thermoregulation in tennis. Br J Sports Med. 2008; 42:679–85; discussion 685.
50. Ozgünen KT, Kurdak SS, Maughan RJ, Zeren C, Korkmaz S, Yazici Z, et al. Effect of hot environmental conditions on physical activity patterns and temperature response of football players. Scand J Med Sci Sports. 2010; 20 Suppl 3:140–7.
51. Périard JD, Racinais S, Knez WL, Herrera CP, Christian RJ, Girard O. Thermal, physiological and perceptual strain mediate alterations in match-play tennis under heat stress. Br J Sports Med. BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine; 2014; 48:i32–8.
52. Périard JD, Wilson MG, Tebeck ST, Gilmore JB, Stanley J, Girard O. Influence of the thermal environment on work rate and physiological strain during a uci world tour multistage cycling race. Med Sci Sports Exerc. 2022; 10.1249/MSS.0000000000003028.
53. Pugh LG, Corbett JL, Johnson RH. Rectal temperatures, weight losses, and sweat rates in marathon running. J Appl Physiol. American Physiological Society; 1967; 23:347–52.
54. Ross ML, Stephens B, Abbiss CR, Martin DT, Laursen PB, Burke LM. Fluid balance, carbohydrate ingestion, and body temperature during men's stage-race cycling in temperate environmental conditions. Int J Sports Physiol Perform. 2014; 9:575–82.
55. Rüst CA, Knechtle B, Rosemann T. Changes in body core and body surface temperatures during prolonged swimming in water of 10°C a case report. Extreme Physiol Med. 2012; 1:8.
56. Singh NR, Denissen EC, McKune AJ, Peters EM. Intestinal temperature, heart rate, and hydration status in multiday trail runners. Clin J Sport Med Off J Can Acad Sport Med. 2012; 22:311–8.
57. Stay S, Cort M, Ward D, Kountouris A, Orchard J, Holland J, et al. Core temperature responses in elite cricket players during australian summer conditions. Sports. 2018; 6.
58. Stephenson B, Shill A, Lenton J, Goosey-Tolfrey V. Physiological correlates to in-race paratriathlon cycling performance. Int J Sports Med. 2020; 41.
59. Stevens CJ, Ross ML, Périard JD, Vallance BS, Burke LM. Core temperature responses to elite racewalking competition. Int J Sports Physiol Perform. Human Kinetics; 2020; 15:892–5.
60. Taylor L, Thornton HR, Lumley N, Stevens CJ. Alterations in core temperature during World Rugby Sevens Series tournaments in temperate and warm environments †. Eur J Sport Sci. 2019; 19:432–41.
61. Tippet ML, Stofan JR, Lacambra M, Horswill CA. Core temperature and sweat responses in professional women's tennis players during tournament play in the heat. J Athl Train. 2011; 46:55–60.
62. Valentino TR, Stuempfle KJ, Kern M, Hoffman MD. The influence of hydration state on thermoregulation during a 161-km ultramarathon. Res Sports Med Print. 2016; 24:212–21.
63. Veltmeijer MTW, Eijsvogels TMH, Thijssen DHJ, Hopman MTE. Incidence and predictors of exertional hyperthermia after a 15-km road race in cool environmental conditions. J Sci Med Sport. 2015; 18:333–7.
64. Veltmeijer MT, Pluim B, Thijssen DH, Hopman MT, Eijsvogels TM. Thermoregulatory responses in wheelchair tennis players: a pilot study. Spinal Cord. Nature Publishing Group; 2014; 52:373–7.
65. Wyndham CH, Strydom NB. The danger of an inadequate water intake during marathon running. South Afr Med J Suid-Afr Tydskr Vir Geneeskd. 1969; 43:893–6.
66. Yeargin SW, Dickinson JJ, Emerson DM, Koller J, Torres-McGehee TM, Kerr ZY. Exertional heat illness risk factors and physiological responses of youth football players. J Sport Health Sci. 2021; 10:91–8.
67. Sports Medicine Australia. Hot weather guidlines for sporting lubs and associations and the physically active [Internet]. 2009. Available from: https://sma.org.au/sma-site-content/uploads/2009/05/hot-weather-guidelines-web-download-doc-2007.pdf.
68. Bishop DJ, Girard O. Determinants of team-sport performance: implications for altitude training by team-sport athletes. Br J Sports Med. BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine; 2013; 47:i17–21.
69. Bouscaren N, Millet GY, Racinais S. Heat Stress Challenges in Marathon vs. Ultra-Endurance Running. Front Sports Act Living [Internet]. 2019 [cited 2022 May 3]; 1. Available from: doi: 10.3389/fspor.2019.00059.
70. Phillips KE, Hopkins WG. Determinants of cycling performance: A review of the dimensions and features regulating performance in elite cycling competitions. Sports Med – Open. 2020; 6:23.
71. Noakes TD. Fatigue is a brain-derived emotion that regulates the exercise behavior to ensure the protection of whole body homeostasis. Front Physiol. 2012; 3:82.
72. Gregson W, Drust B, Atkinson G, Salvo VD. Match-to-match variability of high-speed activities in premier league soccer. Int J Sports Med. 2010; 31:237–42.
73. Nassis GP, Brito J, Dvorak J, Chalabi H, Racinais S. The association of environmental heat stress with performance: analysis of the 2014 FIFA World Cup Brazil. Br J Sports Med. 2015; 49:609–13.
74. Higham DG, Pyne DB, Anson JM, Eddy A. Movement patterns in rugby sevens: effects of tournament level, fatigue and substitute players. J Sci Med Sport. 2012; 15:277–82.
75. Casa DJ, DeMartini JK, Bergeron MF, Csillan D, Eichner ER, Lopez RM, et al. National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses. J Athl Train. 2015; 50:986–1000.
76. Wendt D, van Loon LJ, Lichtenbelt WD. Thermoregulation during exercise in the

heat: Strategies for maintaining health and performance. Sports Med. 2007; 37:669–82.
77. Stevens CJ, Mauger AR, Hassmèn P, Taylor L. Endurance performance is influenced by perceptions of pain and temperature: theory, applications and safety considerations. Sports Med. 2018; 48:525–37.
78. Zhang Y, Bishop PA. Risks of heat illness in athletes with spinal cord injury: Current evidence and needs. Front Sports Act Living. 2020; 1:68.
79. Smith C, Saulino M, Luong K, Simmons M, Nessler JA, Newcomer SC. Effect of wetsuit outer surface material on thermoregulation during surfing. Sports Eng. 2020; 23:17.
80. Byrne C, Lim CL. The ingestible telemetric body core temperature sensor: A review of validity and exercise applications. Br J Sports Med. 2007; 41:126–33.
81. Bongers CCWG, Daanen HAM, Bogerd CP, Hopman MTE, Eijsvogels TMH. Validity, reliability, and inertia of four different temperature capsule systems. Med Sci Sports Exerc. 2018; 50:169–75.
82. Stevens CJ, Plews DJ, Laursen PB, Kittel AB, Taylor L. Acute physiological and perceptual responses to wearing additional clothing while cycling outdoors in a temperate environment: A practical method to increase the heat load. Temperature. Taylor & Francis; 2017; 4:414–9.

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Applications of near-infrared spectroscopy in "anaerobic" diagnostics – SmO_2 kinetics reflect PCr dephosphorylation and correlate with maximal lactate accumulation and maximal pedalling rate

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ABSTRACT: We investigated the relationship of the time-dependent behaviour of muscle oxygen saturation $SmO_2(t)$, phosphagen energy supply $W_{PCr}(t)$ and blood lactate accumulation ΔBLC(t) during a 60-s all-out cycling sprint and tested $SmO_2(t)$ for correlations with the end of the fatigue-free state t_{Ff}, maximal pedalling rate PR_{max} and maximal blood lactate accumulation rate $\dot{v}La_{max}$. Nine male elite track cyclists performed four maximal sprints (3, 8, 12, 60 s) on a cycle ergometer. Crank force and cadence were monitored continuously to determine PR_{max} and t_{Ff} based on force-velocity profiles. SmO_2 of the vastus lateralis muscle and respiratory gases were measured until the 30th minute after exercise. W_{PCr} was calculated based on the fast component of the post-exercise oxygen uptake for each sprint. Before and for 30 minutes after each sprint, capillary blood samples were taken to determine the associated ΔBLC. Temporal changes of SmO_2, W_{PCr} and ΔBLC were analysed via non-linear regression analysis. $\dot{v}La_{max}$ was calculated based on ΔBLC(t) as the highest blood lactate accumulation rate. All models showed excellent quality ($R^2 > 0.95$). The time constant of $SmO_2(t)$ $\tau_{SmO2} = 2.93 \pm 0.65$ s was correlated with the time constant of $W_{PCr}(t)$ $\tau_{PCr} = 3.23 \pm 0.67$ s ($r = 0.790$, $p < 0.012$), $\dot{v}La_{max} = 0.95 \pm 0.18$ mmol·l^{-1}·s^{-1} ($r = 0.768$, $p < 0.017$) and $PR_{max} = 299.51 \pm 14.70$ rpm ($r = -0.670$, $p < 0.049$). t_{Ff} was correlated with τ_{SmO2} ($r = 0.885$, $p < 0.001$). Our results show a time-dependent reflection of SmO_2 kinetics and phosphagen energy contribution during a 60-s maximal cycling sprint. A high $\dot{v}La_{max}$ results in a reduction, a high PR_{max} in an increase of the desaturation rate. The half-life of SmO_2 desaturation indicates the end of the fatigue-free state.

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INTRODUCTION

As an approach to the assessment of training and performance, the kinetics of skeletal muscle oxygenation are being examined more and more extensively in the laboratory and the field [1]. The application of the Beer-Lambert law to near-infrared spectroscopy (NIRS) allows for non-invasive and convenient measurement of changes in local muscle tissue oxygenation [2–4]. The procedure has been validated for use during dynamic exercise in adults [5], so that the NIRS signal obtained during exercise can be used to estimate the relationship between local O_2 supply and demand (SmO_2) or to describe changes in tissue blood volume at the site of O_2 exchange via changes in total haemoglobin and myoglobin mass (tHb) [6].

Since the recovery of phosphocreatine (PCr) levels in muscle following activity or ischaemia depends primarily on production of ATP by mitochondria, which, in turn, depends on oxygen availability [7–10], oxygen supply and demand as reflected in NIRS and the levels of high-energy phosphates are closely correlated [3, 4]. For example, in muscles at rest, a relationship between dephosphorylation of PCr and desaturation has been demonstrated. Utilizing NIRS and magnetic resonance spectroscopy (MRS) in combination, Hamaoka and colleagues [11] observed that arterial occlusion resulted in an exponential decrease in SmO_2. Upon reaching desaturation, the level of PCr decreased linearly, a phenomenon proposed to be required for maintenance of ATP levels.

The observed delay between SmO_2 desaturation and the reduction in PCr levels in muscle under ischaemic conditions at rest results from the interaction of different systems of energy supply. At rest, energy requirements are usually met almost exclusively by mitochondrial respiration. Subsequent transport of this energy from the mitochondria to the sarcomere involves a potential gradient created by rephosphorylation of PCr [10, 12–14]. Under ischaemic conditions at rest, the level of PCr in muscle remains stable until decreasing availability of oxygen lowers the rate of mitochondrial energy

ABBREVIATIONS

a	Slope of the fatigue-free F/v profile
A_{FC}	Amplitude of oxygen consumption of the fast component of EPOC
A	Amplitude of extra-vascular lactate concentration
AO	Arterial occlusion
ATP	Adenosine triphosphate
ADP	Adenosine diphosphate
AMP	Adenosine monophosphate
b	y-axis intercept of the F/v profile
B	Amplitude of lactate formation rate in the muscle
B_{SC}	Amplitude of oxygen consumption of the slow component of EPOC
BLC	Blood lactate concentration
BLC_{max}	Maximal blood lactate concentration
BLC(0)	Pre-exercise blood lactate concentration
C	Limit value of blood lactate accumulation during maximal exercise
CE	Caloric equivalent
Cr	Creatine
EPOC	Excess post-exercise oxygen consumption
F	Pedal force
F/v	Force/velocity
F_{max}	Theoretical maximal mean pedal force
Hb	Haemoglobin (Hb)
k_1	Rate constants of BLC appearance (k_1)
k_2	Rate constants of BLC disappearance (k_1)
k_3	Time constant of appearance of lactate in the blood
k_4	Time constant of disappearance of lactate in the blood
Mb	Myoglobin
MRS	Magnetic resonance spectroscopy
NIRS	Near-infrared spectroscopy
P/v	Power/velocity
PCr	Phosphocreatine
P_{max}	Maximal power output derived from P/v profile
PR_{max}	Maximal pedalling rate, maximal cadence
RER	Respiratory exchange rate
rpm	Revolutions of the crank per minute, cadence
SmO_2	Muscle oxygenation, oxygen saturation
SmO_{2A}	Amplitude of muscle oxygen desaturation
SmO_{2Base}	Baseline level of muscle oxygenation, pre-exercise level of SmO_2
t_{alac}	Time-point of the end of the alactic timespan, alactic timespan
t_{Ff}	Time-point just before the first systematic deviation of the fatigue-free F-v profile, end of the fatigue-free state
t_{resat}	Time-point of the beginning of oxygen resaturation
T	Exercise duration
TD	Time delay
v	Velocity of the crank or pedal
$\dot{v}La$	Rate of blood lactate accumulation
$\dot{v}La_{max}$	Maximal rate of blood lactate accumulation
$\dot{V}O_2(0)$	Initial oxygen uptake, oxygen uptake at t = 0
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2A}$	Amplitude of oxygen uptake
$\dot{V}O_{2EPOC}$	Excess post-exercise oxygen consumption
$\dot{V}O_{2PCr}$	Oxygen consumption to replenish PCr after exercise; oxygen consumption of the fast component of EPOC
$\dot{V}O_{2SC}$	Oxygen consumption of the slow component of EPOC
W_{PCr}	Phosphagen energy supply, alactic energy supply
W_{PCrTOT}	Total amount of phosphagen energy supply
ΔBLC	Blood lactate accumulation
ΔSmO_2	Change in oxygen saturation
$\Delta\dot{V}O_2$	Change in oxygen uptake
τ_a	Time constant of the fast component of EPOC(t)
τ_b	Time constant of the slow component of EPOC(t)
τ_{PCr}	Time constant of phosphagen energy supply
τ_{SmO2}	Time constant of muscle oxygen desaturation
$\tau\dot{V}_{O2}$	Time constant of oxygen uptake
$\tau_{\Delta BLC}$	Time constant of blood lactate accumulation
W_{PCrTOT}	Total amount of phosphagen energy supply
ΔBLC	Blood lactate accumulation
∈	In
∀	For all

production; thereafter, the rate of PCr dephosphorylation reflects the energy consumption.

Boushel et al. [15] reported a two-fold higher rate of SmO_2 desaturation during exercise than at rest under ischaemic conditions and attributed this to a greater demand for energy in combination with glycolysis. However, the exact relationship between SmO_2, the level of PCr and glycolysis during maximal dynamic exercise, e.g., maximal bouts of cycling, remains to be elucidated. Under such conditions, we would predict a close temporal correlation between the kinetics of SmO_2 desaturation and PCr dephosphorylation, which could be influenced by the rate of glycolysis.

During exercise, the rate of ATP resynthesis is determined by the phosphorylation of ADP by enyzmatic dephosphorylation of PCr in combination with glycolytic and mitochondrial ATP production [12, 16]. For instance, during twitch contractions, loss of ATP is buffered through usage of PCr by creatine kinase to phosphorylate ADP [13, 17]. Following such a contraction, the level of PCr recovers more rapidly than during the final period of stimulation, indicating the involvement of different mechanisms [17]. Chung and coworkers [17] reported that during exercise the phosphorylation status is closely coupled to the rate of glycolysis and oxidative phosphorylation. Assuming unchanged levels of creatine kinase activity, rephosphorylation of PCr depends on these two systems and deficient rephosphorylation leads to compensatory increases in mitochondrial and glycolytic ATP production [12, 17]. When the rate of ATP consumption changes suddenly, glycolysis, which occurs in the sarcoplasm, contributes more rapidly to the ADP/ATP gradient than mitochondrial respiration does [9]. During the initial phase of muscle contraction, an increase in oxidative phosphorylation is limited until the cardiopulmonary system has adapted to supply the greater amount of oxygen in demand [18, 19].

Consequently, during the first seconds of maximal exercise, the aerobic contribution to energy production is likely to be relatively small, and PCr is restored predominantly by glycolysis. As glycolysis is sensitive to pH and ATP hydrolysis during maximal exercise leads to a rapid reduction in muscle pH [20], the glycolytic flux may decline within a few seconds [12], whereas mitochondrial ATP synthesis increases with time [19]. In addition, acidic conditions also favour dissociation of O_2 [19].

When sprinting maximally, the PCr consumed is rephosphorylated by creatine kinase utilizing ATP produced by glycolysis and mitochondrial respiration. From the increase in the rate of glycolysis and associated production of lactate within seconds after the start of exercise [21, 22] it could be concluded that oxidation of lactate is likely to play a key role in energy equilibrium and, thereby, in SmO_2 kinetics. We hypothesize that during maximal sprint exercise, the kinetics of SmO_2 desaturation reflect those of PCr dephosphorylation and are correlated with the maximal rate of lactate accumulation $\dot{v}La_{max}$ as an indirect parameter of maximal glycolytic activity.

Maximal energy flow can only be generated until PCr stores are reduced to a maximum of half [23]. The time span for maximal

energy flow and maximal power output seems to be well reflected by the half-life of PCr dephosphorylation, which is a function of its time constant. In our recent work, we presented a new approach to determine the end of the time interval of maximal energy flow (fatigue-free time span) the timespan up to the first systematic deviation from the fatigue-free force-velocity (F/v) profile (t_{Ff}) [24]. Assuming a temporal overlap of the SmO_2 desaturation and PCr dephosphorylation kinetics, a correlation between t_{Ff} and the time constant of SmO_2 can be hypothesised.

Further assuming a correlation between the maximal rate of energy, the rate of PCr dephosphorylation and muscle fibre type composition [25], with maximal pedalling rate being dependent on the proportion of fast-twitch muscle fibres in the muscles involved [26], we also predict an increase in the rate of PCr dephosphorylation and of SmO_2 desaturation with increasing pedalling rate. According to the model presented, direct measurement of SmO_2 should provide a powerful approach to assessment of changes in the levels of high-energy phosphates and lactate with time.

MATERIALS AND METHODS

Participants

Nine male (21.1 ± 3.4 years, 184.9 ± 5.1 cm, 89.6 ± 6.4 kg, BFP: 13.4 ± 1.7% , $\dot{V}O_{2max}$: 53.9 ± 4.6 ml kg^{-1} min^{-1}, P_{max}: 1744 ± 111 W) (mean ± standard deviation) elite track cycling sprinters took part in this study. Since our study design required high-level neuromuscular and metabolic performance, only athletes who had demonstrated closely linear F/v profiles ($R^2 > 0.95$) in previous tests and who had shown constant performance across all races per day in track cycling sprint events at international championships were included.

Participants were requested to refrain from consuming alcohol and from intense training and asked to maintain their normal drinking and eating habits 24 h prior to the experimental session. All participants provided written informed consent for participation in this study. The study was approved by the institute's ethical committee and performed in accordance with the Declaration of Helsinki.

Exercise protocol

Each participant visited the laboratory once, completing four maximal sprints in a seated position on a cycle ergometer. As the testing protocol was similar to the daily training and competition among these track cyclists, who had also previously carried out similar performance tests in the laboratory, no additional test familiarisation was considered necessary. All participants used their own cycling shoes and pedals during these efforts. The ergometer settings resembled actual competition demands.

The participants warmed up before each sprint with 6 minutes of low-intensity cycling (1–1.5 W·kg^{-1} body weight), followed by a 3-s maximal sprint. Participants rested passively for 10 minutes between warm-up and testing. Four maximal sprints (3, 8, 12, 60 s) were performed in an isokinetic mode at a cadence of 120 rpm on an SRM cycle ergometer (Schoberer Rad Messtechnik GmbH, Jülich, Germany) with a 9-kg flywheel, in 7th gear. With these settings, the pedal force decreased linearly during the initial acceleration phase and the target cadence of 120 rpm was reached after 3–4 s.

The participants were asked to accelerate as rapidly as possible from a simulated rolling start at approximately 20 rpm to 120 rpm at a self-selected time-point and to continue sprinting with maximal effort until the end of each sprint, with the investigators providing emphatic verbal encouragement throughout the entire test. 30 min after the 12-s sprint, each participant performed 6 s of maximal-cadence, low-resistance cycling (the motoric test) on an ergometer [24]. The settings enabled the athletes to reach a cadence of ≥ 160 rpm within the first 3 s, which generated additional data in the high-frequency cadence range. Combination of these data with the fatigue-free rate of pedalling during the acceleration phase of each sprint allowed more valid determination of the F/v profiles [27].

Tests were separated by approximately 2 hours, during which the athletes were asked to eat a light meal, corresponding to the individual's calculated energy expenditure during the preceding test. The next test began when comparable levels of blood lactate and blood glucose were observed.

Equipment and Measurements

Data collection started from 3 minutes before the beginning of the standardized warm-up and ended 30 minutes after exercise, while participants remained seated, with as little movement as possible.

A commercially available continuous-wave NIRS device was used (Moxy Monitor; Fortiori Designs LLC, MN, USA) to continuously measure SmO_2 and tHb (total mass of haemoglobin and myoglobin) of the vastus lateralis muscle (VL), as this muscle has been used most commonly in recent studies using NIRS in cyclists [1]. The sensors were fixed in place using medical adhesive tape (Hypafix; BSN Medical, DE) and covered with a compatible commercially available light shield to eliminate possible ambient light intrusion. The device uses four wavelengths (680, 720, 760 and 800 nm) to assess absorbency via the modified Beer-Lambert law resulting in a relative concentration of SmO_2 as a percentage in the following equation: oxygenated Hb + Mb / oxygenated Hb + Mb + deoxygenated Hb + Mb = SmO_2 [28]. The device detectors are spaced at 12.5 mm and 25 mm from the emitter. The sampling rate was set to 0.5 Hz, which samples the four wavelengths over 10 cycles for an averaged output every second and gathered using the Idiag Moxy software (Idiag AG, CH). With the emitter-detector spacing of 25 mm, a penetration depth of 15.0 mm can be expected (ibid.). The adipose tissue thickness (ATT) of the subjects at the measurement site was individually measured and none breached the upper threshold of 15.0 mm; therefore ATT interference is considered negligible.

Net crank torque (M) and angular velocity (ω) were monitored continuously at a sample rate of 500 Hz with an SRM power meter (Schoberer Rad Messtechnik GmbH, Jülich, Germany). The average data from units of 10 Hz were used for calculations.

Before and directly after each sprint, as well as 1, 3, 5, 7, 10, 15, 20, 25 and 30 minutes after the 8- and 12 s-sprints, 20 μl of capillary blood was collected from the hyperaemic ear lobe for haemolysis and enzymatic-amperometric determination of lactate and glucose (Biosen, EKF Diagnostics, Magdeburg, Germany). Since accumulation of blood lactate during the 3-s test was expected to be limited and the participants had already performed a considerable number of such samplings, capillary blood was only collected during the first, third, fifth and tenth minutes following this sprint to ensure sufficient blood flow, prevent sample contamination and enhance comfort.

Respiratory gases were measured continuously with a breath-by-breath portable gas analyser (Metamax 3B, Cortex, Leipzig/Germany). Prior to each test the gas analyser was calibrated using a known concentration of gases and a 3-litre syringe following the manufacturer's recommendations.

Data processing

Raw data from the ergometer were obtained at a sample rate of 10 Hz. From these values, the mean tangential force F at both pedals, averaged over one revolution (taking into account individual crank length), as well as the corresponding pedalling rate, was derived.

To determine fatigue-free maximal pedalling rate, the fatigue-free force-velocity (F/v) profile was created based on the pedalling rate and corresponding mean crank force during the first 3–4 cycles of pedalling (≤ 3 s in duration, data point in the cadence range from 30 to 120 rpm) in each sprint, during which the crank force decreased linearly. As recommended by Dunst et al. [27, 29] 1 or 2 revolutions with very high pedalling rate (data point in the cadence range ≥ 160 rpm) attained during the first 3 s of the motoric test and its corresponding mean crank force were incorporated into these calculations. The data points with the best F/v relationship were selected. Since pedalling rate is directly proportional to the tangential speed of motion at the pedal, the F/v profile was based on pedalling rate (as specific movement velocity) and corresponding mean crank force F [29]. Parameters of the linear model function

$$F(v) = a \cdot v + b \quad (1),$$

were determined by linear regression analysis and characterise the fatigue-free relationship between mean pedal force (N) and specific movement velocity v (rpm) (ibid.). Maximal pedalling rate was calculated as $PR_{max} = -b\ a^{-1}$.

With the onset of fatigue, reflected in reduced energy production by the main propulsion muscles, the mean pedal force decreases at each cadence so that the F/v profile at time t F(v,t) is lower than the fatigue-free maximum F(v). We defined the timespan up to the first systematic deviation from F(v) by the time-point t_{Ff} after which F(v,t) fell below and thereafter never returned to the fatigue-free maximal F(v) [24]:

$$t_{Ff} := \min\{\tilde{t} \in [s;T] | F(v,t) < F(v)\ \forall\ t \in [s;T] : t > \tilde{t}\}, \quad (2),$$

where s=0 represents the initiation and T the termination of each performance test

Parameters of the exponential model function of $SmO_2(t)$ were determined by non-linear regression analysis based on the SmO_2 data of the participants' 60-s-sprint [30]:

$$SmO_2(t) = SmO_{2Base} - SmO_{2A} \cdot \left(1 - e^{\frac{-t+TD}{\tau_{SmO_2}}}\right) \quad (3),$$

with SmO_{2base} as the resting level before the start of a sprint, SmO_{2A} as the amplitude of the Sm_{O2} drop and τ_{SmO2} as the time constant of desaturation.

For each sprint test, excess post-exercise oxygen consumption ($\dot{V}O_{2EPOC}$) was determined by non-linear regression analysis using the following bi-exponential 4-parameter model to establish the phosphagen energy supply [31]:

$$\dot{V}O_{2EPOC}(t) = A_{FC} \cdot e^{\frac{-t+TD}{\tau_a}} + B_{SC} \cdot e^{\frac{-t+TD}{\tau_b}} + \dot{V}O_{2Base} \quad (4),$$

where A_{FC} and B_{SC} represent the amplitudes of the fast component (associated with post-exercise resynthesis of creatine phosphate) and the slow component (associated with post-exercise lactate oxidation), τa and τb the corresponding time constants and $\dot{V}O_{2Base}$ the asymptotic resting oxygen uptake at time $\rightarrow\infty$.

For equations (3) and (4), a time delay (TD) was used to compensate for any delays in the measurement data.

Replenishment of high-energy phosphates was estimated based on the product of the amplitude A_{FC} and time constant τ_a of the fast component ($\dot{V}O_{2PCr} = A_{FC}\tau_a$). Phosphagen energy supply was calculated from the latter by [16, 32]:

$$W_{PCr} = VO_{2PCr} \cdot CE \quad (5),$$

employing a caloric equivalent (CE) of 20.9 J ml^{-1} [16].

Based on W_{PCr} of the single sprint tests, time-dependent energy contribution of the phosphagen energy system during the 60-s test was analysed with the following mono-exponential 2-parameter model by non-linear regression analysis:

$$W_{PCr}(t) = W_{PCrTOT} \cdot \left(1 - e^{\frac{-t}{\tau_{PCr}}}\right) \quad (6),$$

where W_{PCrTOT} represents the maximum of phosphatic energy supply at time $\rightarrow\infty$ and τ_{PCr} represents the corresponding time constant.

Since the time-point when maximal blood lactate concentration occurs is unpredictable, the dynamics of blood lactate response were calculated by non-linear regression analysis using a 3-parameter-model to determine maximal blood lactate concentration [33, 34]:

$$BLC(t)=\frac{A\cdot k_1}{k_1-k_2}\cdot\left(e^{-k_1\cdot t}-e^{-k_2\cdot t}\right)+BLC(0) \quad (7),$$

with extra-vascular increase (A) and rate constants of BLC appearance (k_1) and disappearance (k_2). For each sprint test, corresponding ΔBLC (mmol · l^{-1}) was calculated by subtraction of the maximum of BLC(t) and pre-exercise blood lactate (BLC_{max}-BLC(0)) as described by Mader [35].

Following the model function of lactate formation rate reported by Mader [35, 36], the time-dependent ΔBLC was analysed by non-linear regression analysis using the following 3-parameter bi-exponential model:

$$\Delta BLC(t)=B\cdot\left(-\frac{1}{k_3}e^{-k_3\cdot t}+\frac{1}{k_4}e^{-k_4\cdot t}\right)+C \quad (8),$$

where B may represent the amplitude of lactate formation rate in the muscle, k_3 and k_4 represent the time constants of appearance and disappearance of lactate in the blood and C depicts the limit value of blood lactate accumulation during maximal exercise.

t_{alac} reflects the time delay of the onset of lactate accumulation in the blood [16], so that ΔBLC (t_{alac})=0. Maximal rate of lactate accumulation ($\dot{v}La_{max}$ mmol l^{-1} s^{-1}) was calculated by:

$$\dot{v}La_{max} := \max_{t\in]t_{alac};60]}\dot{v}La(t) \quad (9),$$

where the function of the lactate accumulation rate was the derivative of ΔBLC(t).

The kinetics of oxygen uptake during the 60 s-sprint were described by Barstow & Molé [37]:

$$\dot{V}O_2(t)=\dot{V}O_{2A}\cdot\left(1-e^{\frac{-t}{\tau\dot{V}O2}}\right)+\dot{V}O_2(0) \quad (10),$$

where $\dot{V}O_2(t)$ represents the oxygen uptake at time t. $\dot{V}O_2(0)$ is the initial oxygen uptake or starting value immediately before the start of exercise. $\dot{V}O_{2A}$ defines the amplitude or denotes the change between the initial and current oxygen demand. To investigate the dependence of oxygen saturation on oxygen availability, the time-dependent quotient of changes in oxygen saturations ($\Delta SmO_2(t) = SmO_2(t)/SmO_2(t + 1)100$ [%]) and changes in oxygen uptake ($\Delta\dot{V}O_2(t) = \dot{V}O_2(t)/\dot{V}O_2(t + 1))100$ [%]) was calculated.

Statistical analyses

All data were checked for normality using the Shapiro-Wilk test and are presented as mean ± SD. The Pearson product-moment correlation test was used for analysing interrelationships between variables. Pearson's correlation coefficient r (small; $r \geq 0.1$; medium: $r \geq 0.3$; large: $r \geq 0.5$) was employed as a measure of effect size. Statistical significance was set at an alpha level of < 0.05. Linear and non-linear regression analysis was used to study the relationship between data. The least squares method was used in the regression analysis to determine the model parameters and time delays of the various model functions. The absolute difference was used to determine the bias of measurements. The quality of the regression analyses was examined by calculating the coefficient of determination . Mathematical analysis and statistical tests were processed using IBM SPSS Statistics version 24 for Windows (IBM Corp., Amonk, NY, USA), Office Excel 2016 (Microsoft Corporation, Redmond, WA, USA) and MATLAB 9.10.0 R2021a (The MathWorks, Inc., Natick, MA, USA).

RESULTS

Figure 1 illustrates the time-course of power output, oxygen uptake and blood lactate concentration in an exemplary 60-s test.

After the initial acceleration phase, the athletes reached the specified cadence of 120 rpm within the first 4 s in all sprint tests. To control the quality of the performance within the tests, individual fatigue-free F/v profiles were compared. No statistically significant differences were found.

Considering only the best F/v profile of each athlete (the profile with the highest calculated maximal power output), mean maximal force was 1343 ± 107 N and mean maximal cadence was 300 ± 15 rpm. The slope of the F/v profile was a = -4.51 ± 0.53 N rpm^{-1}. The coefficient of determination R^2 for the F/v profile was calculated to be ≥ 0.99 for all athletes. The time-point immediately before the first systematic deviation from the fatigue free F/v profile was located at t_{Ff} = 2.06 ± 0.32 s.

Mean power output, ΔBLC and the model parameters of EPOC(t) of the different sprint tests are shown in Table 1.

The average R^2 of all EPOC-models was 0.90 ± 0.03. The mean EPOC(t) of a 60-s test with the different components is illustrated in Figure 2.

Mean model parameters of oxygen desaturation (equation 3) of the VL were SmO_{2Base} = 75.13 ± 8.60%, SmO_{2A} = 65.94 ± 9.36% and τ_{SmO2} = 2.93 ± 0.65 s. An $R^2 > 0.99$ was calculated. The time-point at which modelled $\Delta SmO_2(t)$ started to increase systematically above 100% and therefore SmO_2 values differ from the model function was t_{resat} = 32.60 ± 4.96 s. An example of SmO_2 data and the determined model $SmO_2(t)$ of an athlete's 60-s sprint test is shown in Figure 3.

tHb values ranged between 12.95 ± 0.33 mg dl^{-1} and 12.74 ± 0.31 mg dl^{-1} with 0.22 mg dl^{-1} as the largest difference observed. The maximal value of tHb was reached at 24.8 ± 22.8 s, the minimal value at 15.3 ± 16.0 s, not indicating any time-dependent systematics.

Mean parameters of oxygen uptake kinetics were $\dot{V}O_{2A}$ = 3.70 ± 0.44 l min^{-1}, $\tau_{\dot{V}O2}$ = 14.73 ± 3.00 s and $\dot{V}O_2(0)$ = 0.68 ± 0.20 l min^{-1} with a mean R^2 of 0.85 ± 0.10.

The time-dependent quotient of changes in oxygen saturation and changes in oxygen uptake ($\Delta SmO_2(t)$ $\Delta\dot{V}O_2(t)^{-1}$) was >> 1 in the relevant period of exercise ($t_{resat} < t \leq 60$ s).

Based on W_{PCr} of the different sprint tests, the parameters of equation 6 to describe the time-dependent energy supply of the phosphagen energy system $W_{PCr}(t)$ were W_{PCrTOT} = 53.02 ± 9.30 kJ and τ_{PCr} = 3.23 ± 0.67 s with an R^2 of > 0.98.

Based on ΔBLC of the different sprint tests, the parameters of equation 8 describing the time-dependent blood lactate accumulation ΔBLC(t) were B = 1.59 ± 0.40 mmol·l^{-1}·s^{-1}, k_3 = 0.07 ± 0.02 s, k_4 = 0.62 ± 0.28 s and C = 18.78 ± 2.99 mmol·l^{-1} with an R^2 of > 0.99. t_{alac} was determined at 2.09 ± 0.41 s. Mean maximal rate of lactate accumulation was $\dot{v}La_{max}$ = 0.95 ± 0.18 mmol·l^{-1}·s^{-1}. The mean kinetics of SmO_2(t), W_{PCr}(t), ΔBLC(t) and La(t) in the 60-s sprint tests are shown in Figure 4. SmO_{2A} showed a significant strong correlation with SmO_{2Base} (r = 0.911; p < 0.002). τ_{SmO2} was positively correlated with τ_{PCr} (r = 0.790, p < 0.012), $\dot{v}La_{max}$ (r = 0.768, p < 0.017) and t_{alac} (r = 0.822, p < 0.001). t_{Ff} was positively correlated with τ_{SmO2} (r = 0.885, p < 0.001) and τ_{PCr} (r = 0.781,

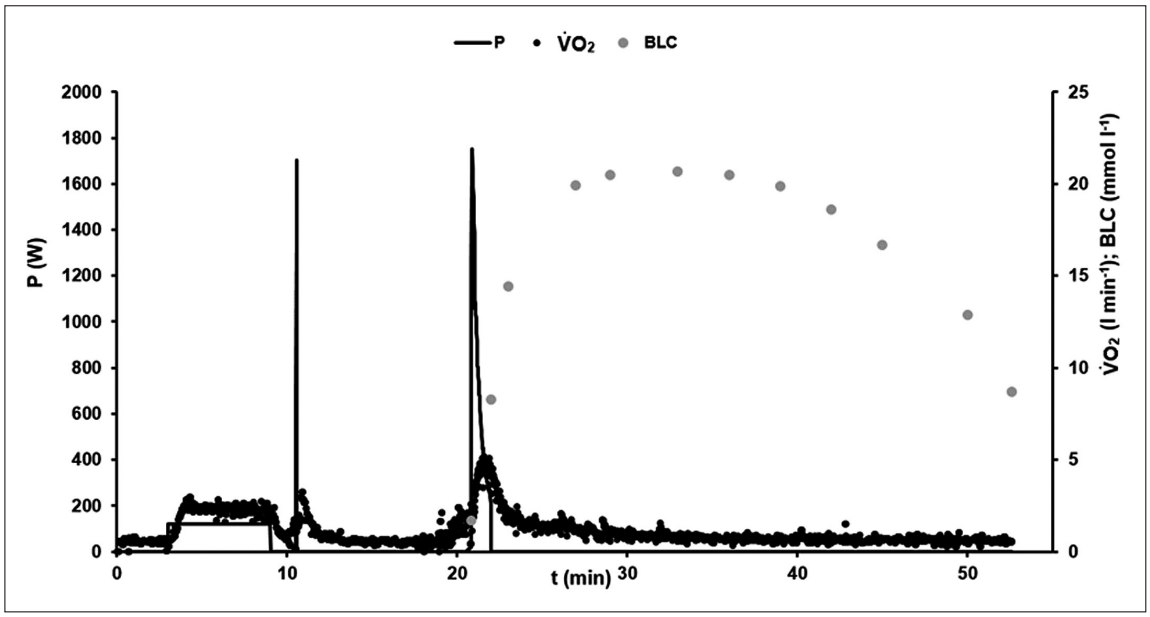


FIG. 1. Example of the time-course of power output P (W), oxygen consumption $\dot{V}O_2$ (l·min^{-1}), and blood lactate concentration BLC (mmol·l^{-1}) during the 60-s cycling sprint test protocol.

TABLE 1. Mean power output (P_{mean}), mean blood lactate accumulation (ΔBLC), mean parameters of excess post exercise oxygen consumption EPOC(t) and mean phosphagen energy supply (W_{PCr}) of the 3-, 8-, 12- and 60-s sprint test (n = 9).

Parameters	3 s	8 s	12 s	60 s
	M ± SD	M ± SD	M ± SD	M ± SD
P_{mean} (W)	1151 ± 116	1395 ± 109	1371 ± 102	715 ± 42
ΔBLC (mmol·l^{-1})	0.66 ± 0.25	4.73 ± 0.65	8.16 ± 0.90	17.70 ± 2.62
A_{FC} (ml·min^{-1})	1985 ± 436	2740 ± 381	2878 ± 501	3032 ± 447
τ_a (min)	0.82 ± 0.14	0.84 ± 0.12	0.84 ± 13	0.85 ± 13
B_{SC} (ml·min^{-1})	195 ± 167	418 ± 133	577 ± 119	981 ± 298
τ_b (min)	5.72 ± 2.52	6.46 ± 3.38	8.03 ± 3.10	9.36 ± 5.11
$\dot{V}O_{2Base}$(ml·min^{-1})	391 ± 58	391 ± 43	411 ± 58	532 ± 106
W_{PCr} (kJ)	31.83 ± 6.98	46.50 ± 3.79	51.24 ± 9.52	53.73 ± 9.96

Abbrev.: P_{mean}: Mean power output; ΔBLC: Blood lactate accumulation; A_{FC}: Amplitude of the fast component of EPOC(t); τ_a: Time constant of the fast component of EPOC(t); B_{SC}: Amplitude of the slow component of EPOC(t); τ_b: Time constant of the slow component of EPOC(t); $\dot{V}O_{2Base}$: Oxygen consumption at rest as the limit value of EPOC(t); W_{PCr}: Anaerobic alactic energy supply calculated based on the fast component of EPOC(t).

$p < 0.008$). Furthermore, a negative correlation of τ_{SmO2} and PR_{max} ($r = -0.670$, $p < 0.049$) was found.

The associations between these parameters are shown in Figure 5.

Using the mean time constant of $SmO_2(t)$ in combination with W_{PCrTOT} to estimate $W_{PCr}(t)$ results in a maximum error of 1.91 kJ. The results of the linear regression analysis comparing the two functions at each second during the 60-second sprint are shown in Figure 6.

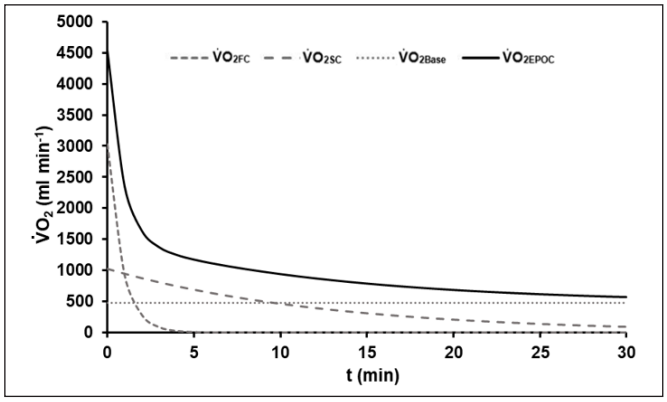


FIG. 2. Mean model function of EPOC(t) after the 60-s sprint test with its fast ($\dot{V}O_{2FC}$) and slow components ($\dot{V}O_{2SC}$) and the asymptotic resting level of oxygen uptake ($\dot{V}O_{2Base}$). The fast component corresponds to the amount of energy gained from the dephosphorylation of high-energy phosphates during exercise.

DISCUSSION

In accordance with Hamaoka et al. [2, 11], Jones et al. [38], Hamaoka & McCully [39] and Vasquez-Bonilla et al. [40], our results demonstrate a significant correlation between desaturation behaviour of SmO_2 and the time-dependent change in PCr. In addition, significant correlations of $SmO_2(t)$ with maximal pedalling rate and maximal lactate accumulation rate were found.

All models show excellent quality, qualifying them as suitable for describing the time-dependent behaviour of SmO_2 desaturation ($SmO_2(t)$), phosphagen energy supply ($W_{PCr}(t)$), blood lactate accumulation ($\Delta BLC(t)$) and oxygen uptake ($\dot{V}O_2(t)$) in an isokinetic 60-s all-out test on a cycle ergometer.

$W_{PCr}(t)$ was described by a mono-exponential function that shows a steep increase in phosphagen energy contribution in the first seconds of maximal exercise. After approximately 10 s, the rate of phosphagen energy contribution is significantly reduced and at approximately 12 s $W_{PCr}(t)$ reaches a quasi-steady state close to the maximum, which is mathematically reflected by the limit value of the function. According to the results of di Prampero and colleagues [41] the calculated amount of total W_{PCr} of ~ 53 kJ, assuming an active muscle mass of circa 30% in cycling exercises [42], corresponds to about 26 mmol phosphagen split per kg active wet muscle. This value is in the same order of magnitude as the total phosphagen content of the resting muscle [16]. The time to maximum is in line with previous observations. Barclay [13] reported that during maximal exercise, the energy received from the phosphagen system peaks after 10–15 s. Therefore, a glycolytic and mitochondrial contribution sufficient to maintain a quasi-steady state of

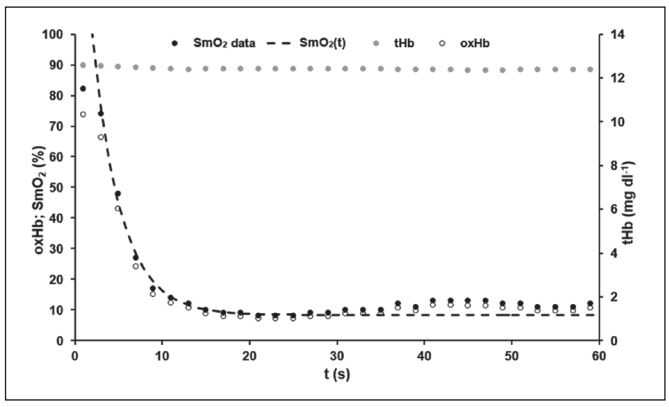


FIG. 3. A typical example of the data for the total mass of haemoglobin and myoglobin (tHb) with its oxygenated portion (oxHb) and for the muscle oxygen saturation data (SmO_2) with the calculated model $SmO_2(t)$ during the 60-s sprint test. $SmO_2(t)$ showed a very good description of the SmO_2 raw data until the middle of the test. After that, a slight increase in SmO_2 could be observed despite the athlete's maximal effort. The level of tHb was almost constant throughout the sprint. This phenomenon could be observed in all athletes.

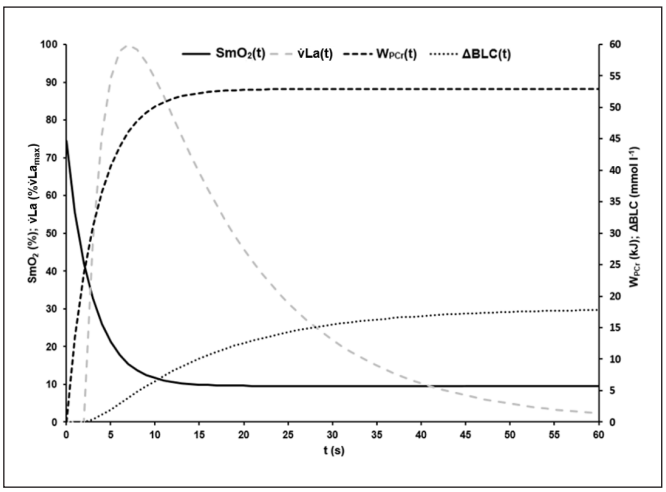


FIG. 4. Mean time-dependent O_2 saturation of the vastus lateralis muscle ($SmO_2(t)$), mean time-dependent blood lactate accumulation ($\Delta BLC(t)$) and mean time-dependent phosphagen energy supply ($W_{PCr}(t)$) during the 60-s sprint test. By visual comparison, a high correlation of the kinetics can be assumed, which could be confirmed statistically.

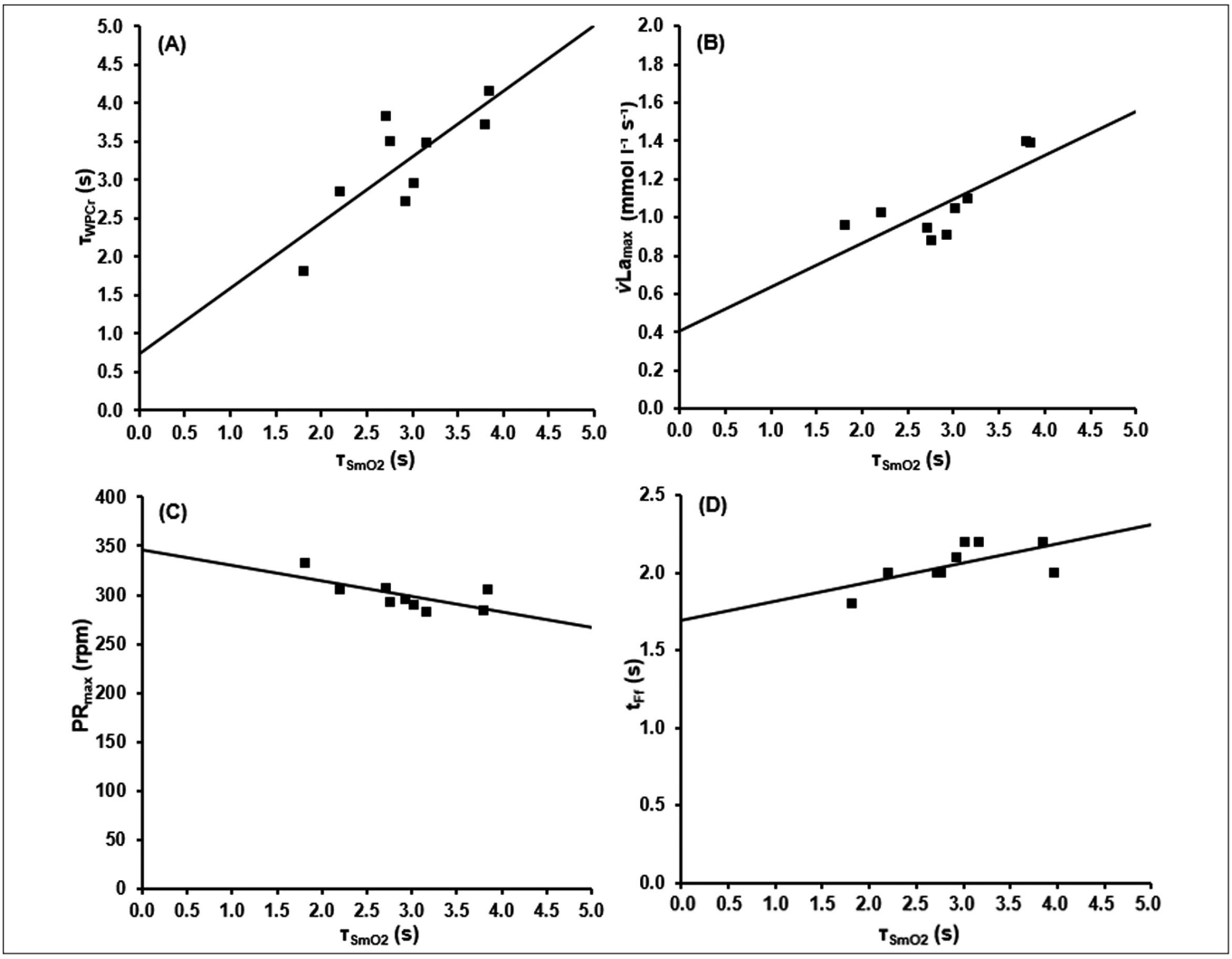


FIG. 5. Results of the correlation analysis between the time constant of $SmO_2(t)$ (τ_{SmO2}) and A) the time constant of $W_{PCr}(t)$ (τ_{PCr}), B) the maximal rate of blood lactate accumulation ($\dot{v}La_{max}$), C) the maximal pedalling rate (PR_{max}) and D) the end of the fatigue-free state (t_{Ff}).

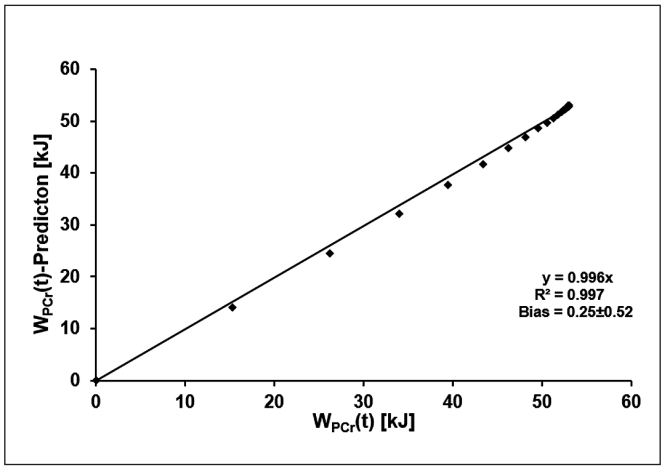


FIG. 6. Deviation of the model of the time-dependent amount of alactic energy predicted using the mean time constant of $SmO_2(t)$ from the mean original model of $W_{PCr}(t)$ in each second during the 60-s sprint with bias and standard deviation (SD).

re- and dephosphorylation of PCr in the working muscles is assumed at the time-point of near zero energy contribution of the phosphagen system. This state is also reflected in the desaturation behaviour of SmO_2 up to ~30 s.

Similar to $W_{PCr}(t)$, $SmO_2(t)$ can be described mono-exponentially and reflects the PCr dephosphorylation behaviour well. $SmO_2(t)$ also shows a steep desaturation in the first few seconds of the test. After a subsequent decrease in the desaturation rate after approximately 10 s, $SmO_2(t)$ also approaches a plateau after approximately 12 s. Unlike $W_{PCr}(t)$, $SmO_2(t)$ eventually increases slightly after the initial steep desaturation from the beginning of the test (see Figure 3). Maximal voluntary effort was ensured retrospectively by applying our previously published method [29]. Even though individuals continued their efforts at maximal voluntary intensity, relative SmO_2 extraction decreases.

The correlation of the time constants τ_{SmO2} and τ_{PCr} and the high agreement of the time courses indicate a close relationship between PCr dephosphorylation and SmO_2 desaturation in maximal cycling sprints. This statement is supported in contemporary exercise physiological literature [4, 42, 43]. If the O_2 stored in the tissue primarily serves PCr resynthesis between twitch contractions during exercise, the SmO_2 desaturation rate should depend on the PCr dephosphorylation rate [7, 9]. This is in line with di Prampero [41] and Francescato and colleagues [44], who described a transfer of O_2 from Hb on Mb on the working muscle with the onset of exercise. The differences of the time constants calculated in this study could be explained by measurement inaccuracies (especially in determination of the fast component of EPOC, which represents the greatest uncertainty in this study), the difference between local and systemic measurement or by the additional inhibiting influence of high glycolytic activity on PCr dephosphorylation state, whereas the shift of the cell pH to acidic due to high ATP hydrolysis additionally favours O_2 dissociation [19].

Our results indicate that the time-point immediatley before the first systematic deviation from the fatigue-free F/v profile could reflect the half-life SmO_2 and W_{PCr} and could indicate the onset of accumulation of lactate in the blood. Assuming an activation of glycolytic and oxidative ATP resynthesis after a depletion of 10–12 mmol PCr [16], which, applied to our data, corresponds to approximately 40–45%, the temporal proximity of these parameters seems plausible.

ΔBLC(t) was described by a bi-exponential function using t_{alac} to describe the delayed onset of blood lactate accumulation [41]. After a mean t_{alac} of 2.09 s, ΔBLC(t) rises steeply in an approximately linear manner until the tenth to twelfth second of exercise. After 10–12 s the increase in blood lactate accumulation is reduced, reflecting a sudden decrease of glycolytic activity caused by pH reduction in the active muscle cells [12, 20]. Extrapolated ΔBLC for 30 s of maximum effort is in accordance to the values reported by Beneke et al. [45] and Leithäuser et al. [46], which provides confirmation of model validity.

The onset of sudden significant reduction of lactate accumulation seems to coincide with the time-point when PCr dephosphorylation and SmO_2 desaturation approach their respective plateaus (see Figure 7). A positive correlation between the maximal lactate accumulation rate and the time constant of O_2 desaturation of the VL was observed. The higher $\dot{v}La_{max}$, the higher τ_{SmO2} and the longer it takes for the SmO_2 desaturation to reach a steady state. Considering the correlation of SmO_2 desaturation and PCr dephosphorylation, a higher $\dot{v}La_{max}$ representing a higher rate of PCr replenishment via glycolysis between twitch contractions can be assumed, reducing the need for oxidative rephosphorylation of PCr due to a smaller initial alactic debt in the dominant working muscle.

Hautier et al. [26] and Hansen et al. [47] found a positive correlation in the proportion of fast glycolytic IIx muscle fibres in the VL with maximal pedalling rate. A significant correlation between the maximal pedalling rate and the time constant of SmO_2 desaturation was found. As fast contracting glycolytic muscle fibres have the highest ATPase activity, highest maximal energy flow rate and the fastest dephosphorylation of PCr [48, 49], the correlation between τ_{SmO2} and τ_{PCr} as well as PR_{max} and the muscle fibre spectrum seems plausible.

Although the potential for a high rate of glycolysis increases with the proportion of fast fibres [25], no correlation between PR_{max} and $\dot{v}La_{max}$ was found within this sample of elite power athletes. This result suggests that the specific enzyme activity required for high glycolytic energy flow is not exclusively morphologically determined, but represents a specific training adaptation.

The previously described sudden resaturation of SmO_2 in the VL after approximately 30 s of maximal exercise could be a multifactorial phenomenon reflecting the onset of a decrease in the active muscle fibre spectrum in the muscle, the delayed response of the cardiovascular system to rapid changes in peripheral energy demand and the haemodynamics of the capillary beds to maintain oxygen supply to the muscle.

Thomas and Victor [19] reported that a kind of contraction-induced sympathetic ischaemic state prevails in the muscles, which does not allow the influx of oxygenated blood for the very first seconds of maximal exercise. If this was the case, resaturation of SmO_2 in the working muscle would not be possible initially. With accumulation of metabolites in the interstitial fluid ($K+$, lactate) [40], vasomotor relaxation occurs, mediated by the endogenous vasodilator nitric oxide (NO), attenuating sympathetic vasoconstriction in active muscles and contributing to greater hyperaemia during exercise [19]. Although such an effect cannot be excluded, our results do not indicate any significant reduction of blood flow and thus no restriction of oxygen availability during exercise due to temporary ischaemic states. Thus, a non-significant and time-related non-systematic change in tHb by a maximum of $< 2\%$ could be detected.

Although $\dot{V}O_2(t)$ increased exponentially from the initial value of ~15% to ~85% of the athletes' $\dot{V}O_{2max}$ during the 60-s sprint, oxygen uptake kinetics cannot explain the sudden resaturation of SmO_2 after ~ 30 s of exercise, which, at a nearly constant tHb, has to represent a resaturation of Hb and Mb in the VL.

The $\dot{V}O_2(t)$ time constant ($\tau_{\dot{V}O2} \sim 15$ s) leads to a steep increase in oxygen uptake during the first 15 s of maximal sprinting. After 30 s of exercise, about 90% of the $\dot{V}O_{2peak}$ was reached. In the second half of the sprint, oxygen uptake only increased by $< 10\%$ with increments of $< 0.75\%\ s^{-1}$.

The relationship of resaturation rate and changes in oxygen uptake indicates a decoupling of resaturation and oxygen uptake in the second half of exercise ($\Delta SmO_2(t) > 100\%$, $\Delta\dot{V}O_2\ (t) < 100\% \forall\ 30 < t \leq 60$ s). From our results, we suggest that the resaturation during exercise is neither an effect of blood flow restriction nor a delayed response of the cardiovascular system to rapid changes in peripheral energy demand.

Considering the exponential decrease in maximal power output [29] and the reported exponential increase in blood lactate

concentration, it can be speculated that the progressive increase in resaturation of Hb and Mb from mid-exercise onwards may reflect the onset of rephosphorylation of PCr in fatigued high-glycolytic IIx fibres, which no longer contribute to power output [29, 50].

The assumption that resaturation during maximal exercise is an indication of a decrease in the number of working motor units in the dominant working muscles is also supported by the findings of Vasquez-Bonilla et al. [40]. In a repeated sprint protocol, a decrease in desaturation amplitude was observed in elite female football players with a simultaneous decrease in sprint performance in each bout. This is consistent with our observations of NIRS signalling during repeated cycling sprints.

Finally, Figure 7 illustrates the possible interpretation of SmO_2 kinetics based on the results of our study.

LIMITATIONS

The study is based on a considerable amount of mathematical modelling of physiological responses during maximal exercise. Despite the high quality of the individual models and plausibility of the overall modelling, the simplifying character of a model in favour of the identification of interrelationships and systematic behaviour has to be considered.

The models are based on data points derived from several maximal sprint tests. The validity of the models requires a high

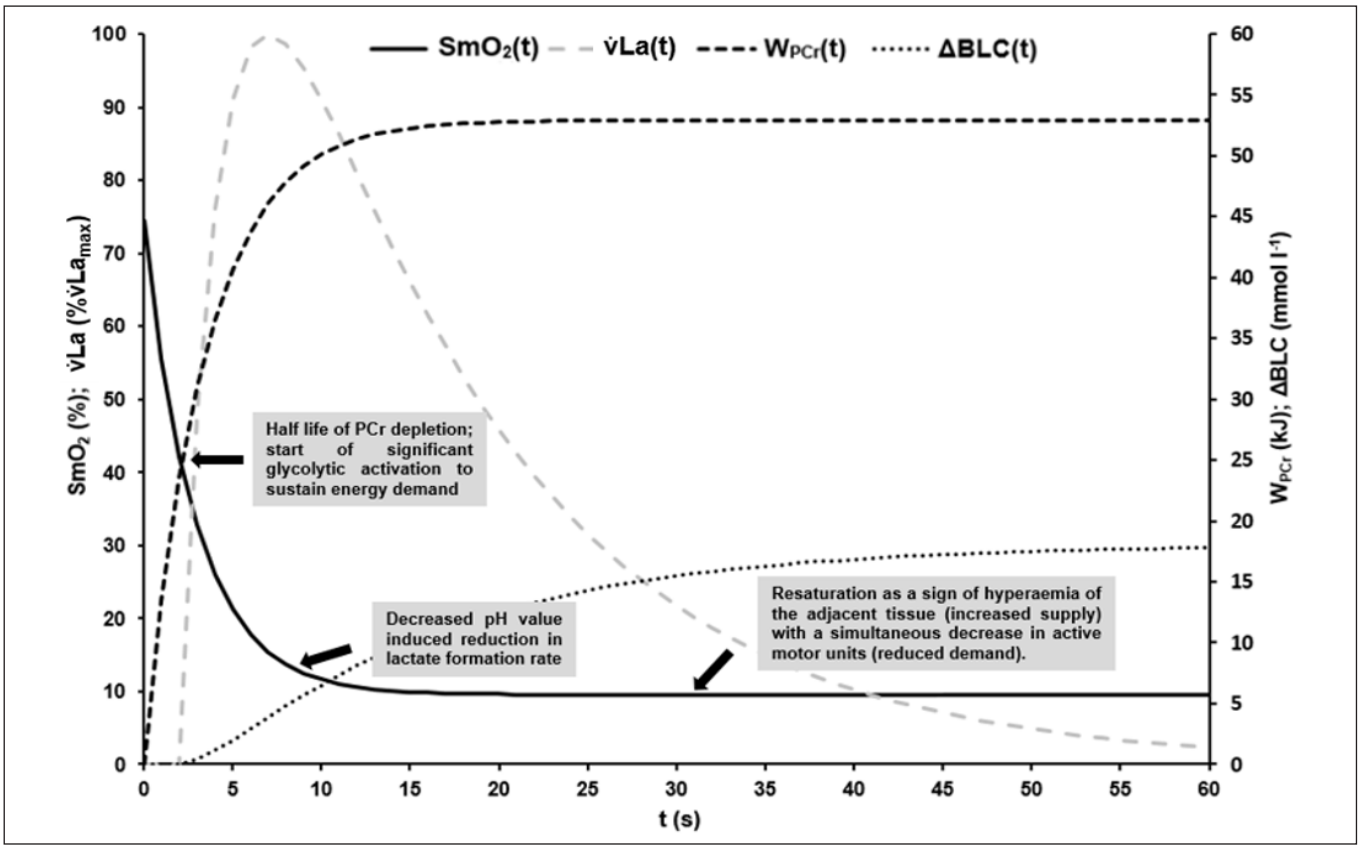


FIG. 7. Visualisation of the mean time courses of oxygen saturation $SmO_2(t)$ [%], time-dependent anaerobic alactic energy contribution $W_{PCr}(t)$ [kJ], time-dependent blood lactate accumulation $\Delta BLC(t)$ [mmol · l^{-1}] and resulting lactate formation rate $\dot{v}La(t)$ [mmol · l^{-1} · s^{-1}] with suggested interpretation of characteristic point in times: At the onset of maximal exercise the rate of PCr split reflects the energy demand of the working muscle [16, 17]. About the have of the PCr stored in the muscle can be depleted without significant changes in ATP depletion rate and ATP concentration in the working muscle [16]. Assuming that glycolytic and oxidative ATP resynthesis is activated by the cell's ADP concentration or phosphorylation deficit, a subsequent rapid increase in ADP or Cr will then activate glycolytic and mitochondrial ATP resynthesis to compensate for an increased rate of dephosphorylation [12]. The higher the rate of glycolytic and mitochondrial rephosphorylation, the slower the rate of PCr dephosphorylation subsequently. Due to the comparatively low glycolytic and the even lower oxidative ATP resynthesis rate – especially at the beginning of maximal exercise – the energy flow in the muscle cell continuously decreases, which leads to a corresponding continuous decrease in muscle performance. Although oxidative phosphorylation subsequently continues to increase until the cardiopulmonary system has adapted to the maximal energy demand, an exponential decrease in maximal power output can be observed [29]. This is due to a successive decrease in glycolytic energy flux with decreasing cell pH, resulting in a decrease in active muscle mass when energy flux falls below the minimum demand required for excitability and muscle contraction, especially in dominant phosphagenic and glycolytic type IIx muscle fibres. If SmO_2 always reflects the balance between oxygen demand and supply of a muscle, the sudden resaturation of SmO_2 at the midpoint of the sprints could indicate a decrease in total PCr restoring demand and therefore a decrease in the active muscle mass (see Figure 3).

reliability of performance, metabolic stress and their measurements. Despite our efforts to standardise the tests and ensure similar test conditions, it must be pointed out that it is an indirect reconstruction of the metabolic response during the 60-s effort, so that misinterpretation cannot be excluded completely.

Due to the limited number of participants, elite training status and the possible sources of error presented, further investigations are required to check our results, especially in different cohorts. When recruiting participants, care must be taken to ensure a sufficient level of capability and proficiency, as the method used here requires the athletes to sustain maximal neuromuscular performance. If this performance is below the time-dependent maximum, metabolism in the fibres of the active muscles may vary, altering total metabolic response and its systematics.

PRACTICAL APPLICATIONS

For practical application, the SmO_2 kinetics of the muscle with the highest desaturation within the main propulsive/working muscles can be used as a representation for the PCr dephosphorylation state of the system.

By combining the value of total alactic energy derived from oxygen uptake of the fast component of EPOC with the time constant of $SmO_2(t)$ derived from NIRS measurements, PCr dephosphorylation kinetics can be estimated on the basis of a single sprint with an error < 2 kJ.

A direct measurement of the lactate accumulation rate based on NIRS measurements does not seem to be possible, but the time interval from the onset to the maximum activation of the lactate accumulation rate can be represented by NIRS measurements.

CONCLUSIONS

Our results indicate that SmO_2 kinetics of the dominant working muscle reflect the time-dependent phosphagen energy contribution and the dephosphorylation of high-energy phosphates in a 60-s maximal sprint in elite track cyclists. The rate of SmO_2 desaturation is dependent on the maximal pedalling rate and the maximal lactate accumulation rate reflecting the maximal glycolytic energy flux. While higher PR_{max} accelerates desaturation, higher $\dot{v}La_{max}$ reduces it. The half-life of SmO_2 represents the end of the fatigue-free state and could indicate the beginning of accumulation of lactate in the blood. Reaching an SmO_2 plateau after maximal desaturation seems to be temporally associated with a reduction in lactate accumulation rate.

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Conflicts of interest/Competing interests

On behalf of all authors, the corresponding author states that we have no conflicts of interest.

Ethics approval

All procedures were approved by the ethics committee and conducted in accordance with the Declaration of Helsinki.

Authors' contributions

AKD designed and conducted the study and analysed the data. AKD, CH, CM and AF were responsible for drafting the paper and revising it critically with respect to important intellectual content. AKD, CH, CM and AF approved the final version of this manuscript for publication.

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REFERENCES

1. Perrey S, Ferrari M. Muscle Oximetry in Sports Science: A Systematic Review. Sports Med. 2018; 48:597–616. https://doi.org/10.1007/s40279-017-0820-1.
2. Hamaoka T, McCully KK, Quaresima V, Yamamoto K, Chance B. Near-infrared spectroscopy/imaging for monitoring muscle oxygenation and oxidative metabolism in healthy and diseased humans. J Biomed Opt. 2007; 12(6), 062105. https://doi.org/10.1117/1.2805437.
3. Ryan TE, Southern WM, Reynolds MA, McCully KK. A cross-validation of near-infrared spectroscopy measurements of skeletal muscle oxidative capacity with phosphorus magnetic resonance spectroscopy. J Appl Physiol. 2013; 115:1757–66. https://doi.org/10.1152/japplphysiol.00835.2013.
4. Ryan TE, Brophy P, Lin C Te, Hickner RC, Neufer PD. Assessment of in vivo skeletal muscle mitochondrial respiratory capacity in humans by near-infrared spectroscopy: A comparison with in situ measurements. J Physiol. 2014; 592:3231–41.
5. McManus CJ, Collison J, Cooper CE. Performance comparison of the MOXY and PortaMon near-infrared spectroscopy muscle oximeters at rest and during exercise. J Biomed Opt. 2018; 23(1):1–14. doi: 10.1117/1.jbo.23.1.015007.
6. Bouschel R, Langberg, H, Olese J, Gonzales-Alonzo J, Bülow J, Kjaer M. Monitoring tissue oxygen availability with near infrared spectroscopy (NIRS) in health and disease. Scand J Med Sci Sports. 2001; 11(14):213–222. doi: 10.1034/j.1600-0838.2001.110404.x.
7. Kemp GJ, Taylor DJ, Radda GK. Control of phosphocreatine resynthesis during recovery from exercise in human skeletal muscle. NMR Biomed. 1993; 6(1):66–72. https://doi.org/10.1002/nbm.1940060111.

8. Grassi B, Quaresima V, Marconi C, Ferrari M, Cerretelli P. Blood lactate accumulation and muscle deoxygenation during incremental exercise. J Appl Physiol. 1999; 87(1):348–355. https://doi.org/10.1152/jappl.1999.87.1.348.
9. Haseler LJ, Hogan MC, Richardson RS. Skeletal muscle phosphocreatine recovery in exercise-trained humans is dependent on O_2 availability. J Appl Physiol. 1999; 86(5):2013–8. doi: 10.1152/JAPPL.1999.86.6.2013.
10. Saks V, Guzun R, Timohhina N., Tepp K, Varikmaa M, Monge C, Beraud N, Kaambre T, Kuznetsov A, Kadaja L, Eimre M, Seppet E. Structure–function relationships in feedback regulation of energy fluxes in vivo in health and disease: mitochondrial interactosome. Biochim Biophys Acta. 2010; 1797; 678–697. doi: 10.1016/j.bbabio.2010.01.011.
11. Hamaoka T, Iwane H, Shimomitsu T, Katsumura T, Murase N, Nishio S, et al. Noninvasive measures of oxidative metabolism on working human muscles by near-infrared spectroscopy. J Appl Physiol. 1996; 81(3):1410–7. doi: 10.1152/jappl.1996.81.3.1410.
12. Mader A. Glycolysis and oxidative phosphorylation as a function of cytosolic phosphorylation state and power output of the muscle cell. Eur J Appl Physiol. 2003; 88:317–338. doi: 10.1007/s00421-002-0676-3.
13. Barclay CJ. Energy demand and supply in human skeletal muscle J Muscle Res Cell Motil. 2017; 38:143–155. doi: 10.1007/s10974-017-9467-7.
14. Rigoulet M, Bouchez CL, Paumard P, Ransac S, Cuvellier S, Duvezin-Caubet S, Mazat JP, Devin A. Cell energy metabolism: An update. Biochim Biophys Acta Bioenerg. 2020; 1861(11):148276. doi: 10.1016/j.bbabio.2020.148276.
15. Boushel R, Pott F, Madsen P, Rådegran G, Nowak M, Quistorff B, et al. Muscle metabolism from near infrared spectroscopy during rhythmic handgrip in humans. Eur J Appl Physiol Occup Physiol. 1998; 79:41–8. doi: 10.1007/s004210050471.
16. di Prampero PE. Energetics of muscular exercise. Rev Physiol Biochem Pharmacol. 1981; 89:143–222. doi: 10.1007/BFb0035266.
17. Chung Y, Sharman R, Carlsen R, Unger SW, Larson D, Jue T. Metabolic fluctuation during a muscle contraction cycle. Am J Physiol.1998; 274:C846–52.
18. Barstow TJ, Molé PA. Simulation of pulmonary O_2 uptake during exercise transients in humans. J Appl Physiol. 1987; 63.2253–2261.
19. Thomas GD, Victor RG. Nitric oxide mediates contraction-induced attenuation of sympathetic vasoconstriction in rat skeletal muscle. J Physiol. 1998; 506:817–826. doi: 10.1111/j.1469-7793.1998.817bv.x.
20. Robergs RA, Ghiasvand F, Parker D. Biochemistry of exercise-induced metabolic acidosis. Am J Physiol Regul Integr Comp Physiol. 2004; 287:R502–16. doi: 10.1152/ajpregu.00114.2004.
21. Jacobs I, Tesch PA, Bar-Or O, Karlsson J, Dotan R. Lactate in human skeletal muscle after 10 and 30 s of supramaximal exercise. J Appl Physiol Respir Environ Exerc Physiol. 1983; 55:365–7. doi: 10.1152/JAPPL.1983.55.2.365.
22. Jones NL, McCartney N, Graham T, Spriet LL, Kowalchuk JM, Heigenhauser GJ, et al. Muscle performance and metabolism in maximal isokinetic cycling at slow and fast speeds. J Appl Physiol. 1985; 59:132–6. https://journals.physiology.org/doi/abs/10.1152/jappl.1985.59.1.132.
23. Edwards RHT, Wilkie DR, Joan Dawson M, Gordon RE, Shaw D. Clinical use of nuclear magnetic resonance in the investigation of myopathy. Lancet. 1982; 319:725–731. doi: 10.1016/S0140-6736(82)92635-6.
24. Dunst AK, Hesse C, Feldmann A., Holmberg HC. A novel approach to determine alactic timespan in the assessment of the maximal lactate accumulation rate in elite track cyclists. Int J Sport Physiol Perform. 2023;18(2):157-163.
25. Pette DWG, Spamer C. Metabolic properties of muscle fibers. Fed Proc. 1987; 45(13):2910–4. https://doi.org/10.2337/diab.28.1.S25.
26. Hautier CA, Linossier MT, Belli A, Lacour JR, Arsac LM. Optimal velocity for maximal power production in non-isokinetic cycling is related to muscle fibre type composition. Eur J Appl Physiol Occup Physiol. 1996; 74:114–118. doi: 10.1007/BF00376503.
27. Dunst AK, Hesse C, Ueberschär O, Holmberg HC. Fatigue-Free Force-Velocity and Power-Velocity Profiles for Elite Track Sprint Cyclists: The Influence of Duration, Gear Ratio and Pedalling Rates. Sports. 2022; 10(9):130. doi: 10.3390/sports10090130.
28. Feldmann A, Schmitz R, Erlacher D. NIRS on a functional scale of 0–100%: Establishing practicality of the Moxy Monitor for sport science. J Biomed Opt. 2019; 24(11):115001. doi: 10.1117/1.JBO.24.11.115001.
29. Dunst AK, Grüneberger R, Holmberg HC. Modeling optimal cadence as a function of time during maximal sprint exercises can improve performance by elite track cyclists. Appl Sci. 2021; 11(24):12105.
30. Ferrari M, Muthalih M, Quaresima V. The use of near-infrared spectroscopy in understanding skeletal muscle physiology: recent developments. Philos Trans A Math Phys Eng Sci. 2011; 28; 369(1955):4577–90. doi: 10.1098/rsta.2011.0230.
31. Knuttgen HG. Oxygen dept after submaximal exercise. J Appl Physiol. 1970; 29:651–657.
32. Beneke , Beyer T, Jachner C, Erasmus J, Hütler M. Energetics of karate kumite. Eur J Appl Physiol. 2004; 92:518–523. https://doi.org/10.1007/s00421-004-1073-x.
33. Mader A, Heck H, Hollman W. Leistung und Leistungsbegrenzung des menschlichen Organismus interpretiert am Modell thermodynamischer offener Systeme. Ein Beitrag zur Diskussion biologischer Grenzen im Hochleistungssport. In A. Mader, H. Heck, & W. Hollman (eds.), Sport an der Grenze menschlicher Leistungsfähigkeit. 1981; 69–83.
34. Beneke R, Jumah M, Leithäuser RM. Modelling the lactate response to short-term all out exercise. Dyn Med. 2007; 6:10.
35. Mader A. Die Komponenten der Stoffwechselleistung in den leichtathletischen Ausdauerdisziplinen – Bedeutung für die Wettkampfleistung und Möglichkeiten zu ihrer Bestimmung. In P. Tschiene (ed.), Neue Tendenzen im Ausdauertraining. Frankfurt a. M.: Bundesausschuss Leistungssport. 1994; 12:127–220.
36. Mader A. Eine Theorie zur Berechnung der Dynamik und des steady state von Phosphorylierungszustand und Stoffwechselaktivität der Muskelzelle als Folge des Energiebedarfs. Habilitationsschrift. Köln: DSHS Köln. 1994.
37. Barstow TJ, Molé PA. Simulation of pulmonary O_2 uptake during exercise transients in humans. J App Physiol. 1987; 63,:2253–2261.
38. Jones AM, Fulford J, Wilkerson DP. Influence of prior exercise on muscle [phosphorylcreatine] and deoxygenation kinetics during high-intensity exercise in men. Exp Physiol. 2008; 93(4):468–478.
39. Hamaoka T, McCully KK. Review of early development of near-infrared spectroscopy and recent advancement of studies on muscle oxygenation and oxidative metabolism. J Physiol Sci. 2019; 69:799–811. https://doi.org/10.1007/s12576-019-00697-2.
40. Vasquez-Bonilla AA, Camacho-Cardeñosa A, Timón R, Martínez-Guardado I, Camacho-Cardeñosa M, Olcina G. Muscle Oxygen Desaturation and Re-Saturation Capacity Limits in Repeated Sprint Ability Performance in Women Soccer Players: A New Physiological Interpretation. Int J Environ

Res Public Health. 2021; 18(7):3484.
41. di Parmpero PE, Peeters LLH, Margaria R. Alactic O_2 debt and lactic acid production after exhausting exercise in man. J Appl Physiol. 1973; 34(5):628–32. doi: 10.1152/jappl.1973.34.5.628.
42. Mader A. A Transcription-Translation Activation Feedback Circuit as a Function of Protein Degradation, with the Quality of Protein Mass Adaptation Related to the average functional Load. J Theoretical Biol. 1988; 134:135–157.
43. Sako T, Hamaoka T, Higuchi H, Kurosawa Y, Katsumura T. Validity of NIR spectroscopy for quantitatively measuring muscle oxidative metabolic rate in exercise. J Appl Physiol. 2001; 90:338–44. https://www.physiology.org/doi/10.1152/jappl.2001.90.1.338.
44. Francescato MP, · Cettolo V, di Parmpero PE. Relationships between mechanical power, O_2 consumption, O_2 deficit and high-energy phosphates during calf exercise in humans. Pflugers Arch – Eur J Physiol. 2003; 445:622–628. doi: 10.1007/s00424-002-0992-9.
45. Beneke R, Pollmann C, Bleif I, Leithäuser RM, Hütler M. How anaerobic is the Wingate Anaerobic Test for humans. Eur J Appl Physiol. 2002; 87:388–392.
46. Leithäuser RM, Böning D, Hütler M, Beneke R. Enhancement on Wingate Anaerobic Test Performance With Hyperventilation. Int J Sports Physiol Perform. 2016; 11:627–634.
47. Hansen EA, Andersen JL, Nielsen JS, Sjøgaard G. Muscle fibre type, efficiency, and mechanical optima affect freely chosen pedal rate during cycling. Acta Physiol Scand. 2002; 176:185–194. doi: 10.1046/j.1365-201X.2002.01032.x.
48. Bottinelli R, Pellegrino MA, Canepari M, Rossi R, Reggiani C. Specific contributions of various muscle fibre types to human muscle performance: an in vitro study. J Electromyogr Kinesiol. 1999; 9:87–95.
49. Pette DWG, Staron RS. Transitions of muscle fiber phenotypic profiles. Histochem Cell Biol. 2001; 115:359–372.
50. Douglas J, Ross A, Martin JC. Maximal muscular power: lessons from sprint cycling. Sports Med Open. 2021; 7:48. doi: 10.1186/s40798-021-00341-7.

Do maturation, anthropometrics and leg muscle qualities influence repeated change of direction performance in adolescent boys and girls?

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ABSTRACT: The ability to change direction rapidly is a key fitness quality especially in invasive sports where young players perform approximately 300 changes of direction in a game. There is currently limited understanding of how anthropometric characteristics and maturation status influence change of direction ability in adolescent. Therefore, the purpose of this investigation is to assess the influence of anthropometrics and maturation status on change of direction ability in young people. The study involved 706 adolescents (367 girls) aged 14–19-year-old attending the same high school in Northern Italy. Stature, body mass, seated height and leg length were measured to determine the anthropometrics and maturation status of the participants. Repeated change of direction ability (10×5 m shuttle run test), lower limb power and muscle strength were evaluated using field tests from the Eurofit test battery. Maturity offset was calculated separately for boys and girls, in accord with the equation proposed by Mirwald. Preliminary analysis with 10×5 m as a dependent variable and sex and PHV as a fixed factor, suggests a significant difference between sex ($p < 0.001$; $d = 0.35$) but not with PHV ($p = 0.986$; $d = 0.000$) and interaction PHV $\times$ sex ($p = 0.836$; $d = 0.000$). Our results suggested that repeated change of direction performance was influenced by anthropometrics, maturation and muscle qualities in adolescent boys and girls.

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INTRODUCTION

The ability to change direction (COD) rapidly is a key physical fitness component for many invasive sports [1]. Moreover, an athlete's ability to change direction effectively provides the technical underpinning for their agility which is the ability to produce an accurate and effective change of direction in response to a stimulus [2]. Change of direction ability has been shown to possess discriminative ability between higher and lower-level youth performers in invasive team sports [3] and individual sports [1, 4]. Changes of direction are performed frequently in many sports [5, 6]. In fact, it has been recently noted that youth soccer players perform approximately 300 changes of direction in a game [7]. A successful COD involves a quick deceleration and a coordinated repositioning of the body prior to a re-acceleration in a new direction [7]. An individual's technical ability, lower limb strength capabilities, and sprinting speed are noted underpinning factors of COD ability [4, 7, 8].

Owing to of the complexity associated with growth and maturation the development of COD ability in youth is highly variable [9]. As a young person matures, changes in limb length and body composition can significantly influence movement quality [10, 11]. For example, shuttle run and 30 m sprint performance have been found to significantly improve at the moment of peak height velocity (PHV) occurrence in a large cohort of youth soccer players [11]. Due to the variable nature of maturation, theoretical models of exercise prescription in youth have proposed "windows of opportunity" where specific physical qualities can be emphasized at appropriate time associated with a young person's maturation status [9, 12]. Within these

models' it is postulated that the development of COD ability should be targeted at an individual's PHV alongside the development of strength, speed and power [12].

Evidence to support these 'windows of opportunity' are well established within the literature for the development of strength and endurance in youth [13, 14, 15]. However, there is currently limited understanding of how anthropometric characteristics (e.g., height, leg length, waist circumference) and maturation status influence COD ability in young people. Therefore, the purpose of this investigation is to assess the influence of anthropometric measures and maturation status on COD ability in young people. Clarity on the interplay between COD ability and a young person's anthropometrics and maturation status will help practitioners such as Physical Education (PE) teachers, coaches and trainers understand when and how to best prescribe exercise to improve this valuable physical fitness component.

MATERIALS AND METHODS

Participants

The study involved 706 adolescents (367 girls) aged 14–19-year-old attending the same high school in Northern Italy.

All the subjects were healthy (in possession of a medical certificate of good health status) injury free and did not possess and neurological disorders. All outcome measures were collected during Physical Education classes as part of routine fitness testing with the Eurofit test battery.

A cross-sectional cohort design was incorporated in the study and provides separate descriptive measures for both boys and girls. This study was approved by the Ethics Committee at Regional School (Lombardia), (number: "UP 1819-15") in Italy. Written information of the study, aim and procedures was given to teachers and students. An informed consent was obtained from all participant's parents or legal guardians.

Procedure

All the tests were conducted by a team of 5 students enrolled in the Sports Sciences Master's during the period of the PE program [16]. To increase reliability and validity each assessor undertook one week of training for the specific test that were administrating. Previous determination of the reliability of the assessor was performed to ensure accuracy and repeatability of the procedure (inter- and intra-examiner ICC of 0.96 and 0.98, respectively).

The school' PE teacher was present during test administration to ensure that students participating in the investigation complied with the procedures.

Anthropometric (body mass, height, sitting height, leg length) and physical fitness assessments (three field tests) of the adolescents were completed over a four week period with a one round of measurements obtained per week to avoid fatigue. All the participants were free to withdraw their participation at any time. Anthropometrics characteristics were evaluated 1 day before the performance test. The order of the test battery was as follows, 10×5 m test, sit up test, and finally the standing broad jump. Between each test the subjects had a five-minute rest to facilitate recovery.

Anthropometric measures

Anthropometric characteristics were taken by trained operators (quality-control coefficient for inter-and intra-observer reliability, 95% confidence interval). Standing height was evaluated to the nearest 0.5 cm (Seca Stadiometer 208) without shoes, feet together, and head in the Frankfort plane. Body mass was measured to the nearest 0.5 kg (Seca Beam Balance 710), with participants wearing minimal clothing [17, 18].

Measure of Maturity

Maturity off set was calculated separately for boys and girls, in accord with the equation proposed by Mirwald et al. [19].

In boys the predictive equation was as follows: Maturity Offset = -29.769 + 0.0003007 · Leg Length and Sitting Height interaction + 0.01177 · Age and Leg Length interaction + 0.01639 · Age and Sitting Height interaction + 0.445 · Leg by Height ratio, where R = 0.96, R^2 + 0.915, and SEE = 0.490 [19].

In girls, the predictive equation was Maturity Offset = -16.364 + 0.0002309 · Leg Length and Sitting Height interaction + 0.006277 · Age and Sitting Height interaction + 0.179 · Leg by Height ratio + 0.0009428 · Age and Weight interaction, where R = 0.95, R^2 = 0.910, and SEE = 0.499 [19].

Corresponding statistics (except for actual offset) were calculated relative to years before/after observed Peak Height Velocity (PHV): -3 = -2.51 to -3.50, -2 = -1.51 to -2.50, -1 = -0.51 to -1.50, 0 = -0.50 to +0.49, +1 = +0.50 to +1.49, +2 = +1.50 to +2.49 and +3 = +2.50 to +3.49 [20].

Measures of Physical Fitness

Three physical fitness components were evaluated using field tests from the Eurofit battery [21]. These tests are reliable and valid instruments for measuring fitness and are considered independent of one another [22].

10 × 5 m Shuttle run test: Two parallel lines (2 meters long) are drawn on the floor 5 m apart. On command, the subject ran as fast as possible from the starting line to the other line and returns to the starting line, crossing each line with both feet every time. The stopwatch was stopped when the participant crossed the end line with one foot. Results recorded to the nearest 0.1 s. The 10×5 m shuttle run test presents high reliability, and the ICC was calculated as 0.95 [23].

Standing Broad Jump: from a standing position immediately behind a line with feet approximately shoulder width apart, the adolescent jumped as far as possible with feet together. The rearmost foot was recorded as the final measure (cm.) of the jump. The swing of the upper limbs was permitted. The standing broad jump presents high reliability from test-retest analysis, and the ICCs reported

a range from 0.94 to 0.95 [23]. and the coefficient of variation range was 7.3–11.9% [24].

Sit-Ups: the efficiency of abdominal musculature was measured by the maximum number of sit-ups (crunch) achieved within half a minute. The starting arrangement involved the participant lying on their back, fingers interlocked behind the nape, knees bent at a 90° angle and heels/feet flat on the floor. The participant was required to rise from the sitting position with the elbows straightened so that they touch the knees. The total number of sit-ups performed correctly within 30 s was counted and retained for analysis. The sit-ups test is a valid and reliable method to assess abdominal dynamic endurance and the ICC was 0.91 [25].

Statistical analyses

Data analysis was performed using SPSS Statistics (IBM Corp. Released 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp). Preliminary ANOVA with 10 × 5 m as a dependent variable and sex and PHV as fixed factor it was performed, with Bonferroni post-hoc test. Stepwise linear regression was performed on the dataset to evaluate preliminary which factor influence change of direction (10 × 5 m test). 10 × 5 m as a dependent variable, and SBJ, SUP, Height, Body mass, and Leg length as independent variables. The reliability of the regression models was expressed with adjusted R Square and standard error of estimate. Data was linearized with a log transformation (Ln = loge). Analysis of covariance (ANCOVA) was used to evaluate the influence of sex (boys,

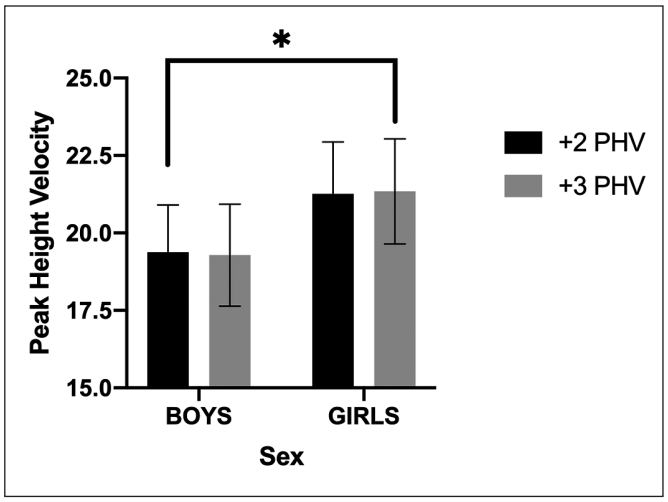


FIG. 1. The trend for both sexes between the peak height velocity in 10x5m performance.

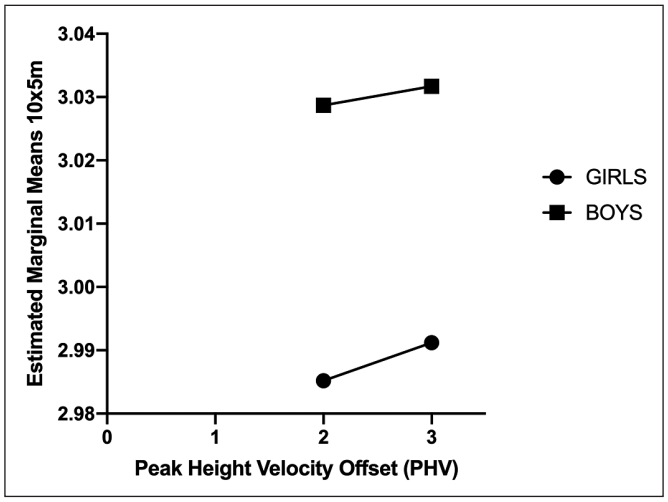


FIG. 2. Estimated marginal means of 10x5m performance between sexes and the peak height velocity.

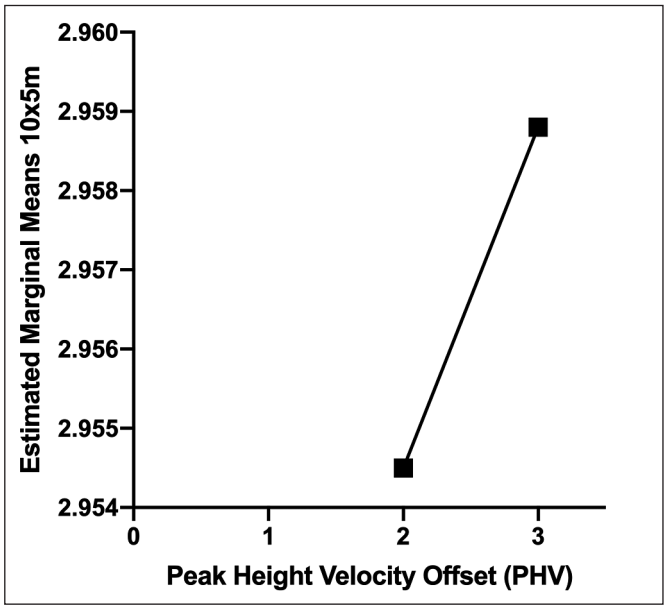


FIG. 3. Estimated marginal means of 10x5m performance between the peak height velocity only for girls.

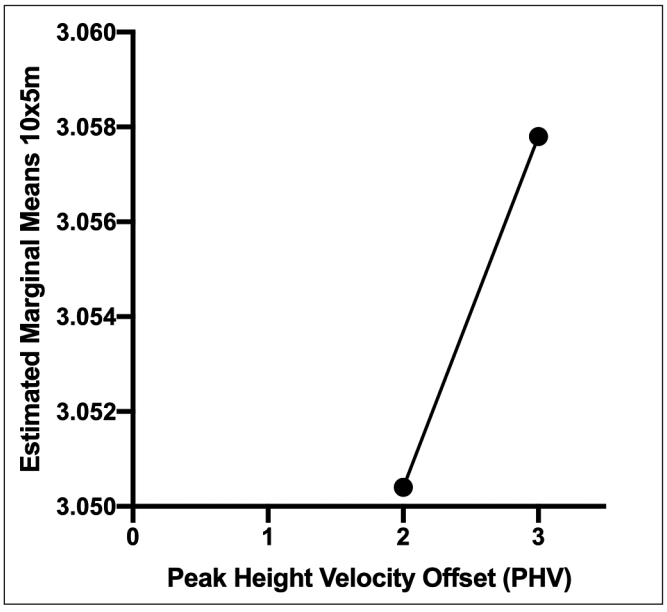


FIG. 4. Estimated marginal means of 10x5m performance between the peak height velocity only for boys.

girls); and PHV [19, 20]. as fixed factor on 10 × 5 m (as predictor of change of direction performance). Further, SBJ (as predictor of lower limb strength), SUP (as predictor of trunk strength), height, body mass, and leg length as covariates on 10 × 5 m. The significance level was set at $P < 0.05$.

RESULTS

Preliminary

Preliminary analysis with 10 × 5 m as a dependent variable and sex and PHV as fixed factor, suggesting a significative difference between sex ($p < 0.001$) but not with PHV ($p = 0.986$) and interaction PHV × sex ($p = 0.836$) (Figure 1).

The Bonferroni post-hoc within PHV suggested a significant difference between +1 PHV and +2 PHV ($p < 0.001$), and between +1 PHV and +3 PHV ($p < 0.001$), but not between +2 PHV and +3 PHV ($p = 0.962$).

Preliminary stepwise linear regression results are presented in Table 1.

Boys and Girls

Trend of both sexes per PHV are visually represented in Figure 2. The model involved sex and PHV as fixed factors, and Height, Body mass, Leg length, SBJ, and SUP as covariates showed an adjusted R square of 0.473.

The output from ANCOVA (B parameter) of Body mass (-0.008), SBJ (-0.232), Leg length (-0.315), SUP (-0.081) and PHV2 (-0.005) are negative, suggesting that these parameters negatively influenced the performance. Only Height (0.579) was positive.

Girls

Trend per PHV is shown in Figure 3.

The model involved PHV as fixed factor, and Height, Body mass, Leg length, SBJ, and SUP as covariates showed an adjusted R square of 0.328

The output from ANCOVA (B parameter) of Body mass (-0.018), Height (-0.021), SBJ (-0.214), Leg length (-0.06), SUP (-0.113), and PHV2 (-0.008) was negative, suggesting that all the outcomes negatively influenced the performance in girls.

Boys

Trend per PHV is shown in Figure 4.

The model involved PHV as fixed factor, and Height, Body mass, Leg length, SBJ, and SUP as covariates showed an adjusted R square of 0.271

The output from ANCOVA (B parameter) of Height (-0.188), Leg length (-0.324), SUP (-0.04) and PHV2 (-0.004) was negative, suggesting that these parameters negatively influenced the performance. Body mass (0.016), SBJ (0.183), was positive.

DISCUSSION

In sports, COD ability is a common outcome measure used to identify talented young athletes and monitor changes in performance [1]. Therefore, the purpose of this investigation was to assess the influence of anthropometric measures and maturation status on COD ability in adolescent males and females when these key variables can have a profound impact on this key fitness quality.

TABLE 1. Data from stepwise linear regression declared among both boys and girls, only boys, and only girls.

Model	R	R Square	Adj R Square	Std. Er of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
Boys, Girls									
SBJ	0.579	0.335	0.334	1.573	0.335	385.309	1.000	766	0.000
SBJ, Leg length	0.665	0.443	0.441	1.441	0.108	148.563	1.000	765	0.000
SBJ, Leg length, SUP	0.689	0.474	0.472	1.401	0.031	45.617	1.000	764	0.000
Boys									
SBJ	0.504	0.254	0.252	1.382	0.254	134.688	1.000	396	0.000
SBJ, SUP	0.520	0.271	0.267	1.368	0.017	9.139	1.000	395	0.003
SBJ, SUP, Leg Length	0.527	0.278	0.273	1.362	0.008	4.094	1.000	394	0.044
Girls									
Leg Length	0.518	0.268	0.266	1.468	0.268	134.77	1.000	368	0.000
Leg Length, SUP	0.572	0.327	0.324	1.409	0.059	32.437	1.000	367	0.000

Note. The models are ordered by adjusted R square value from smallest to largest.

Adj R Square = Adjusted R square; Std. Er of the Estimate = Standard Error of the Estimate; df = degree of freedom; SBJ = Standing Broad Jump; SUP = Sit-Up Test;

The results of this investigation suggest that repeated COD performance was influenced by anthropometrics, maturation and muscle qualities in adolescent boys and girls. In fact, the results of the current study demonstrated that in the female cohort all outcome variables negatively influenced the COD performance. However interestingly, lower limb strength as measured by the standing broad jump and body mass positively affected the COD performance in the male cohort. Considering these results, anthropometric characteristics and maturity offset affect COD performance and are different in girls and boys. The COD performance in girls appears to be negatively affected by maturation compared to boys. This result may be linked to the different hormonal responses during growth and maturation between adolescent males and females [26]. More specifically, the decreased performance in COD ability observed in females may be caused by an increase in body mass that is not adequately balanced by an increase in lower limb muscle strength and power [27].

The maturation status of the participant as measured by PHV was shown to influence repeated COD ability. This influence was demonstrated to be greater in the period immediately post PHV (PHV+1 to PHV+2) compared to later in maturation. This finding is consistent with current youth athlete development models [28] whereas a spurt in growth is not necessarily considered a positive influence on adolescent athlete's performance. In fact, a faster maturation in youth when not adequately supported by correct training of physical qualities could become a negative influence on future performance. For these reasons, proper assessment of maturation provides valuable information that can be utilized by specialist sports coaches, strength and conditioning coaches and Physical Education teachers to inform the design of training programs to enhance COD ability.

Within the Youth Athlete Development Model [11] "agility" which is underpinned by COD ability is proposed to have an optimal window of opportunity immediately following PHV and can be trained at any point during the developmental process. In first instance, during this phase of development, there are rapid increases in size and weight with reported improvements in physical performance primarily as a result of changes in the hormones and maturation [24]. Furthermore, Negra et al. [29], suggested that maturity status is one of the more significant predictors of COD ability when measured via the 505 test. The results from the current study confirm these findings, adolescents with a greater maturity status (PHV+3) performed better than their counterparts at a lower maturation level [30, 31]. Indicating that a maturation level corresponding with PHV+2 could be the optimal window of opportunity to train to change of direction (180°) performance.

Regarding anthropometric outcome measures from the current study, leg length negatively influenced COD performance. This negative relationship indicates a faster time to completion, most likely because longer legs foster shorter time to complete in the 10 × 5 m test. Similar results have recently been published by Negra and colleagues [29] who reported a significant association between leg length and COD performance in a large cohort of young soccer players. However, the COD test used in the study by Negra et al. [29] was a single 5-0-5 test. The influence of leg length on a test, such as the 10 × 5 shuttle run, is likely to be exponential because of the increased number of directional changes. In the light of this, Bourgeois et al. [32], suggested that during a change of direction task or test, the athlete is required to rapidly lower the mass center to obtain a proper force production. This is a benefit for shorter athletes (low leg length), as they generally have a lower mass center than athletes with long legs.

The results of the current investigation indicate that increased muscle power measured by the standing broad jump and muscle endurance measured by the sit-up test relate to shorter times in the 10 × 5 test. Demonstrating that these muscular qualities are important for performance in repeated COD tests. The nature of a 180° turns means the COD is strongly influenced by stretch shortening cycle performance and subsequent expression of power [33]. In fact, each 180° turn requires an acceleration phase from the beginning of a COD, a deceleration phase prior to the subsequent COD, the execution of a 180° turn and then a further acceleration. Previous research from de Hoyo et al. [34], has demonstrated that strength training targeting lower limb power is effective for increasing performance in COD tasks especially in adolescent with greater levels of maturations.

Of course, the results of this investigation must be considered alongside its limitation. The primary sports that the participants were competing in was not factored into the analysis. The sport a participant competes may influence their COD ability and future research should consider investigating this influence. Additionally, a standing broad jump can considered a superficial measure of an individual's lower limb power. Whilst the results of this study demonstrated that lower limb power is important, a detailed force-velocity-power profile of the students was not possible due to the relatively large sample size and the applied nature of the study. More detailed kinetic and kinematic profiling of lower limb muscle function may provide diagnostic insight influence of strength and power on COD ability in adolescent males and females. The results of this study can inform the training prescription of programs targeting the improvement of COD ability in adolescent males and females. Practitioners designing these programs should target the development of lower limb strength and power and evaluate the maturation status of their athletes to ensure the timing is correct to maximize improvement in this important fitness quality.

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Conflict of Interest

The authors declared no conflicts of interest.

REFERENCES

1. Brughelli M, Cronin J, Levin G, Chaouachi A. Understanding change of direction ability in sport: a review of resistance training studies. Sports Med. 2008; 38(12):1045–63.
2. Young WB, Dawson B, Henry GJ. Agility and change of direction speed are independent skills: implications for training agility in invasion sports. Int J Sports Sci Coach. 2015; 10(1):159–169.
3. Makhlouf I, Tayech A, Mejri MA, Haddad M, Behm DG, Granacher U, Chaouachi A. Reliability and validity of a modified Illinois change-of-direction test with ball dribbling speed in young soccer players. Biol Sport. 2022; 39(2):295–306.
4. Paterson S, McMaster DT, Cronin J. Assessing change of direction ability in badminton athletes. Strength Cond J. 2016; 38(5):18–30.
5. Talty PF, McGuigan K, Quinn M, Jones PA. Agility Demands of Gaelic Football Match-Play: A Time-Motion Analysis. Int J Perform Anal Sport. 2022; 22(2):195–208.
6. Morgan OJ, Drust B, Ade JD, Robinson MA. Change of direction frequency off the ball: new perspectives in elite youth soccer. Sci Med Footb. 2022; 6(4):473–482.
7. Dos'Santos T, Thomas C, Jones PA, Comfort P. Mechanical determinants of faster change of direction speed performance in male athletes. J Strength Cond Res. 2017; 31(3):696–705.
8. Young WB, James R, Montgomery I. Is muscle power related to running speed with changes of direction? J Sports Med Phys Fitness. 2002; 42(3):282–8.
9. McBurnie AJ, Dos' Santos T. Multidirectional speed in youth soccer players: theoretical underpinnings. Strength Cond J. 2022; 44(1):15–33.
10. Schepens B, Willems PA, Cavagna GA. The mechanics of running in children. J Physiol. 1998; 15; 509:927–40.
11. Philippaerts RM, Vaeyens R, Janssens M, Van Renterghem B, Matthys D, Craen R, Bourgois J, Vrijens J, Beunen G, Malina RM. The relationship between peak height velocity and physical performance in youth soccer players. J Sports Sci. 2006; 24(3):221–30.
12. Lloyd R, Oliver J. The youth physical development model. Strength and Cond. J. 2012; 34(3):61–72.
13. Beunen G, Malina RM. Growth and physical performance relative to the timing of the adolescent spurt. Exerc Sport Sci Rev. 1988; 16(1):503–40.
14. Viru A, Loko J, Harro M, Volver A, Laaneots L, Viru M. Critical Periods in the Development of performance capacity during childhood and adolescence. Eur J Phys Educ. 1999; 4(1):75–119.
15. Lloyd RS, Oliver JL, Hughes MG, Williams CA. The influence of chronological age on periods of accelerated adaptation of stretch-shortening cycle performance in pre and postpubescent boys. J Strength Cond Res. 2011; 25(7):1889–97.
16. España-Romero V, Artero EG, Jimenez-Pavón D, Cuenca-Garcia M, Ortega FB, Castro-Piñero J, Sjöstrom M, Castillo-Garzon MJ, Ruiz JR. Assessing health-related fitness tests in the school setting: reliability, feasibility and safety; the ALPHA study. Int J Sports Med. 2010; 31(7):490–7.
17. Clarys JP, Provyn S, Marfell-Jones M, Van Roy P. Morphological and constitutional comparison of age- matched in-vivo and post-mortem populations. Morphologie. 2006; (291):189–96.
18. Fredriks AM, van Buuren S, van Heel WJ, Dijkman-Neerincx RH, Verloove-Vanhorick SP, Wit JM. Nationwide age references for sitting height, leg length, and sitting height/height ratio, and their diagnostic value for disproportionate growth disorders. Arch Dis Child. 2005; 90(8):807–12.
19. Mirwald RL, Baxter-Jones AD, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. Med Sci Sports Exerc. 2002; 34(4):689–94.
20. Kozieł SM, Malina RM. Modified maturity offset prediction equations: validation in independent longitudinal samples of boys and girls. Sports Med. 2018; 48(1):221–36.
21. Grgic J. Test–retest reliability of the EUROFIT test battery: A review. Sport Sci Health. 2022; 1–8.
22. Kemper HCG, Van Mechelen W. Physical fitness testing of Children: a European perspective. Pediatr Exerc Sci. 1996; 8(3):201–214.
23. Donncha CM, Watson AW, McSweeney T, O'donovan DJ. Reliability of Eurofit physical fitness items for adolescent males with and without Mental Retardation. Adapt Phys Act Q. 1999; 16(1):86–95.
24. Fernandez-Santos JR, Ruiz JR, Cohen DD, Gonzalez-Montesinos JL, Castro-Piñero J. Reliability and Validity of Tests to Assess Lower-Body Muscular Power in Children. J Strength Cond Res. 2015; 29(8):2277–85.
25. Alaranta H, Hurri H, Heliövaara M, Soukka A, Harju R. Non-dynamometric trunk performance tests: reliability and normative data. Scand J Rehabil Med. 1994; 26(4):211–5.
26. Richmond E, Rogol AD. Endocrine Responses to Exercise in the Developing Child and Adolescent. Front Horm Res. 2016; 47:58–67.
27. Young WB, Talpey S, Bartlett R, Mundy S, Smyth A, Welsh T. Development of muscle mass: how much is optimum for performance? Strength Cond J. 2019; 41(3):47–50.
28. Varghese M, Ruparell S, LaBella C. Youth Athlete Development Models: A Narrative Review. Sports Health. 2022; 14(1):20–29.
29. Negra Y, Sammoud S, Nevill AM, Chaabene H. Change of direction speed in youth male soccer players: the predictive value of anthropometrics and biological maturity. Pediatr Exerc Sci. 2022; 5(1):1–7.
30. Giuriato M, Codella R, Lovecchio N, Carnevale Pellino V, Vandoni M, Nevill AM. Speed agility trends in children according to growth. Ann Hum Biol. 2021; 48(4):271–279.
31. Giuriato M, Kawczynski A, Mroczek D, Lovecchio N, Nevill AM. Allometric association between physical fitness test results, body size/shape, biological maturity, and time spent playing sports in adolescents. PLoS One. 2021; 16(4):e0249626.
32. Bourgeois FA, Gamble P, Gill ND, McGuigan MR. Effects of a six-week strength training programme on change of direction performance in youth team sport athletes. Sports (Basel). 2017; 5(4):83.
33. Ryan C, Uthoff A, McKenzie C, Cronin J. Profiling change of direction ability using sub-phase 5-0-5 analysis. Int Strength Cond Res. 2022; 2(1). https://doi.org/10.47206/ijsc.v2i1.100.
34. de Hoyo M, de la Torre A, Pradas F, Sañudo B, Carrasco L, Mateo-Cortes J, Domínguez-Cobo S, Fernandes O, Gonzalo-Skok O. Effects of eccentric overload bout on change of direction and performance in soccer players. Int J Sports Med. 2015; 36(4):308–14.

Validity and reproducibility of match-derived ratios of selected external and internal load parameters in soccer players: A simple way to monitor physical fitness?

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ABSTRACT: The study aim was to assess whether match-derived external-to-internal load ratios are a valid and reliable tool to measure physical fitness. Sixteen elite youth soccer players (17 ± 1 years) performed two maximal fitness tests. Subsequently, players participated in three intra-squad soccer matches in three consecutive weeks. Three GPS-based parameters of external load (total distance, PlayerLoad, high-intensity distance) were divided by three heart rate-based parameters of internal load (iTRIMP, Banister TRIMP, average percentage heart rate reserve) for the ratio calculations. Validity was established by comparing the ratios with results of the fitness tests, while between-athlete and within-athlete reliability were quantified. Most integrated load ratios were moderately-to-largely correlated with the various fitness parameters. Overall, a ratio consisting of PlayerLoad and average percentage heart rate reserve demonstrated the most consistent correlations with maximum treadmill speed ($r = 0.69$, $P = 0.003$) and the speeds associated with 4 mmol/L of blood lactate ($r = 0.56$, $P = 0.024$) and 80% of heart rate reserve ($r = 0.54$, $P = 0.031$). Most of the ratios displayed acceptable levels of reproducibility (intraclass correlation coefficient > 0.8 and coefficient of variation $< 10\%$), with the minimal detectable change of all ratios ranging between 7.1 and 37.8%. Given their associations with physical fitness and non-invasive nature, certain external-to-internal load ratios may be used to monitor physical fitness in soccer players. However, the ratios may not be sensitive enough to detect small yet practically relevant alterations in player fitness.

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INTRODUCTION

The development and in-season maintenance of high levels of physical fitness is an important consideration for practitioners tasked with maximising the performance potential of soccer players. Ideally, accurate information on fluctuations in player fitness can be obtained regularly to tailor training interventions to the individual player needs [1]. These insights are typically derived from (maximal) laboratory- or field-based fitness tests. However, due to their exhaustive nature and the difficulty of finding suitable time points within an oftentimes congested playing schedule, it is unrealistic to expect frequent testing opportunities at the higher levels of professional soccer [2]. Given these limitations, it would seem desirable to establish alternative testing protocols which are valid, reliable, minimally invasive and require little to no extra time or effort by the players [3, 4].

Within elite soccer, training and match physical demands are commonly recorded using a host of different internal and external load monitoring tools [2]. It has been proposed that the relationship between identified markers of internal and external load may provide suitable information regarding how a player is coping with their training programme [5]. As such, under standardised and non-fatigued conditions, improved fitness would be assumed for players experiencing a lower internal load relative to a standardised external task, which may be attributed to various central and peripheral adaptations resulting in improved exercise economy, whole-body peak oxygen uptake, lactate threshold and oxygen uptake kinetics [6]. Vice versa, players with a higher internal load relative to the same external task would be suspected to have experienced negative fitness adaptations [5]. Similar conclusions may be deduced from relative changes in internal load in response to non-standardised external stimuli. Several studies have demonstrated significant correlations between external-to-internal load ratios during sport-specific, non-standardised activity and parameters of aerobic performance in soccer [7, 8], rugby [9] and hurling players [10]. Given that markers of external load have been shown to be highly variable in competition [11] and may be impacted by contextual factors [12], the integration of external and internal load into a ratio represents a rather elegant way to assess athlete fitness since the parameters necessary for calculation are typically

recorded as part of the monitoring routine of elite soccer teams [13], avoiding the need for any additional 'touch points' with and burden on the players [14].

Akubat et al. [7, 8] investigated different combinations of integrated external-internal load ratios obtained during a soccer match-specific running simulation. The authors used five different GPS- or accelerometer-derived parameters of external load (total distance, high-intensity distance, PlayerLoad, mean metabolic power, distance covered at high metabolic power) and individualised TRIMP (iTRIMP) as the only parameter of internal load. Since heart rate (HR)-based parameters are easily and precisely measured, observing the cardiocirculatory response to exercise is frequently the preferred method of monitoring internal load in a team-sport context. In a recent study, iTRIMP was found to be the training load measure with the strongest relationship to changes in aerobic fitness over a 6-week pre-season period in elite youth soccer players [15], and therefore its inclusion in the integrated external-internal load ratios seems to be justified. However, since the calculation of iTRIMP is based on each player's lactate profile to generate an individual exponential weighting factor for the TRIMP calculation [16], it is very context-dependent whether the necessary testing procedures can be carried out (potentially multiple times per season). It would appear worthwhile to investigate whether other more easily obtainable parameters of cardiocirculatory load might be a feasible alternative to iTRIMP in the calculation of the integrated ratios. Furthermore, since the two studies assessing the relationship between different external-internal load ratios and aerobic fitness in soccer players were based on running protocols looking to replicate typical match running demands [7, 8], it remains to be confirmed whether ratios based on actual match-derived markers of external and internal load are equally related to parameters of cardiocirculatory fitness. If so, this would potentially allow for continuous fitness monitoring based on match data alone.

When interpreting any test score, it is important to be aware of and appreciate the uncertainty associated with the measure [17]. Preferably, a test chosen for implementation should be responsive to small but relevant changes over time. As such, if match-derived external-to-internal load ratios are to be used for monitoring changes in player fitness, the ratios should be able to differentiate signal (real change) from noise (random measurement error). In this context, the minimal detectable change (MDC) and the smallest worthwhile change (SWC) [18–20] are two important test statistics which can help quantify signal (SWC) in comparison to noise (MDC). MDC refers to the smallest change that can be detected with an acceptable probability level, while SWC relates to the smallest change that can be considered important.

Therefore, the aims of this study were twofold: (1) to investigate whether different combinations of match-derived external-internal load ratios were associated with markers of aerobic fitness; and (2) to quantify the reliability of these measures across multiple time points.

MATERIALS AND METHODS

Participants

Twenty-one youth outfield players (17 ± 1 years, 179 ± 8 cm, 72 ± 7 kg) belonging to an elite Portuguese soccer team were recruited to participate in the study [21]. An a priori sample size calculation (G*Power, version 3.1.9.7, Heinrich Heine University Düsseldorf, Germany) indicated that 21 participants were required to have a sufficient power (> 0.8) based on the alpha selected (5%) and a large effect size (d = 0.5). This effect size was based on previous studies on this topic [7, 8]. Players were eligible to participate in the study if they had been free of injury up to four weeks prior to the beginning of the study and accustomed to the regular training routine of the team. The players and their parents were informed about the study procedures and provided their written informed consent. Performance data were anonymised to ensure complete player confidentiality. The investigation was conducted in accordance with the Declaration of Helsinki and ethical approval was received



FIG. 1. Overview of study design.

from the local ethics committee (Saarland University, approval number 20–26).

Design and Data Collection

Due to local COVID-19 regulations during the study period, the participating team was not involved in official competition. However, the team had been training for 14 weeks straight before the beginning of the investigation, with the training week consisting of four training sessions from Monday to Thursday and an intra-squad, full-pitch 90 min match each Friday, followed by two days of rest. This weekly structure was largely maintained for our study purposes (Fig. 1).

This observational study began with an evaluation of the players' cardiocirculatory fitness. Throughout the morning (8 am–12 pm) and 90 minutes after their last meal, all players performed a stepwise incremental treadmill running test with determination of capillary blood lactate and HR responses. The test was initiated at a running velocity of 8 $km \cdot h^{-1}$, with a step duration of 3 min, a 2 $km \cdot h^{-1}$ velocity increment for each successive step until volitional exhaustion occurred, with steps separated by a 1 min passive recovery period for the collection of capillary blood samples from the participants' earlobes (Lactate Pro 2, Arkray KDK, Kyoto, Japan). HR was continuously monitored (Firstbeat Sports Sensor, Firstbeat Technologies Oy, Jyväskylä, Finland) at a sampling frequency of 0.2 Hz and exercise HR for a given velocity was defined as the mean HR over the last 30 s for each step. The treadmill gradient was set at 1% to reflect the energetic cost associated with outdoor running [22]. After the test, the data were fed into specialised software (Ergonizer, Kai Röcker, Freiburg, Germany) and the following parameters were calculated for further analysis: (1) running velocity at volitional exhaustion (Vmax) (if subjects did not complete the final stage, Vmax was calculated as: (running velocity of last completed stage) + (x/180*2 $km \cdot h^{-1}$), where × equals the duration of the final stage in s), (2) running velocity associated with a fixed lactate concentration of 4 mmol/L (V4 mmol), and (3) the physical working capacity (running velocity) at 80% of the participants' individual HR reserve (V80%HR_{Res}). During the late afternoon of day 1 (4 pm–6 pm) and after at least 6 h of passive recovery from the previous assessment, the players performed a Yo-Yo Intermittent Recovery level 1 test (Yo-Yo IR1). The test was executed on an artificial outdoor turf, at an ambient temperature of 15°C. The Yo-Yo IR1 has been shown to possess high levels of construct validity and may therefore be considered a good indicator of intermittent team sport-specific physical fitness [23]. The running distance associated with the last completed stage before failing to maintain the indicated running velocity was recorded as the final test result.

All training sessions throughout the study period were planned and led by the team's coaching staff. Before the beginning of the investigation, team coaches were instructed to maintain their normal training periodisation leading up to the matches and, as such, expose the players to the regular training volumes and intensities associated with their training approach. Overall training load throughout the study protocol was kept consistent to maintain the players' physical condition. In addition, players continued to perform two gym-based training sessions per week as per their usual training routine. These sessions took place four and two days prior to the match and consisted of full-body, multi-joint strength and power exercises (first weekly session) and exercises focused on lumbo-pelvic control, landing mechanics and balance (second weekly session).

During all matches, player movement was recorded using portable GPS devices (Catapult Vector, Melbourne, Australia). Previous studies have found 10 Hz GPS systems to be the most valid and reliable across linear and team sport simulated running. Accuracy measures of total distance and high-intensity distance displayed a coefficient of variation (CV) of between 1.9 and 10.5% compared to criterion measures [24]. After the match, all data were downloaded using the respective proprietary software (Catapult Openfield, version 3.2.0) and adequate positional data quality was verified. In accordance with previous research [25], GPS connection to at least 6 satellites and a horizontal dilution of precision (HDOP) ≤ 2 were required for data to be included. Throughout the final dataset, the number of connected satellites and HDOP were 14.7 ± 0.6 and 0.7 ± 0.1, respectively. The players' total distance (TD) covered, the distance covered at running speeds > 18 $km \cdot h^{-1}$ (HID) and PlayerLoad (PL – a widely used external load metric derived from three-dimensional measures of the instantaneous rate of change of acceleration) [26] were collected as markers of external load over the course of the three matches. These three parameters were deemed relevant since they are commonly used to quantify training and match demands. HR was continuously recorded throughout the matches and the resulting cardiorespiratory intensity and load were calculated in three different ways: (1) as the average percentage of HR_{Res} (ave%HR_{Res}), (2) as a Banister TRIMP score (BanTRIMP) [27], and (3) as an iTRIMP score [16]. Consequently, nine different external-to-internal load ratios were calculated and investigated.[1]

Resting HR for each player was determined one morning following two days of rest, in a quiet room with players remaining in a supine position for 5 min. Resting HR was assumed as the lowest 5 s value. Maximal HR was assumed as the highest 5 s value throughout all testing, training and match activities during the study period.

Statistical Analysis

Unless stated otherwise, all data are presented as mean ± standard deviation (SD). The assumption of normality was verified using the Shapiro-Wilk test. Pearson's correlation coefficients were used to quantify the relationship between external-to-internal load ratios recorded during the first match and fitness markers. The magnitude of the correlation was interpreted as follows: < 0.1, trivial; 0.1–0.29, small; 0.3–0.49, moderate; 0.5–0.69, large; 0.7–0.89, very large;

[1] It must be pointed out that ave%HR_{Res} represents internal intensity rather than internal load. As such, ratios involving this parameter should be more correctly classified as load-intensity ratios.

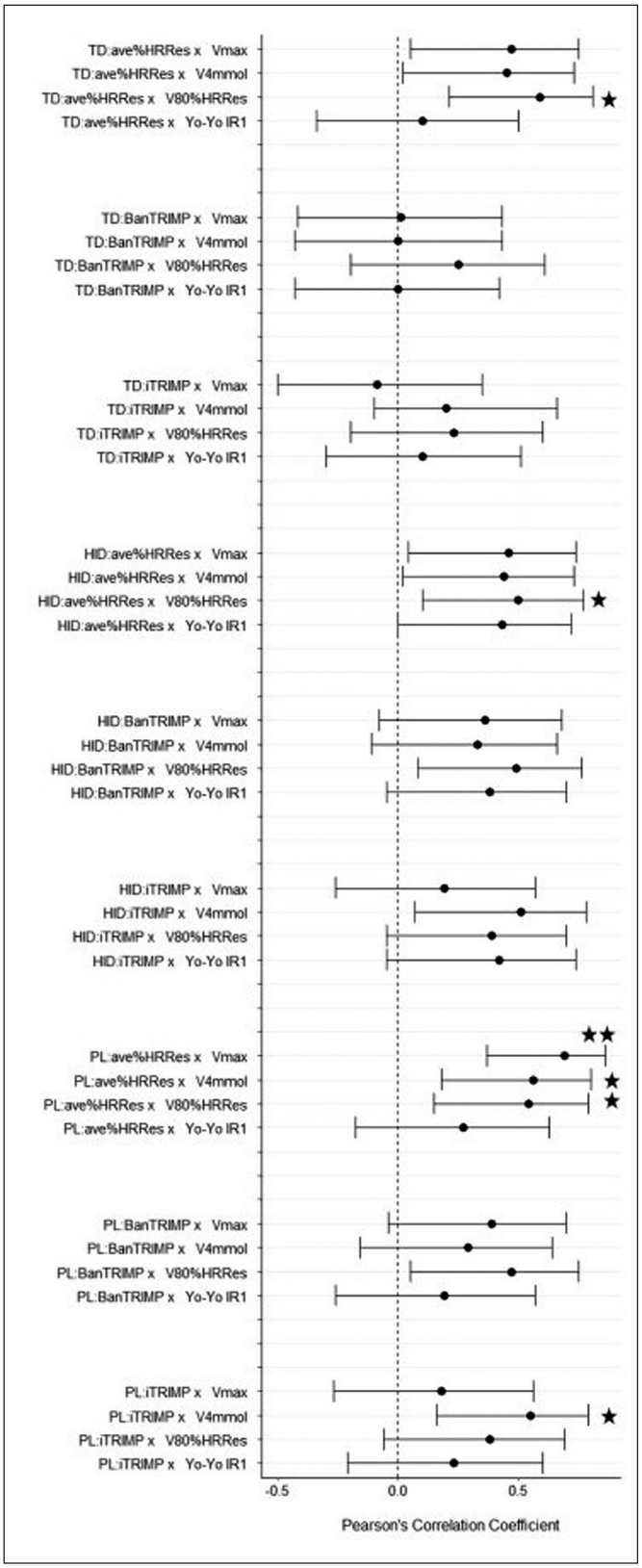


FIG. 2. Relationship between the different external-to-internal load ratios derived during the first half of match play and selected markers of physical fitness.

Note: TD – total distance; HID – high-intensity distance; PL – PlayerLoad; Vmax – velocity at volitional exhaustion; V4 mmol – velocity associated with 4 mmol/L of blood lactate; V80%HR_{Res} – velocity at 80% of heart rate reserve; Yo-Yo IR1 – Yo-Yo intermittent recovery level 1 test performance; * – $P \leq 0.05$; ** – $P \leq 0.01$.

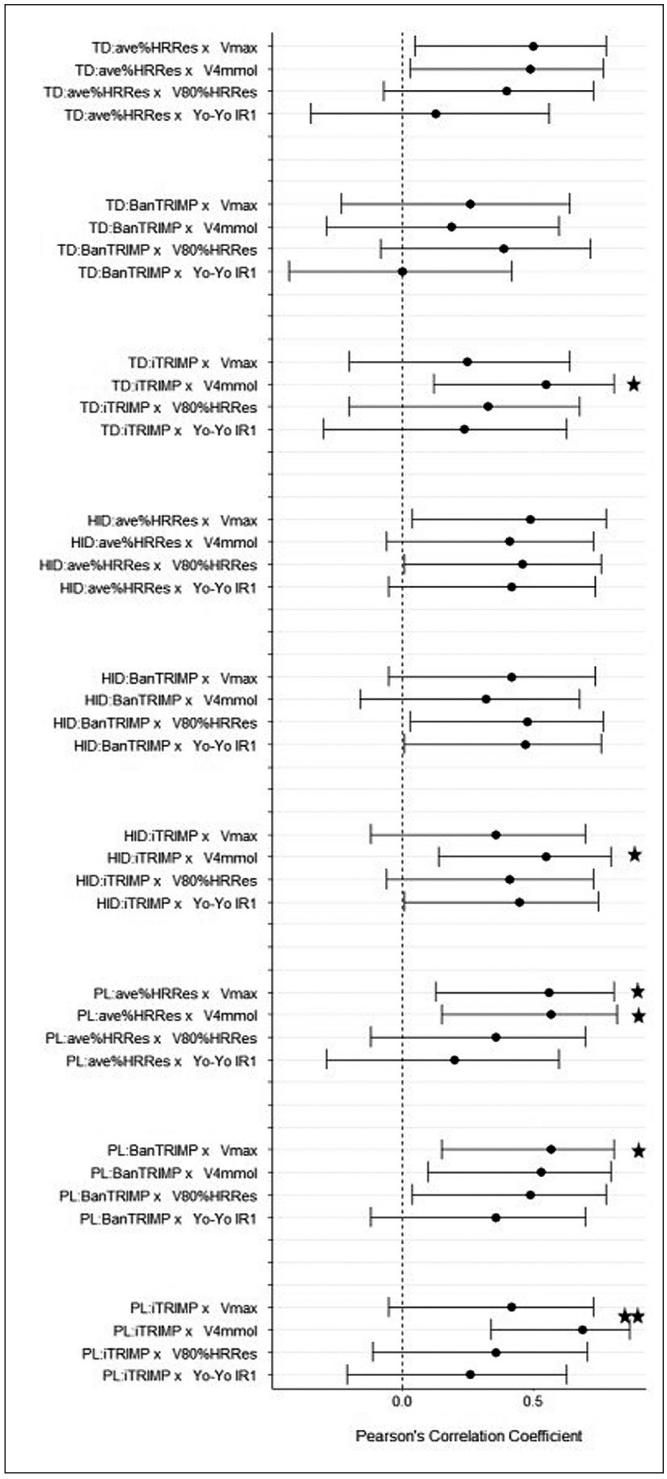


FIG. 3. Relationship between the different external-to-internal load ratios derived during the second half of match play and selected markers of physical fitness.

Note: TD – total distance; HID – high-intensity distance; PL – PlayerLoad; Vmax – velocity at volitional exhaustion; V4 mmol – velocity associated with 4 mmol/L of blood lactate; V80%HR_{Res} – velocity at 80% of heart rate reserve; Yo-Yo IR1 – Yo-Yo intermittent recovery level 1 test performance; * – $P \leq 0.05$; ** – $P \leq 0.01$.

0.9–0.99, nearly perfect; and 1, perfect [28]. Between-athlete and within-athlete reliability were assessed using intraclass correlation coefficients (ICC) and CV, respectively. ICC estimates and their 90% CI were calculated based on a mean-rating (k = 3), absolute agreement, 2-way random-effects model. The following thresholds for interpretation of ICC results were used: < 0.5, low; 0.5–0.74, moderate; 0.75–0.89, high; 0.9–0.98, very high; and > 0.98, extremely high. CV was calculated by dividing the within-subject SD by the mean multiplied by 100. Furthermore, MDC at 90% CI level was calculated as $1.645 \times SEM \times \sqrt{2}$ [18] and SWC was calculated using a distribution-based method as $0.2 \times$ between-subject standard deviation [19]. Standard error of measurement (SEM) was estimated as the square root of the mean square error from the ANOVA [29]. Ratio reliability and association with fitness markers were analysed separately for first and second halves of the matches. A player entering a match at halftime was considered the same as playing the first half of the match and only players competing in at least a full half were included for analysis. Only players competing in all three matches were considered for the reliability analysis. An α-level of $P \leq 0.05$ was accepted as statistically significant. All statistical analyses were conducted using specialised Excel spreadsheets [30].

RESULTS

During the initial incremental treadmill test, players achieved a Vmax of 17.7 ± 1.3 km·h^{-1}, at a HR of 195 ± 7 beats·min^{-1}, representing 98.2 ± 1.7% of their maximal HR (HR_{max}), with a maximal blood lactate concentration of 8.4 ± 2.5 mmol/l. V4 mmol was associated with a running velocity of 15.1 ± 1.4 km·h^{-1}, at 93.3 ± 2.5% of HR_{max}. V80%HR_{Res} occurred at 12.1 ± 1.3 km·h^{-1} and an average blood lactate concentration of 2.3 ± 0.4 mmol/l. The last completed stage of the Yo-Yo IR1 test corresponded to a running distance of 2181 ± 484 m, at 96.6 ± 2% of HR_{max}.

Relationship between load ratios and fitness markers

Two players dropped out of the investigation during the first week of training, one due to injury and the other due to illness. Furthermore, three players were excluded from the analysis due to incomplete HR recordings during the first match. 14 of the remaining 16 players completed the entire first match, while two players only completed the first half. The relationships between the different external-to-internal load ratios and fitness markers are presented for the first and second half in Figures 2 and 3, respectively.

TABLE 1. Between-athlete and within-athlete reproducibility of the different external-to-internal load ratios

External: Internal Ratio	Half	ICC (90% CI)	CV (90% CI)	SEM	MDC	SWC	SEM %	MDC %	SWC %
TD:iTRIMP	1st	0.90 (0.77; 0.96)	7.6 (6.0; 10.8)	4.5	10.5	2.4	8.1	18.8	4.3
	2nd	0.90 (0.8; 0.98)	8.7 (6.4; 14.5)	5.6	13.0	3.0	10.0	22.3	5.2
PL:iTRIMP	1st	0.78 (0.56; 0.91)	9.6 (7.6; 13.5)	0.5	1.2	0.2	9.2	21.3	3.8
	2nd	0.88 (0.65; 0.97)	10.7 (7.9; 18.0)	0.6	1.5	0.3	10.7	24.8	4.9
HID:iTRIMP	1st	0.88 (0.73; 0.95)	15.6 (12.3; 21.8)	0.9	2.2	0.5	16.3	37.8	8.0
	2nd	0.91 (0.73; 0.98)	15.5 (11.5; 25.9)	0.9	2.1	0.5	14.9	34.7	8.1
TD:BanTRIMP	1st	0.83 (0.64; 0.93)	4.8 (3.8; 6.7)	2.5	5.8	1.1	5.0	11.7	2.1
	2nd	0.75 (0.38; 0.93)	6.7 (5.0; 11.3)	3.7	8.6	1.1	7.4	17.1	2.3
PL:BanTRIMP	1st	0.70 (0.43; 0.87)	6.9 (5.5; 9.8)	0.3	0.8	0.1	6.6	15.4	2.4
	2nd	0.79 (0.45; 0.94)	7.9 (5.7; 13.2)	0.4	1.0	0.1	8.2	19.0	2.8
HID:BanTRIMP	1st	0.80 (0.59;0.92)	14.5 (11.5; 20.4)	0.8	1.8	0.3	15.2	35.4	6.0
	2nd	0.79 (0.45; 0.94)	14.7 (10.9; 24.6)	0.7	1.5	0.3	12.6	29.3	5.3
TD:ave%HR_{Res}	1st	0.83 (0.65; 0.93)	2.8 (2.2; 4.0)	2.1	4.9	0.9	3.1	7.1	1.3
	2nd	0.89 (0.67;0.97)	3.3 (2.5; 5.6)	2.6	6.1	1.1	3.8	8.9	1.6
PL:ave%HR_{Res}	1st	0.87 (0.71; 0.95)	5.6 (4.4; 8.0)	0.4	0.9	0.2	5.6	13.1	2.8
	2nd	0.95 (0.85; 0.99)	4.2 (3.1; 7.0)	0.4	0.8	0.2	4.9	11.4	2.9
HID:ave%HR_{Res}	1st	0.75 (0.50; 0.90)	15.0 (11.8; 21.1)	1.1	2.6	0.4	16.1	37.6	5.5
	2nd	0.65 (0.22; 0.9)	16.2 (12.1; 27.2)	0.9	2.1	0.4	12.9	29.9	4.9

Note: ICC – intraclass correlation coefficient; CI – confidence interval; CV – coefficient of variation; SEM – standard error of measurement; MDC – minimum detectable change; SWC – smallest worthwhile change; TD – total distance; PL – PlayerLoad™; HID – high-intensity distance; iTRIMP – individualized TRIMP; BanTRIMP – Banister TRIMP; ave%HR_{Res} – average percentage of heart rate reserve

Reproducibility of load ratios

The three matches were played on the same regulation size, natural grass outdoor pitch under very similar environmental conditions (humidity: 92 ± 9%, temperature: 14 ± 3ºC, wind speed: 17 ± 6 km·h^{-1}). Both teams played in a 4-3-3 formation with players maintaining their tactical position through all games. Three players missed a game due to being called up to train with an older team within the club's academy structure and one player had to be excluded from the analysis due to injury during the final match. Of the remaining 12 players, 7 completed the full 90 minutes in all three consecutive matches. Throughout the three matches, those 7 players on average covered a TD of 11,130 ± 909 m, with a HID of 1,067 ± 236 m, a PL of 1,184 ± 183 AU, at an average of 80 ± 4% of HR_{Res}, with a BanTRIMP score of 226 ± 23 AU, and an iTRIMP score of 214 ± 40 AU. Between-athlete and within-athlete reproducibility of the different integrated external-to-internal load ratios is presented in Table 1.

DISCUSSION

The present study sought to establish the association of different combinations of match-derived external-to-internal load ratios with various submaximal and maximal fitness parameters and to quantify their reproducibility across three time points. The main findings were that (i) while most combinations of integrated load ratios were moderately-to-largely correlated with the various fitness parameters at a single time point, these results must be interpreted cautiously due to the rather wide confidence intervals; (ii) the combination of PL as an external load parameter and ave%HR_{Res} as an internal load parameter demonstrated the most consistent associations with different fitness markers in comparison to other load ratios; (iii) ave%HR_{Res} can be used as a simpler internal load alternative to iTRIMP for the ratio calculations; (iv) combinations involving HID showed reduced within-athlete reproducibility compared to combinations involving TD and PL as external load parameters; and (v) none of the ratios may be sensitive enough to detect small but relevant changes in athlete fitness.

In comparison to previous studies [7, 8], the relationships between different combinations of external-to-internal load ratios and markers of physical fitness found in the current study were less strong and less consistent. This may be partially explained by the use of actual match-derived external and internal load data as opposed to data derived from soccer match running simulations. While the results of simulations of physical match demand may be associated with isolated markers of physical fitness and may reproduce certain aspects of match running performance [31], these protocols miss important physical actions and their impact on internal load, specifically in relation to short but intense accelerations and decelerations, changes of directions, dives, jumps or tackles [32]. Furthermore, the cognitive stressors associated with ball movement activities and the tactical reading of the game cannot be adequately replicated by match running simulations. In fact, it has been suggested that team sport athletes may experience mental fatigue due to prolonged and demanding match-related cognitive activity and that mental fatigue may induce reductions in physical performance during intermittent team sport activity [33]. It is important to point out that the observed reduction in physical performance in those studies was most likely due to an increased perception of effort rather than cardiovascular or metabolic mechanisms. Therefore, it seems fair to speculate that match-derived external-to-internal load ratios may be influenced not only by physical, but also by mental requirements. As such, comparably weaker associations between these load ratios and laboratory-derived markers of physical fitness are not necessarily surprising. This should not, however, automatically be interpreted as a potential weakness of the load ratios. While isolated fitness tests can more accurately determine changes in the physiological profile of a player, integrated load ratios may still be able to more holistically capture a player's ability to withstand competition-specific demands.

Apart from match-derived load ratios, another promising approach may be the integration of external and internal load data derived from standardised training drills. Training drills can be designed to possess fewer degrees of freedom compared to match play and may therefore correlate better with markers of fitness tests. In fact, Taylor et al. [9] demonstrated that integrated load ratios derived from a sprint interval training drill (6 × 6-second sprint with 54 seconds recovery) and from a small-sided game (6 vs. 6, 10 minutes on a 39 × 51 m pitch) showed large-to-very large associations with submaximal fitness markers and acceptable reliability in academy rugby union players. While similar results might be expected for soccer players and, therefore, potentially represent an interesting alternative to match-derived data, we want to highlight that no training drill can totally replicate all physical, technical, tactical, and cognitive demands that players experience during actual match play. As such, a certain trade-off between standardization and specificity should be expected.

Previous studies have already investigated different external load parameters to be included in the integrated load ratio calculations [7–10]. However, iTRIMP was the sole parameter of internal load to be examined. The results of the present study indicate for the first time that ave%HR_{Res} can be used as a less complex alternative to iTRIMP, facilitating an easier use of external-to-internal load ratios as a marker of physical fitness. While these findings seemingly favour a simpler approach with regards to the internal load parameter, a reduction of the chaotic nature of professional soccer matches into a single locomotive parameter might be overly simplistic. Lacome et al. [34] argue, for instance, that a more individualised approach taking into account player-specific combinations of external load variables may be more suitable to detect alterations in player-specific fitness. While their approach largely correlates with the results of a submaximal running test, the magnitude in correlation is not substantially larger than the best performing ratio in the present study. Therefore, it appears that more sophisticated approaches with regards to both external and internal load calculations do not

necessarily outperform integrated ratios consisting of more easily derived parameters. Also, the attractiveness of easy-to-use indicators with high face value must be emphasised.

The present study was the first to quantify the between-athlete reliability of integrated load ratios, generally demonstrating high-to-very high reproducibility. With regards to within-athlete reliability, one prior study examined several external-to-internal load ratios during three different training drills (continuous shuttle run, sprint interval training, small-sided game) in academy rugby union players [9] and found the CV of the ratios to range between 7.1 and 36.3%. Higher variability was found for ratios involving high-speed running as an external load parameter, which was in line with the present study. Given that match-to-match variability in high-speed running has been shown to be high among professional soccer players [11], it seems likely that this variability carries over into the integrated load ratios. As such, it is not advised to use these specific ratios as indicators of aerobic fitness. In contrast, ratios involving TD and PL as external load parameters showed reduced variability. One possible explanation may be that TD and PL are more volume-based parameters and, therefore, are not as affected by match-to-match variability as more intensity-based parameters such as HID. Nevertheless, an analysis of MDC and SWC revealed that none of the ratios may be sensitive enough to detect small but practically meaningful changes in athlete fitness. This may not be entirely surprising given that the ratios entail the variability specific to both the external [11, 35] and the internal load [36] parameters. As such, for an integrated load ratio consisting of PL and ave%HR_{Res}, only changes greater than 11–13% can be confidently assumed to be greater than the normal day-to-day variability, while changes greater than 3% may already be practically meaningful. It needs to be pointed out, however, that due to the way MDC and SWC are calculated and the probabilities of finding the true value associated with both approaches (90% confidence for MDC vs. 16% confidence for SWC), readers should not compare SWC and MDC. Instead, the values provided by the present study should be critically evaluated and interpreted specifically to a given context.

Previous research on match-derived external-to-internal load ratios has shown that there may be substantial within-athlete ratio differences between the first and second halves of a match [37], indicating that – as the match goes on – external output decreases disproportionally in relation to internal load due to accumulated fatigue. Taking this finding into account, first and second halves were analysed separately to investigate any potential differences with regards to ratio validity and reproducibility. The results showed, however, that there were no clear and consistent between-half differences, indicating that fatigue does not seem to impact these ratio properties and that periods as short as a single half can be used to calculate and interpret changes in integrated load ratios.

There are limitations to this study that readers should be aware of. Given that the ratios are based on match-derived external and internal load data, they can only be calculated for players participating in the match but not for the rest of the squad. While it is fair to argue that the fitness of starters and substitutes is more relevant to team success than the fitness of fringe players, an alternative perspective would be that changes in fitness in those players might be more likely due to a lack of regular playing time and therefore require closer attention. Furthermore, the present study established load ratio validity at a single time point. While the between-athlete comparison is an important element of a given test, analyses of within-athlete changes over time are likely the more pertinent issue for athlete monitoring purposes and should be evaluated in the future. Thirdly, both maximal fitness assessments were performed on the same day. While a passive rest period of at least 6 h between the two tests was ensured, it is possible that results of the Yo-Yo IR1 test may have been negatively influenced by the earlier treadmill test. Fourthly, it has been pointed out previously that there may be statistical problems associated with the use of ratios. In certain circumstances, ratios might not be scaling consistently across a range of measured values of the denominator, indicating that the ratio would provide biased estimates at the lower and higher ends of the range [38]. Finally, the relatively wide confidence intervals indicate that a larger sample size is required to be more confident about the results of this study.

CONCLUSIONS

In conclusion, the findings of this study indicate that certain match-derived external-to-internal load ratios are largely correlated with submaximal and maximal markers of cardiorespiratory fitness, with a combination of PL and ave%HR_{Res} demonstrating the most consistent associations. Practitioners looking to use integrated ratios to monitor changes in fitness in soccer players need to be aware of the uncertainty associated with the ratios, however. In the case of PL:ave%HR_{Res}, only changes in excess of 11.4–13.1% can be confidently assumed to represent a true change. Hence, the ratios may not be sensitive enough to detect small yet practically relevant alterations in player fitness.

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Disclosure of Interest

The authors report no conflict of interest.

REFERENCES

1. Anderson L, Orme P, Di Michele R, Close GL, Milsom J, Morgans R, Drust B, Morton JP. Quantification of seasonal-long physical load in soccer players with different starting status from the English premier league: Implications for maintaining squad physical fitness. Int J Sports Physiol Perform. 2016 Nov; 11(8):1038–46.
2. Akenhead R, Nassis GP. Training Load and Player Monitoring in High-Level Football: Current Practice and Perceptions. Int J Sports Physiol Perform. 2016 Jul; 11(5):587–93.
3. Shushan T, McLaren SJ, Buchheit M, Scott TJ, Barrett S, Lovell R. Submaximal Fitness Tests in Team Sports: A Theoretical Framework for Evaluating Physiological State. Sports Med. 2022 Nov; 52(11):2605–26.
4. Schimpchen J, Correia PF, Meyer T. Minimally Invasive Ways to Monitor Changes in Cardiocirculatory Fitness in Running-based Sports: A Systematic Review. Int J Sports Med. 2022 Nov 4; a-1925–7468.
5. Impellizzeri FM, Marcora SM, Coutts AJ. Internal and External Training Load: 15 Years On. Int J Sports Physiol Perform. 2019; 14(2):270–3.
6. Stone NM, Kilding AE. Aerobic Conditioning for Team Sport Athletes: Sports Med. 2009 Aug; 39(8):615–42.
7. Akubat I, Barrett S, Abt G. Integrating the internal and external training loads in soccer. Int J Sports Physiol Perform. 2014; 9(3):457–62.
8. Akubat I, Barrett S, Sagarra M, Abt G. The Validity of External: Internal Training Load Ratios in Rested and Fatigued Soccer Players. Sports. 2018; 6(2):44.
9. Taylor RJ, Sanders D, Myers T, Akubat I. Reliability and Validity of Integrated External and Internal Load Ratios as Measures of Fitness in Academy Rugby Union Players. J Strength Cond Res. 2020 Jun; 34(6):1723–30.
10. Malone S, Doran D, Akubat I, Collins K. The Integration of Internal and External Training Load Metrics in Hurling. J Hum Kinet. 2016; 53(1):211–21.
11. Gregson W, Drust B, Atkinson G, Salvo VD. Match-to-match variability of high-speed activities in premier league soccer. Int J Sports Med. 2010; 31(4):237–42.
12. Rampinini E, Coutts A, Castagna C, Sassi R, Impellizzeri F. Variation in Top Level Soccer Match Performance. Int J Sports Med. 2007 Dec; 28(12):1018–24.
13. Lima-Alves A, Claudino JG, Boullosa D, Rangel Couto C, Teixeira-Coelho F, Pimenta EM. The relationship between internal and external loads as a tool to monitor physical fitness status of team sport athletes: a systematic review. Biol Sport. 2022; 39(3):629–38.
14. Drust B. Applied science and soccer: a personal perspective on the past, present and future of a discipline. Sport Perform Sci Rep. 2019;
15. Ellis M, Penny R, Wright B, Noon M, Myers T, Akubat I. The dose–response relationship between training-load measures and aerobic fitness in elite academy soccer players. Sci Med Footb. 2021; 5(2):128–36.
16. Manzi V, Iellamo F, Impellizzeri F, D'Ottavio S, Castagna C. Relation between individualized training impulses and performance in distance runners. Med Sci Sports Exerc. 2009 Nov; 41(11):2090–6.
17. Hopkins WG. Measures of reliability in sports medicine and science. Sports Med. 2000; 30(1):1–15.
18. Beckerman H, Roebroeck ME, Lankhorst GJ, Becher JG, Bezemer PD, Verbeek ALM. Smallest real difference, a link between reproducibility and responsiveness. Qual Life Res. 2001; 10:571–8.
19. de Vet HC, Terwee CB, Ostelo RW, Beckerman H, Knol DL, Bouter LM. Minimal changes in health status questionnaires: Distinction between minimally detectable change and minimally important change. Health Qual Life Outcomes. 2006; 4(May 2014).
20. Hopkins WG, Hawley JA, Burke LM. Design and analysis of research on sport performance enhancement. Med Sci Sports Exerc. 1999; 31(3):472–85.
21. McKay AKA, Stellingwerff T, Smith ES, Martin DT, Mujika I, Goosey-Tolfrey VL, Sheppard J, Burke LM. Defining Training and Performance Caliber: A Participant Classification Framework. Int J Sports Physiol Perform. 2022 Feb 1; 17(2):317–31.
22. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. J Sports Sci. 1996 Aug; 14(4):321–7.
23. Bangsbo J, Iaia FM, Krustrup P. The YoYo intermittent recovery test: A useful tool for evaluation of physical performance in intermittent sports. Sports Med. 2008; 38(1):37–51.
24. Scott MTU, Scott TJ, Kelly VG. The validity and reliability of global positioning systems in team sport: A brief review. J Strength Cond Res. 2016; 30(5):1470–90.
25. Weston M, Siegler J, Bahnert A, McBrien J, Lovell R. The application of differential ratings of perceived exertion to Australian Football League matches. J Sci Med Sport. 2015; 18(6):704–8.
26. Barrett S, Midgley A, Lovell R. PlayerLoad: Reliability, Convergent Validity, and Influence of Unit Position During Treadmill Running. Int J Sports Physiol Perform. 2014; 9(6):945–52.
27. Banister EW. Modeling elite athletic performance. In: MacDougall JD, Wenger HA, Green HJ, editors. Physiological testing of elite athletes. Champaign (Ill.): Human Kinetics; 1991. p. 403–24.
28. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive Statistics for Studies in Sports Medicine and Exercise Science. Med Sci Sports Exerc. 2009; 41(1):3–12.
29. Weir JP. Quantifying the test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res. 2005; 19(1):231–40.
30. Hopkins WG. Spreadsheets for Analysis of Validity and Reliability. Sportscience. 2015; 19:36–45.
31. Williams JD, Abt G, Kilding AE. Ball-Sport Endurance and Sprint Test (BEAST90): validity and reliability of a 90-minute soccer performance test. J Strength Cond Res. 2010; 24(12):3209–18.
32. Bloomfield J, Polman RCJ, Donoghue PGO. Physical Demands of Different Positions in FA Premier League Soccer. J Sports Sci Med. 2007; 6(1):63–70.
33. Smith MR, Marcora SM, Coutts AJ. Mental fatigue impairs intermittent running performance. Med Sci Sports Exerc. 2015; 47(8):1682–90.
34. Lacome M, Simpson B, Broad N, Buchheit M. Monitoring Players' Readiness Using Predicted Heart-Rate Responses to Soccer Drills. Int J Sports Physiol Perform. 2018 Nov; 13(10):1273–80.
35. Thornton HR, Nelson A, Delaney JA, Serpiello F, Duthie GM. Inter-Unit Reliability and Effect of Data Processing Methods of Global Positioning Systems. Int J Sports Physiol Perform. 2019; 14(4):432–8.
36. Lamberts RP, Lambert MI. Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. J Strength Cond Res. 2009 May; 23(3):1005–10.
37. Torreño N, Munguía-Izquierdo D, Coutts A, Sáez de Villarreal E, Asian-Clemente J, Suarez-Arrones L. Relationship Between External and Internal Loads of Professional Soccer Players During Full Matches in Official Games Using Global Positioning Systems and Heart-Rate Technology. Int J Sports Physiol Perform. 2016; 11(7):940–6.
38. Atkinson G, Batterham AM. The use of ratios and percentage changes in sports medicine: Time for a rethink? Int J Sports Med. 2012; 33(7):505–6.

Different pitch configurations constrain the external and internal loads of young professional soccer players during transition games

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ABSTRACT: The aims of this study were to compare the influence of transition game (TG) size on the external and internal loads of young professional soccer players and to describe the high-speed profile of these drills in response to pitch dimensions. Eighteen young professional soccer players (age: 16.1 ± 0.3 years; height: 178.3 ± 5.4 cm; weight: 70.1 ± 6.2 kg) performed a 3vs2 TG on pitches measuring 40 × 30 m (TG_{30}), 40 × 50 m (TG_{50}) and 40 × 70 m (TG_{70}) m. Distance covered (DC); accelerations-decelerations above 1.0 $m \cdot s^{-2}$ and 2.5 $m \cdot s^{-2}$; rate of perceived exertion (RPE); maximal heart rate and time above 90%; DC at 18.0 to 21.0 $km \cdot h^{-1}$ (DC 18–20.9 $km \cdot h^{-1}$); DC at 21.0 to 23.9 $km \cdot h^{-1}$ (DC 21–23.9 $km \cdot h^{-1}$); DC above 24.0 $km \cdot h^{-1}$ (DC > 24 $km \cdot h^{-1}$); and peak speed and sprint profile (duration, distance and maximal speed) were measured. TG_{30} achieved lower DC, DC above 18 $km \cdot h^{-1}$, peak speed, sprint distance and RPE than TG_{50} and TG_{70} ($p < 0.01$ and $p < 0.05$) and lower sprint duration and maximal speed sprint than TG_{70} ($p < 0.01$). TG_{30} and TG_{50} achieved higher Acc > 1.0 and > 2.5 $m \cdot s^{-2}$ respectively than TG_{70} ($p < 0.05$). TG_{70} showed greater DC above 21 $km \cdot h^{-1}$, peak speed, sprint distance and maximal speed sprint than TG_{50} ($p < 0.01$). Soccer coaches should use larger TGs to overload variables related to high speed and sprint demands during training and smaller TG formats to stimulate the accelerations of the soccer players.

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INTRODUCTION

Currently training prescriptions follow a game-based approach in which ball-drill prescriptions are focused on the game as a whole [1]. The use of drill-based games such as small-sided games (SSGs) has become popular since they reflect the multidimensional stimulus provided by matches while allowing the coach to alter players' specific responses by manipulating various task constraints [2–5]. Despite their popularity, it has been reported that these soccer tasks do not always reproduce the distances covered at high or very high speeds of the matches [6, 7]. Taking into account that during official matches counter-attacks are the actions in which players have to run at high or very high speeds [8] and that during the transitions the high-speed activities are 7–9-fold greater than the 90-min demands [9], coaches mostly choose transition games (TG) to develop these running skills in professional soccer through a specific game context. TGs are soccer tasks in which players continuously have to complete counter-attack situations using fast attacking and defensive transitions. Transitions or counter-attacks are crucial phases of the game since they have been found to be the most effective style of play for scoring goals, with more risks taking place during these moments [10, 11]. Despite the critical importance of the transitions in soccer, they have received scarce attention in the scientific literature. To date, only one study has investigated the physical demands of these actions during official matches, confirming that transitions exceeded the high-speed activities of the matches and nearly half of the game sprint distance [9]. Based on this, it is proposed that training programmes for professional soccer players should be focused on training high-speed running to improve sprint capacity with possession of the ball through transitional specific exercises [12], but only one study has analysed these drills during soccer training, showing that TGs induce more high-intensity requirements and lower variability in players' responses than do small- and large-sided games [13]. By contrast, other training strategies such as supplementary time-efficient challenges in the form of high-speed straight runs, running involving directional changes, repeated sprints or modified-sided games have been widely studied [14]. For example, studies have demonstrated that introducing 30 s of running drills in a small-sided game, or changing zones during small-sided games, increases the distance covered by players at moderate and high

speeds to a larger extent than the same tasks without these constraints [8, 15]. Considering this, coaches should develop TGs that stimulate the maximum physical outputs of the soccer players, and the manipulation of the pitch size during these drills needs to be examined [9]. Therefore, the aims of this study were (1) to compare the influence of the TG pitch size on external and internal loads in young professional soccer players and (2) to describe the high speed profile of these training drills with different pitch dimensions.

MATERIALS AND METHODS

Subjects

Eighteen young soccer players (age: 16.1 ± 0.3 years; height: 178.3 ± 5.4 cm; weight: 70.1 ± 6.2 kg) from the professional academy of a Spanish first division club participated in this study. Goalkeepers also participated in the TGs but were excluded from the data analysis. Players participated in five training sessions (80–120 min duration) and one competitive match (normally on Sunday) per week. Although the data were the result of the daily workload monitoring during the training of the team, all players were informed of the aims, requirements, benefits and risks of the study, and provided written and informed consent to participate. The research procedure was approved by the research ethics committee of the local university and was conducted in accordance with the Declaration of Helsinki.

Procedures

Data were collected during the 2021–2022 season. External and internal training loads in the same TGs with three different pitch dimensions were monitored, as shown in Figure 1. TGs were performed in random order, being chosen by two professional coaches with experience in analysing different match situations: counter-attacks near to the opposite goal; counter-attacks in the field; and counter-attacks near to the own goal (representative images of each format during official matches are provided in Figure 2). For the TGs, players were divided into balanced teams according to technical and tactical level, competitive experience, player positions and the subjective evaluation of the coaches. Similarly to previous published work [13], two teams of 9 players operated in groups of 3 players trying to score a goal in a 3 vs 2 counter-attack where 3 players performed an offensive role and 2 were in a defensive role. After the first move, regardless of whether it was a goal or a ball loss, the defensive group rested and another three players from the same team attacked, causing a defensive transition in the opponent group. This action was repeated alternately between teams. Two consecutive actions were performed because it has been demonstrated that in official matches the mean and peak duration of transitions were around 10 s and 22–27 s respectively [9]. To avoid any disruption of play, coaches were prepared to introduce balls as needed, and they verbally encouraged the players to maintain a high work rate

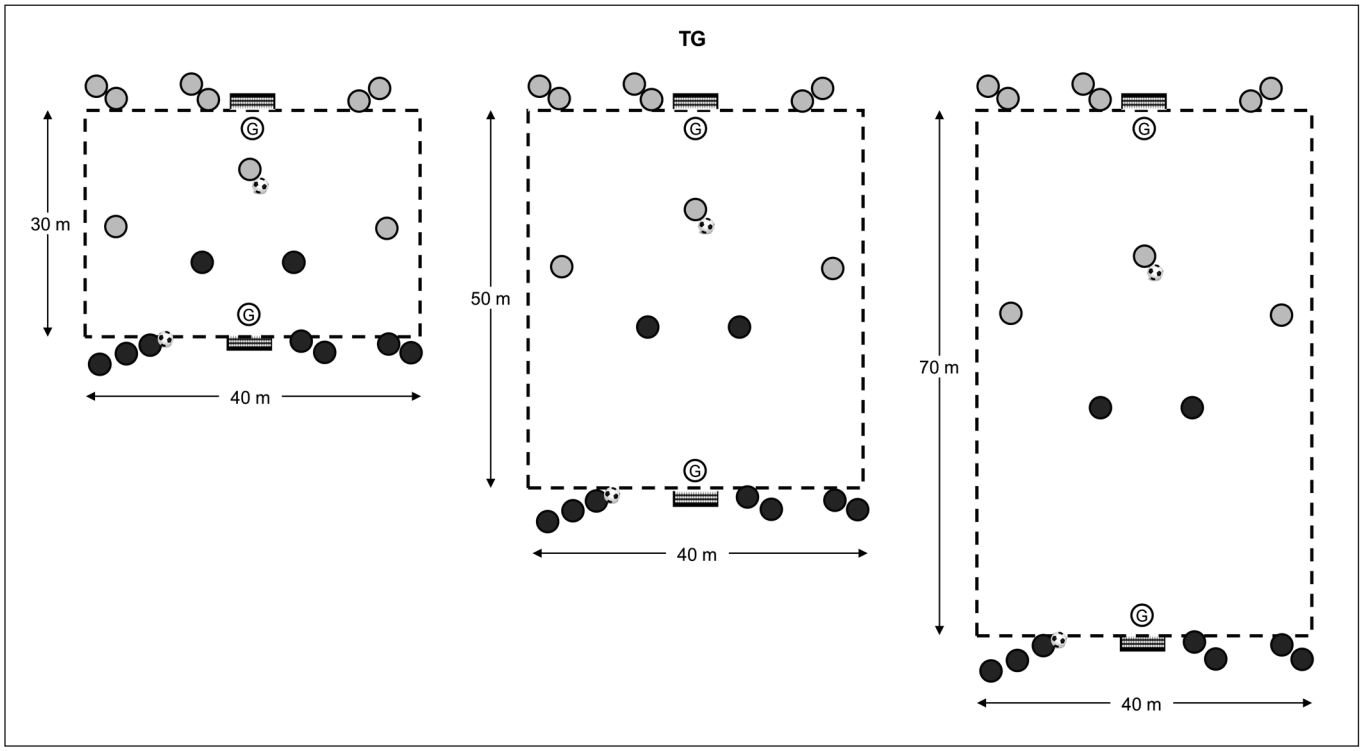


FIG. 1. Graphical representation of TGs.
TG = transition games; numbers 1 to 8 represent the evolution of all moments of each TG.

during the TG bouts. Several reasons justify the 3vs2 formats used. On one hand, investigations carried out on the match analysis in football have demonstrated that situations of numerical inequality often occur in competitive matches [16, 17]. On the other hand, some authors have suggested that less tactical complexity (few players) can facilitate adequate learning [18]. Finally, as can be seen in Figure 2, it is common in professional soccer. Similarly, the size of the TGs (relative area per player of 240 m^2, 400 m^2 and 560 m^2 in the TG_{30}, TG_{50} and TG_{70} respectively) were chosen following the literature, where it has been stated that it is necessary to have a relative area per player of ~288 m^2 [4] or even greater, of 300 m^2 [19], to obtain the maximal running requirements during a drill-based game. Following a standardised 20 min warm-up, a 20-min transition game was performed, distributed as follows: 2 min explanation, 12 min transition game using an intermittent format of 3×4 min bouts and 2 min of passive recovery between bouts. Different versions of the transition game were evaluated on Wednesday (match day -4 and after day-off). The soccer players in this study were well familiarized with these games because they were repeated several times during the season, being a frequent drill used by all the academy coaches. For the analysis, the transition games were performed three times.

Measures

External and internal loads were monitored using a GPS system (Kinexon GNSS, Precision Technologies, Munich, Germany). Total distance covered (DC), number of accelerations and decelerations above 1.0 $m \cdot s^{-2}$ and 2.5 $m \cdot s^{-2}$ (Acc > 1.0 $m \cdot s^{-2}$, Acc > 2.5 $m \cdot s^{-2}$, Dec > 1.0 $m \cdot s^{-2}$ and Dec > 2.5 $m \cdot s^{-2}$), rate of perceived exertion (RPE), maximal heart rate (HR_{max}) and time above 90% of maximal



FIG. 2. Examples of the three TGs during official matches.
A = counter-attacks near to the opposite goal; B = counter-attack in the field, C = counter-attacks near to own goal. Numbers 1 = initial stage of the TG; 2 and 3 = middle stage of the TG; 4 = final stage of the TG.

heart rate ($HR_{>90}$) were recorded to quantify the external and internal load. External load was evaluated through the high-speed profile of the players, using the variables distance covered between 18.0 and 20.9 km·h^{-1} (DC 18–20.9 km·h^{-1}); distance covered between 21.0 and 23.9 km·h^{-1} (DC 21–23.9 km·h^{-1}); distance covered at above 24.0 km·h^{-1} (DC > 24 km·h^{-1}); peak speed; and sprint profile (duration, distance and maximal speed). Most of these variables have been used previously in the literature [13].

Statistical analysis

Data are presented as mean ± standard deviation (SD). All variables presented a normal distribution (Shapiro-Wilk test). Differences between dependent internal and external loads in each transition game were determined using a repeated-measures analysis of variance. Bonferroni post-hoc tests were used to identify significant differences between parameters in each format. The level of statistical significance was set at $p \leq 0.05$. All statistical analyses were performed using SPSS (version 19, SPSS Inc., Chicago, IL, USA). The standardized differences of effect size (ES, 95% confidence interval [95%CI]) in the selected variables were calculated. Threshold values for assessing magnitudes of the ES (changes as a fraction or multiple of baseline standard deviation) were > 0.20, 0.20, 0.60, 1.2 and 2.0 for trivial, small, moderate, large and very large, respectively [20].

RESULTS

Descriptive statistics for the DC, accelerations-decelerations and internal load metrics measured during the three TGs are presented in Table 1, and Figures 3, 4 and 5. The comparisons of the high speed profile variables are presented in Table 2 and Figures 3 and 6. The data analyses showed that TG_{30} reached significantly lower DC, DC 18–20.9 km·h^{-1}, DC 21–23.9 km·h^{-1}, DC > 24 km·h^{-1}, peak speed, sprint distance and RPE than TG_{50} and TG_{70} ($p < 0.01$ for all comparisons except RPE between TG_{30} and TG_{50} where $p < 0.05$), and lower sprint duration and maximal speed sprint than TG_{70} ($p < 0.01$). TG_{30} and TG_{50} achieved significantly higher Acc > 1.0 and > 2.5 m·s^{-2} respectively than TG_{70} ($p < 0.05$). TG_{70} achieved significantly greater DC 21–23.9 km·h^{-1}, DC > 24 km·h^{-1}, peak speed, sprint distance and maximal speed sprint than TG_{50} ($p < 0.01$).

DISCUSSION

In the present study we investigated the influence of three different pitch sizes in TGs on the external/internal load and the speed profile in young professional soccer players. To the best of our knowledge this is the first study that has analysed the effect of pitch size during TGs in locomotor intensity metrics. In general, the results show that enlarging the pitch size increased the total distance covered, the speed profile and the rate of perceived exertion of the players. It was

TABLE 1. Comparison of external and internal load of TG analysed.

	Mean ± SD			p value			F	ES ± SD		
	TG_{30}	TG_{50}	TG_{70}	TG_{30} vs. TG_{50}	TG_{30} vs. TG_{70}	TG_{50} vs. TG_{70}		TG_{30} vs. TG_{50}	TG_{30} vs. TG_{70}	TG_{50} vs. TG_{70}
DC (m)	1203.9 ± 100.9	1457.8 ± 164.4	1475.9 ± 160.2	0.000	0.000	0.150	35.2	1.11 ± 0.24	1.22 ± 0.20	0.17 ± 0.20
#Acc > 1.0 m·s^{-2}	9.1 ± 3.0	7.4 ± 2.8	5.7 ± 2.3	0.105	0.017	0.495	12.3	-0.46 ± 0.47	-0.81 ± 0.51	-0.13 ± 0.34
#Acc > 2.5 m·s^{-2}	9.9 ± 4.5	10.1 ± 3.7	6.1 ± 2.7	0.619	0.097	0.023	11.7	0.25 ± 0.88	-0.54 ± 0.53	-0.61 ± 0.42
#Dec > 1.0 m·s^{-2}	6.8 ± 3.4	6.9 ± 2.8	5.2 ± 2.4	0.740	0.134	0.251	3.3	-0.11 ± 0.58	-0.49 ± 0.55	-0.28 ± 0.42
#Dec > 2.5 m·s^{-2}	6.1 ± 2.9	7.4 ± 3.5	4.9 ± 2.1	0.425	0.970	0.604	6.1	-0.24 ± 0.53	0.01 ± 0.53	0.16 ± 0.54
HR max	208.3 ± 9.2	202.9 ± 19.7	207.5 ± 12.3	0.385	0.640	0.627	1.2	0.21 ± 0.41	0.08 ± 0.29	-0.11 ± 0.39
$HR_{>90}$ (s)	107.8 ± 174.1	109.9 ± 161.4	125.9 ± 156.7	0.686	0.795	0.783	0.5	-0.10 ± 0.45	0.09 ± 0.61	-0.09 ± 0.60
RPE (AU)	4.3 ± 1.1	5.8 ± 1.2	6.4 ± 1.1	0.000	0.048	0.575	27.7	1.07 ± 0.45	0.74 ± 0.59	0.14 ± 0.40

SD = standard deviation; ES = Effect Size; TG = Transition games; DC = total distance covered; #Acc = number of accelerations; #Dec = number of decelerations; HR = Heart Rate; max = maximal; $HR_{>90}$ = time above 90% of maximal heart rate; RPE = rate of perceived exertion.

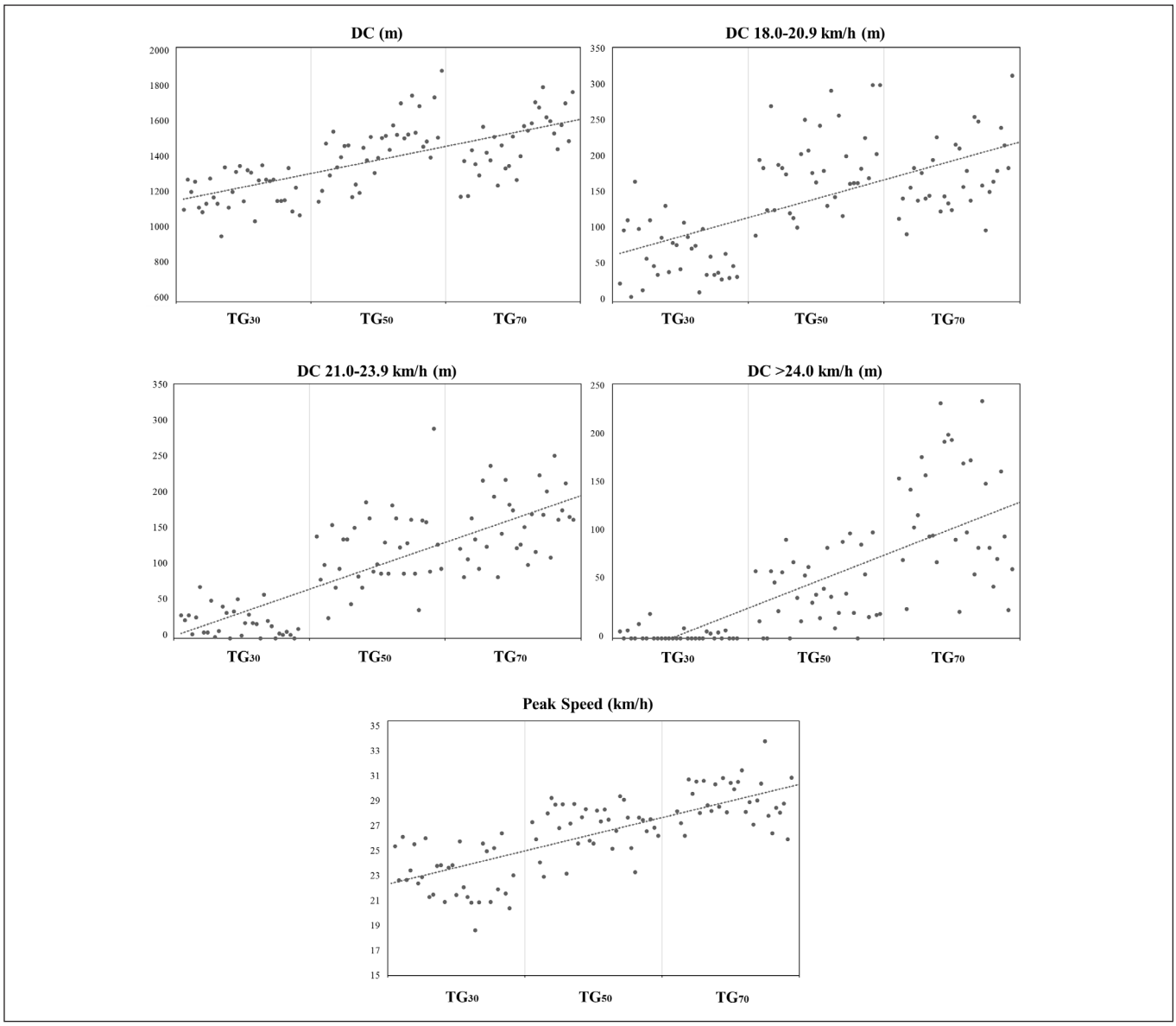


FIG. 3. External load: distance covered and speed.
TG = transition games; DC = total distance covered; max = maximal.

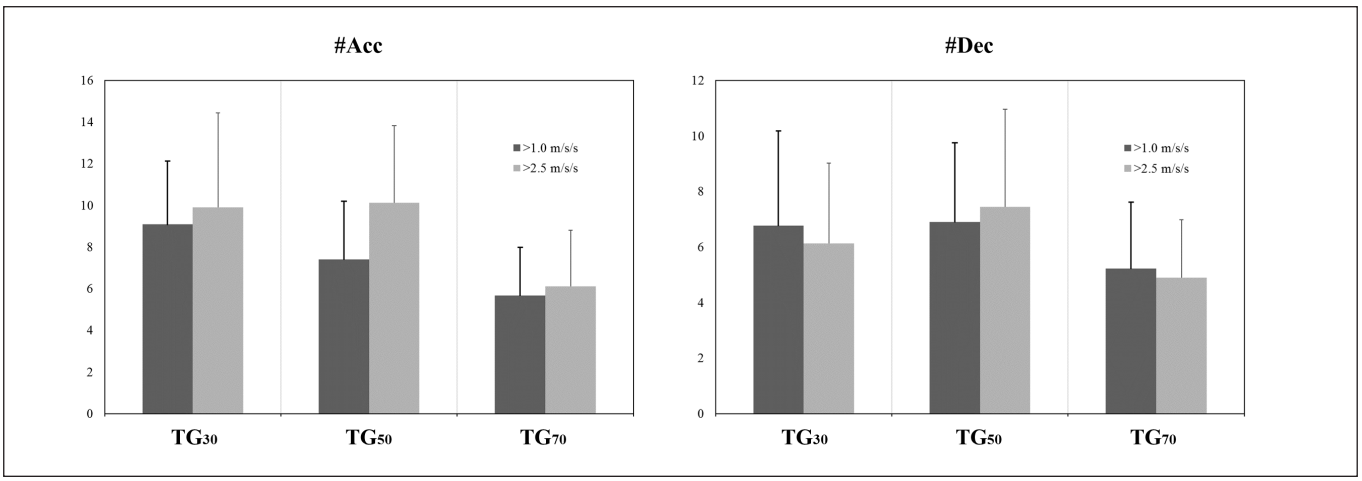


FIG. 4. External load: accelerations and decelerations.
TG = transition games; #Acc = number of accelerations; #Dec = number of decelerations

also observed that mechanical load was practically unaffected by format size and only the number of accelerations was higher in the smallest pitch format.

In the relevant literature it has been shown that one of the main variables influencing training load during the development of variously sided games is the pitch size [21, 22]. In general, most studies have shown that enlarging the pitch size led players to cover greater total, running, and sprinting distances per minute than smaller formats with the same playing conditions [23–25]. Our results reinforce this idea, showing different load patterns in the different playing dimensions proposed. In particular, larger pitch sizes caused more high-speed running, sprint and peak speed demands during TGs. In accordance with previous published literature, these results may be due to two main factors. Firstly, there is a different relative area per player in the three different TGs proposed (TG_{30} = 240 m^2; TG_{50} = 400 m^2; TG_{70} = 560 m^2), as has been demonstrated in variously sided games [19, 25, 26]. In the present study, when the relative area per player was increased from the TG_{30} format (240 m^2) there was an increase in all the variables of the high-speed profile of the players, with the exceptions of sprint duration (between TG_{30} vs TG_{50} and TG_{50} vs TG_{70}) and maximal sprint velocity (between TG_{30} vs TG_{50}) (see Table 2). For some of these variables the enhancement observed was very significant, such as in DC > 24 km·h^{-1} (m) in which players covered 94% more distance in TG_{50} in comparison with TG_{30}, and 62% more distance in TG_{70} than in TG_{50} (see Table 2). Further studies analysing the technical and tactical behaviours of the players during these TGs would be necessary to determine which soccer actions are performed during these displacements at higher speeds.

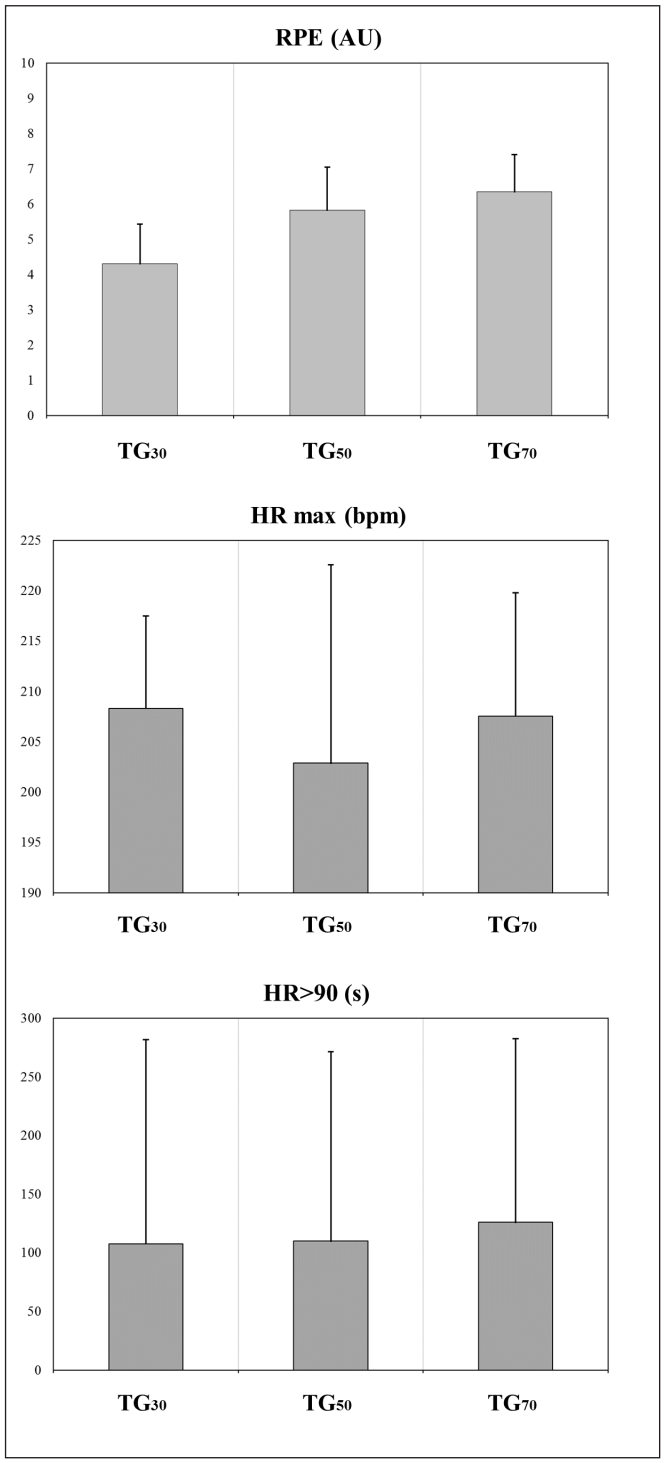


FIG. 5. Internal load.
RPE = rate of perceived exertion; AU = arbitrary units; HR = heart rate; max = maximal; bpm = beats per minute; $HR_{>90}$ = time above 90% of maximal heart rate.

Secondly, the length:width ratio of each TG proposed (0.75, 1.25 and 1.75 arbitrary units for TG_{30}, TG_{50} and TG_{70}, respectively) could also have impacted the load. Previous studies have shown that a longer pitch provides more distance between the goalkeeper and the last defender, allowing the offensive players to exploit it by covering greater distances, more distance at higher intensities, and engaging in greater acceleration [27–29]. In line with these results, we observed that higher length:width ratios were associated with increased high-speed and very high-speed running. TGs are drills developed to simulate the counter-attacking situations that players experience in competition. These situations are characterized by the team in possession of the ball having large spaces in front of the opponent's goal, with a low defensive opposition. This could explain why higher length:width ratios better simulate the speeds players produce in these situations in competition. However, in the present study, higher ratios were associated with higher relative areas per player. Further studies comparing TGs with same area per player and different length:width ratios are needed to elucidate the role of this variable format.

Comparison of our results with the only other work carried out on TGs [13] showed that the formats of 50 m and 70 m produced more similarities with the TG proposed previously (60 m) in terms of DC (1426.5 ± 100.7) DC 18–20.9 km·h^{-1} (201.5 ± 40.4), peak speed (27.0 ± 1.7) and RPE (6.4 ± 0.8). Likewise, it could be hypothesised that the performance for the variables DC 21–23.9 km·h^{-1} and DC > 24 km·h^{-1} would be the same, but unfortunately they uniquely registered the DC > 21 km·h^{-1} (255.9 ± 96.6), adding the distance covered > 24 km·h^{-1} to this zone, so these exercises are adequate

TABLE 2. Comparison of high speed profile of TG analysed.

	Mean ± SD			p value			F	ES ± SD		
	TG_{30}	TG_{50}	TG_{70}	TG_{30} vs. TG_{50}	TG_{30} vs. TG_{70}	TG_{50} vs. TG_{70}		TG_{30} vs. TG_{50}	TG_{30} vs. TG_{70}	TG_{50} vs. TG_{70}
DC 18–20.9 km·h^{-1} (m)	65.5 ± 37.6	185.5 ± 55.6	172.7 ± 49.3	0.000	0.000	0.680	60.4	1.98 ± 0.34	1.88 ± 0.42	-0.05 ± 0.19
DC 21–23.9 km·h^{-1} (m)	21.4 ± 19.3	119.6 ± 50.7	159.1 ± 46.0	0.000	0.000	0.001	93.7	2.31 ± 0.39	2.73 ± 0.44	0.48 ± 0.22
DC > 24 km·h^{-1} (m)	2.8 ± 5.4	46.0 ± 32.1	121.3 ± 58.9	0.000	0.000	0.000	76.6	1.97 ± 0.49	2.66 ± 0.46	0.97 ± 0.32
Max Speed (km·h^{-1})	22.9 ± 2.0	26.6 ± 1.7	28.8 ± 1.7	0.000	0.000	0.000	88.2	1.54 ± 0.28	2.32 ± 0.30	0.78 ± 0.26
Spr Duration (s)	1.7 ± 0.7	2.2 ± 0.9	3.3 ± 1.6	0.147	0.000	0.057	40.9	0.31 ± 0.35	1.06 ± 0.31	0.62 ± 0.52
Spr Distance (m)	11.8 ± 5.3	15.1 ± 6.9	23.1 ± 11.2	0.032	0.000	0.000	40.8	0.36 ± 0.27	0.93 ± 0.27	0.57 ± 0.14
Spr Max Speed (km·h^{-1})	25.0 ± 1.2	25.2 ± 1.5	26.0 ± 1.9	0.505	0.003	0.000	12.1	0.11 ± 0.27	0.64 ± 0.34	0.35 ± 0.15

SD = standard deviation; ES = Effect size; TG = transition games; DC = total distance covered; max = maximal; Spr = Sprint.

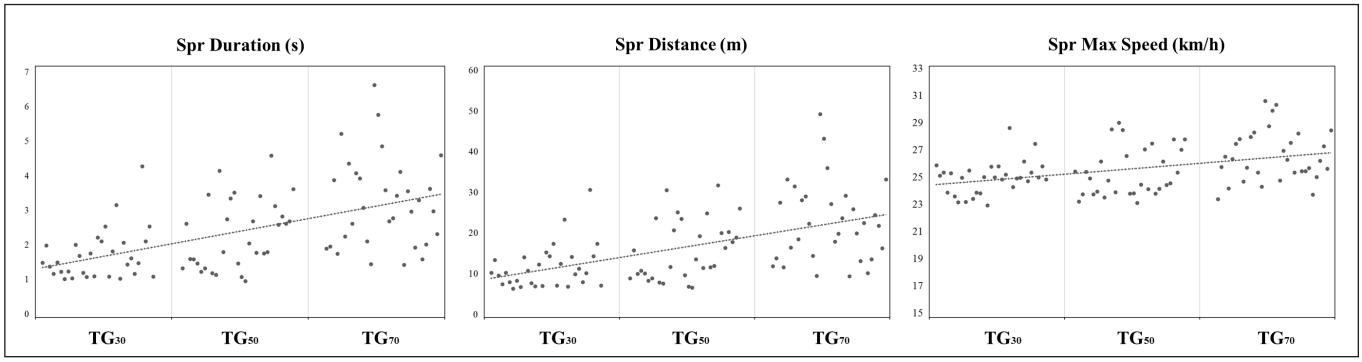


FIG. 6. Sprint profile
TG = transition games; Spr = sprint.

to train high- and very-high speed running in counter-attack contexts [13]. In contrast, mechanical load variables (see Table 1) were practically unaffected by the different pitch sizes studied. Dec did not change and Acc > 1.0 and > 2.5 m·s^{-2} were only significantly less in the largest format with respect to the smallest (TG_{30} vs TG_{70}) and the medium format (TG_{50} vs TG_{70}) respectively. These results agree with others previously reported for small- to large-sided games in which smaller pitch dimensions were associated with greater mechanical load on the players [29–31]. Previous published work on TGs [13] noted greater Acc (> 1.0 m·s^{-2} = 24.0 ± 5.1; > 2.5 m·s^{-2} = 19.9 ± 3.6) and Dec > 1.0 and > 2.5 m·s^{-2} (> 1.0 m·s^{-2} 12.0 ± 3.2; > 2.5 m·s^{-2} = 14.3 ± 3.5) than were measured in the current investigation of TGs, indicating the need to continue examining Acc and Dec during TGs. In addition, considering that high-speed sprint training is considered a key factor for hamstring injury prevention, and considering the need to create specific collective exercises that accumulate high speed running during soccer training sessions [32, 33], TGs could also be used as collective preventive workouts. TG_{50} and TG_{70} could be considered suitable for preparing young soccer players for elite teams because both sizes showed similar values for sprint duration, sprint distance, and mean and maximal speed sprint to those found in high-intensity actions of professional players during regular matches [34] Another important aspect of this work is that there were no differences in the HR_{max} and $HR_{>90}$ between TGs, so the three formats could be considered suitable for eliciting important cardiopulmonary adaptations, as suggested by Buchheit and Laursen [35].

Although this study presents novel results from commonly used training drills, some methodological limitations should be considered. Firstly, a relatively small number of players were included for

analysis and they came from only one club. However, taking into account the limited sample of professional soccer players at an elite academy, the data obtained may be useful to help coaches and sport scientists to understand the load orientation of TGs depending on the selected pitch size. Also, a specific format of TGs (3vs2) was studied, and although this format is very frequent in soccer, other TG compositions should be studied and included in future research, in order to gain a better grasp of the features of TGs. Future studies should analyse TGs performed with a larger sample involving soccer players from different professional academies executing the same task. Likewise, it appears necessary to monitor the training load of TGs carried out with different compositions, for example, 1vs1 and 2vs1.

CONCLUSIONS

The present study shows the internal and external responses of the soccer players to different modifications of the pitch size during the TGs. The results of the present investigation reflect that the total distance covered, the speed requirements and the rate of perceived exertion of the players increase as the pitch size is increased, while the only variable that is greater in the smaller pitches is the number of accelerations.

Practical applications

These results could help the planning process of exercise design in soccer. Considering that coaches periodize the highest weekly training load in the middle of the week [5, 36], TG_{70} and TG_{50} should be used to overload variables related to high speeds and sprints in this phase of the microcycle, for example, four or three days before the match. Similarly, technical staff could use TG_{30} during the latter part of the week (two days before the match) due to the lower load requirements. In this sense, soccer teams could train a specific counter-attack drill any day of the week depending on the desired training load or the days remaining before the match, this last aspect being especially important during congested periods.

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Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. Abad Robles MT, Collado-Mateo D, Fernandez-Espinola C, Castillo Viera E, Gimenez Fuentes-Guerra FJ. Effects of Teaching Games on Decision Making and Skill Execution: A Systematic Review and Meta-Analysis. Int J Environ Res Public Halth. 2020; 17(2):505.
2. Clemente FM, Afonso J, Castillo D, Arcos AL, Silva AF, Sarmento H. The effects of small-sided soccer games on tactical behavior and collective dynamics: A systematic review. Chaos Solitons Fractals. 2020; 134:109710.
3. Sarmento H, Clemente FM, Harper LD, Costa IT, Owen A, Figueiredo AJ. Small sided games in soccer–a systematic review. Int J Perf Anal Sport. 2018; 18(5):693–749.
4. Riboli A, Esposito F, Coratella G. Technical and locomotor demands in elite soccer: manipulating area per player during small-sided games to replicate official match demands. Biol Sport. 2022; 40(3):639–647.
5. Clemente F, Praça GM, Aquino R, Castillo D, Raya-González J, Rico-González M, Afonso J, Sarmento H, Filipa Silva A, Silva R, Ramirez-Campillo R. Effects of pitch size on soccer players' physiological, physical, technical, and tactical responses during small-sided games: a meta-analytical comparison. Biol Sport. 2023; 40(1):111–147.
6. Clemente FM, Sarmento H, Rabbani A, Van Der Linden C, Kargarfard M, Costa IT. Variations of external load variables between medium- and large-sided soccer games in professional players. Res Sports Med. 2019; 27(1):50–59.
7. Martin-Garcia A, Castellano J, Diaz AG, Cos F, Casamichana D. Positional demands for various-sided games with goalkeepers according to the most demanding passages of match play in football. Biol Sport. 2019; 36(2):171–180.
8. Asian-Clemente J, Rabano-Munoz A, Munoz B, Franco J, Suarez-Arrones L. Can Small-side Games Provide Adequate High-speed Training in Professional Soccer? Int J Sports Med. 2021; 42(6):523–528.
9. Bortnik L, Burger J, Rhodes D. The mean and peak physical demands during transitional play and high pressure activities in elite football. Biol Sport. 2022; 39(4):1055–1064.
10. Lago-Ballesteros J, Lago-Peñas C, Rey E. The effect of playing tactics and situational variables on achieving score-box possessions in a professional soccer team. J Sports Sci. 2012; 30(14):1455–1461.
11. Lago-Peñas C, Gómez-Ruano M, Yang G. Styles of play in professional soccer: an approach of the Chinese Soccer Super League. Int J Perf Anal Sport. 2017; 17(6):1073–1084.
12. Chmura P, Oliva-Lozano JM, Muyor JM, Andrzejewski M, Chmura J, Czarniecki S, Kowalczuk E, Rokita A, Konefal M. Physical Performance Indicators and Team Success in the German Soccer League. J Hum Kinet. 2022; 83:257–265.
13. Asian-Clemente J, Rabano-Munoz A, Requena B, Suarez-Arrones L. High-speed training in a specific context in soccer: transition games. Int J Sports Med. 2022; 43(10):881–888.
14. Romero-Moraleda B, Nedergaard NJ, Morencos E, Casamichana D, Ramirez-Campillo R, Vanrenterghem J. External and internal loads during the competitive season in professional female soccer players according to their playing position: differences between training and competition. Res Sports Med. 2021; 29(5):449–461.
15. Koklu Y, Cihan H, Alemdaroglu U, Dellal A, Wong DP. Acute effects of small-sided games combined with running drills on internal and external loads in young soccer players. Biol Sport. 2020; 37(4):375–381.
16. Goncalves B, Marcelino R, Torres-Ronda L, Torrents C, Sampaio J. Effects of emphasising opposition and cooperation on collective movement behaviour during football small-sided games. J Sports Sci. 2016; 34(14):1346–1354.
17. Nunes NA, Goncalves B, Coutinho D, Travassos B. How Numerical Unbalance Constraints Physical and Tactical Individual Demands of Ball Possession Small-Sided Soccer Games. Front Psychol. 2020; 11:1464.
18. Praxedes A, Moreno A, Gil-Arias A, Claver F, Del Villar F. The effect of

small-sided games with different levels of opposition on the tactical behaviour of young footballers with different levels of sport expertise. PloS One. 2018; 13(1):e0190157.
19. Lacome M, Simpson BM, Cholley Y, Lambert P, Buchheit M. Small-Sided Games in Elite Soccer: Does One Size Fit All? Int J Sports Physiol Perform. 2018; 13(5):568–576.
20. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1):3–13.
21. Castillo D, Raya-Gonzalez J, Yanci J, Manuel Clemente F. Influence of Pitch Size on Short-Term High Intensity Actions and Body Impacts in Soccer Sided Games. J Hum Kinet. 2021; 78:187–196.
22. Gantois P, Piqueras-Sanchiz F, Cid M, Pino-Ortega J, Castillo D, Nakamura FY. The effects of different small-sided games configurations on heart rate, rating of perceived exertion, and running demands in professional soccer players. Eur J Sport Sci. 2022:1–9.
23. Bujalance-Moreno P, Latorre-Roman PA, Garcia-Pinillos F. A systematic review on small-sided games in football players: Acute and chronic adaptations. J Sports Sci. 2019; 37(8):921–949.
24. Clemente FM, Afonso J, Sarmento H. Small-sided games: An umbrella review of systematic reviews and meta-analyses. PloS One. 2021; 16(2):e0247067.
25. Gaudino P, Alberti G, Iaia FM. Estimated metabolic and mechanical demands during different small-sided games in elite soccer players. Hum Mov Sci. 2014; 36:123–133.
26. Lacome M, Simpson BM, Cholley Y, Buchheit M. Locomotor and Heart Rate Responses of Floaters During Small-Sided Games in Elite Soccer Players: Effect of Pitch Size and Inclusion of Goalkeepers. Int J Sports Physiol Perform. 2018; 13(5):668–671.
27. Asian Clemente JA, Suarez-Arrones L, Sánchez Gil S. Diferencias entre distintas orientaciones del espacio, relativizadas al perfil individual del jugador (Differences between distinct spatial orientations based on individual player profile). Retos. 2019; 35:3–6.
28. Folgado H, Bravo J, Pereira P, Sampaio J. Towards the use of multidimensional performance indicators in football small-sided games: the effects of pitch orientation. J Sports Sci. 2019; 37(9):1064–1071.
29. Silva H, Nakamura FY, Beato M, Marcelino R. Acceleration and deceleration demands during training sessions in football: a systematic review. Sci Med Footb. 2022; 26:1–16.
30. Casamichana D, Bradley PS, Castellano J. Influence of the Varied Pitch Shape on Soccer Players Physiological Responses and Time-Motion Characteristics During Small-Sided Games. J Hum Kinet. 2018; 64:171–180.
31. Madison G, Patterson SD, Read P, Howe L, Waldron M. Effects of Small-Sided Game Variation on Changes in Hamstring Strength. J Strength Cond Res. 2019; 33(3):839–845.
32. Beato M, Drust B, Iacono AD. Implementing High-speed Running and Sprinting Training in Professional Soccer. Int J Sports Med. 2021; 42(4):295–299.
33. Mendiguchia J, Conceição F, Edouard P, Fonseca M, Pereira R, Lopes H, Morin J-B, Jiménez-Reyes P. Sprint versus isolated eccentric training: Comparative effects on hamstring architecture and performance in soccer players. PloS One. 2020; 15(2):e0228283.
34. Carling C, Le Gall F, Dupont G. Analysis of repeated high-intensity running performance in professional soccer. J Sports Sci. 2012; 30(4):325–336.
35. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: Part I: cardiopulmonary emphasis. Sports Med. 2013; 43(5):313–338.
36. Los Arcos A, Mendez-Villanueva A, Martinez-Santos R. In-season training periodization of professional soccer players. Biol Sport. 2017; 34(2):149–155.

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Exposures to near-to-maximal speed running bouts during different turnarounds in elite football: association with match hamstring injuries

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ABSTRACT: To describe the occurrence of near-to-maximal sprinting speed (near-to-MSS) running bouts during training and hamstring injuries during the consecutive match of the same turnaround in elite football (soccer). Retrospective data from 36 team-seasons (16 elite teams performing in top European leagues) were analyzed (627 players, 96 non-contact time loss match hamstring injuries). We described 1) the occurrence of > 85%, > 90% or > 95% MSS exposures during training within each turnaround and match hamstring injuries and 2) whether the above-mentioned injury occurrences differed depending on the day(s) of the turnarounds (i.e., the period separating two consecutive matches, which is generally from 3 to 8 days) when these speed exposures occurred. The longer the length of the turnarounds and the lower the speed thresholds, the greater the number (and proportion) of near-to-MSS exposures (e.g., 18%, 45% and 72% of turnarounds with > 85% runs for 3, 5 and 7-turnarounds, respectively). For half of the turnarounds examined, there were no match hamstring injuries when players were exposed to running bouts > 95% MSS during training (e.g., injury rates: 0; CI: 0–15). Injuries still occurred during 85% of the turnarounds when there were no or lower relative speed exposures (i.e., > 85 or > 90%, injury rates: 2–5, CI: 0–6). Finally, irrespective of the turnaround length, there were no match hamstring injuries when > 95% MSS exposures occurred at D-2, while in contrast, injuries still happened when players were not exposed at all, or when these exposures occurred at D-3 and/or earlier within the turnaround. While the present observational study design precludes the examination of causal relationships, the programming of > 95% MSS exposures at D-2 may help mitigate match hamstring injury occurrences in elite football.

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INTRODUCTION

Hamstring strain injuries remain the most prevalent time-loss injuries in professional football [1]. While their relative occurrence may have slightly decreased in relation to the likely increased match demands over the past decade [2], practitioners are still seeking mitigation strategies both in the gym and on the pitch [3]. Among the different recommended strategies, the use of eccentric-based exercises [4] and exposures to near-to-maximal sprinting speed (near-to-MSS) running bouts (either with or without the ball) are now the most recommended [5, 6]. Sprinting is indeed both complex and unique at many levels (e.g., legs interaction, elastic energy transfer, reflexes, kinematics, kinetics) [6] and a similar recruitment intensity of the hamstring muscles (i.e., electromyographic activity) cannot be reached with isolated gym exercises [7].

In practice, recent studies have shown relationships between hamstring strain injuries and near-to-MSS exposures both in Australian Rules Football [8, 9] and Gaelic Football [10] players. More precisely, both under and over near-to-MSS exposures were associated with higher injury rates, suggesting the existence of an optimal chronic "dose" i.e., a number of weekly exposures [8, 10] and/or monthly cumulative distance [9]. This optimal chronic dose is likely specific to each population and context, and it is therefore difficult to provide guidelines for all practitioners on the back of those two studies. More importantly, those studies do not provide clear guidelines on how and when to program these near-to-MSS exposures during turnarounds of different lengths. A turnaround refers to the period separating two consecutive matches, which is generally from 3 days (2 full days of recovery and the day of the second match, such as when playing on Sunday and then again on Wednesday) to 8 days (7 days in between matches, such as playing on a Saturday and then the next Sunday). How fast football players should run is also still unclear, since large variations in relative velocities have been reported, ranging from ≥ 80 [9], to 85 [8] or even 95% of MSS [10].

In fact, the questions of 1) the optimal intensity (in % of MSS) and 2) on which day to program these near-to-MSS exposures have not been examined scientifically despite their immense importance in terms of match performance and hamstring injury management [11]. The only partial answer to this question that is available to us today comes from the 100 elite football (soccer) practitioners that we surveyed in 2021 [12]. While the large majority of the responders confirmed the need to regularly expose players to these high-speed running bouts, there was a lack of agreement as to when MSS work should be programmed, especially whether it should occur 2 or 3 days before the match i.e., D-3 vs D-2. This was likely due to the lack of robust evidence, and this programming practice was instead based on experience and/or adherence to typical periodization paradigms and models (e.g., tactical periodization [13], R. Verheijen [14], or el modelo estructurado of FC Barcelona [15]).

In order to shed light on this important topic, we retrospectively analyzed data from 19 elite teams performing in top football leagues across the globe. The first aim of the study was to describe the occurrence of both match hamstring injuries and > 85%, > 90% or > 95% MSS exposures during training within different turnaround lengths. The second aim was to examine match hamstring injury occurrences as a function of the day(s) of the turnarounds when these speed exposures occurred.

MATERIALS AND METHODS

Study design and procedures

The overall research was based on retrospective analyses of both match hamstring injury occurrences and players' training locomotor (running) activities collected via an online database (i.e., Kitman Labs platform, Dublin, Ireland) commonly used by all the football (soccer) teams involved in the study. Figure 1 shows the flow chart of the data selection process.

Population

The elite adult football players from whom data was examined belonged to 19 different teams competing in the EPL, the Italian Serie A, the French Ligue 1, the Bundesliga, the Scottish Premiership, the MLS and the Dutch Eredivisie (from January 2018 to December 2021). This initial sample represented 84 team-seasons (Figure 1). Then various exclusion criteria were applied at the season level:

1) those with no injury information
2) an insufficient number of players with regular exposure throughout the season (considering that 15 is the lowest number of players that may constitute a squad)
3) daily maximal speed not defined or provided while a pitch training session was registered

After applying those exclusion criteria the final sample represented 36 team-seasons.

Data extraction and anonymity

Each player and club is provided with an ID number on the platform. The researchers in charge of the analysis could only pull and analyze data associated with their IDs – no names included. Then, data was transformed and coded for injury occurrence (dates only used for assessing occurrences, such as during a match vs. during training and when in relation from/to the previous match) and type (contact or non-contact injury, without any more details), to provide a final dataset. The medical staff of each team registers injury details in the platform as a part of their daily player care management, including variables such as date of injury, type and location of the injury, as well as severity (days lost). Similarly, players' match and training session participation are recorded as part of the team staff's daily monitoring. Additionally, the measures of training and competitive load are also added to the platform. The fact that all clubs used the same platform ensured the standardisation and the reliability of all types of entries, from medical information to exposure measures (e.g., session duration and GPS data attached to the system calendar). We nevertheless ran a thorough data health check to ensure that all data retained for analysis met the same standard. In addition to all the steps above that guaranteed high levels of both data security and anonymity (https://www.kitmanlabs.com/privacy-security-and-compliance/), permission was granted by the teams for their inclusion in this research study, therefore ethics committee clearance was not required [16].

Turnarounds

A *n*-d turnaround was defined as a microcycle with *n* days between the first and second match, where *n* is the count of days from the first day after a match up to and including the following match day. The shortest observed turnaround was 3 days (3-d) e.g., playing a match on Sunday and again the following Wednesday, while the longest was 8 days (8-d) e.g., playing on Saturday and again the following Sunday. The longer and less common turnarounds (e.g., ≥ 9 days, likely including international breaks or holidays, when the training dynamics are completely different than during typical in-season turnarounds) were excluded from the analysis (Figure 1).

Injuries and turnaround participation

In this study we focused on non-contact hamstring injuries (i.e., a substantial strain of either the biceps femoris, semitendinosus, or semimembranosus muscle), as registered by the medical staff of each club, using the Orchard Sports Injury and Illness Classification System (OSIICS) offered by the online platform. While the exact diagnostic methods are impossible to describe in detail given the large variability of staff involved (i.e., 19 teams with likely more than 25 to 30 practitioners in total), the large majority of teams (if not all) at the elite football level have access to high-quality scans (i.e., Echography, Magnetic Resonance Imaging). In the literature, an injury is often defined as an occurrence sustained during either training or match-play which prevents a player from taking part in training or match-play for

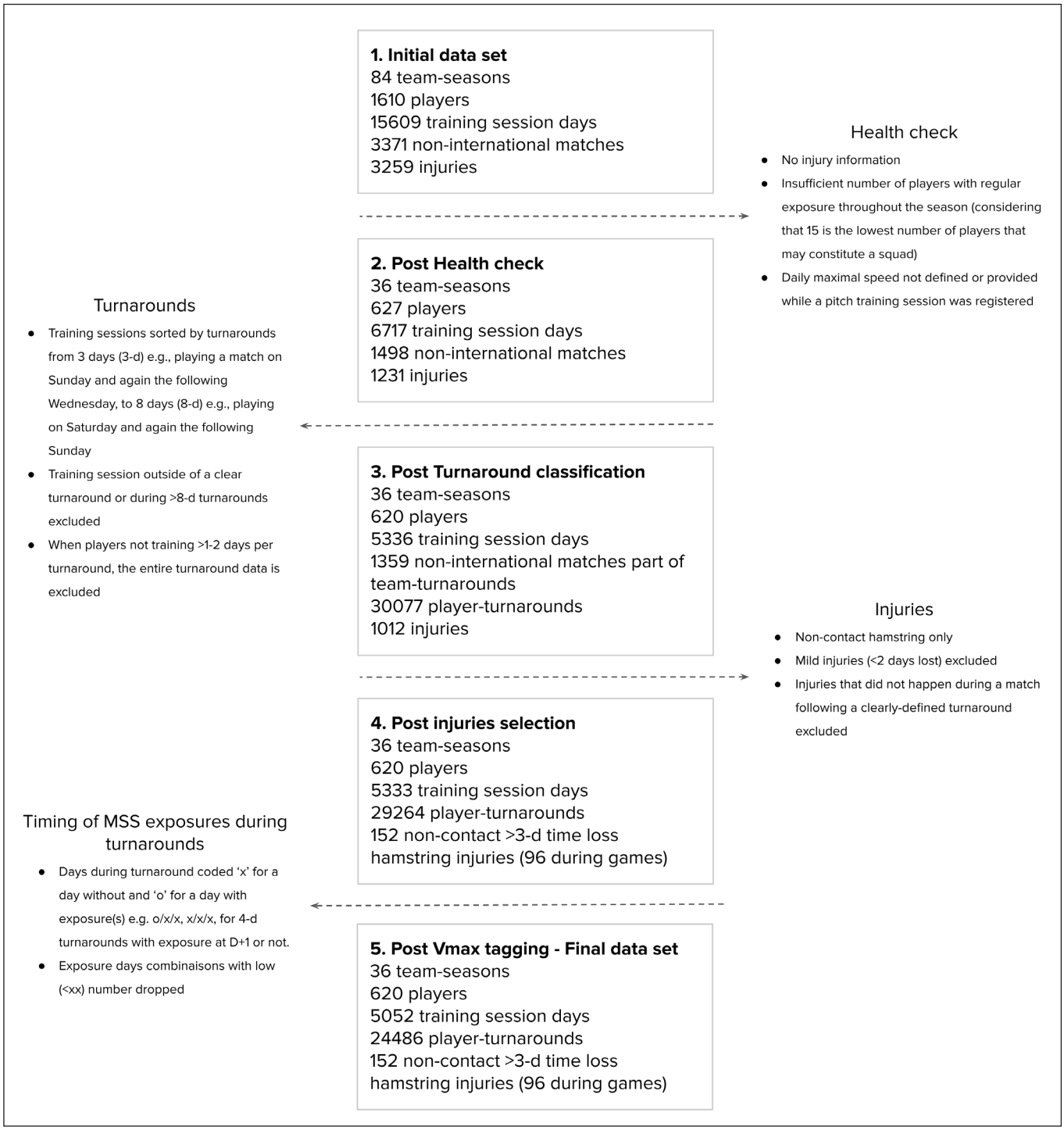


FIG. 1. Flow chart showing the data selection process.

1 or more days following the occurrence [17]. In this study, in contrast, we wanted to focus on hamstring injuries that substantially impact training and match participation; so we only considered injuries that caused a minimum of 3 days of training/playing interruption i.e., ≥ 3-day time loss. In fact, we excluded all mild injuries (< 2 days lost) because injuries in this category could conceivably not have an impact on the next game availability or training dynamic within the same turnaround. In addition, this choice has allowed us to exclude non-substantial injuries that may have resulted in a few days of unavailability due to potential training removal, as it sometimes happens in clubs (i.e., this refers to load management, when players are not injured but taken out of training for precaution – which generally allows them to train fully the next day). If the medical staff registered injuries from the start to the end of the season, we assumed that they strictly adhered to this practice throughout the whole season and that there was no missing data for this metric in this situation.

Only the data of players who played the match that ended the current turnaround were used for analysis, and that was considered as a 'player-turnaround'. Player-turnarounds in which any injuries occurred, other than non-contact time loss hamstring injuries, were removed from the analysis (Figure 1).

Near-to-maximal sprinting speed exposures

The maximal sprinting speed of a player was calculated based on the available data. The ideal scenario was when a club was actually testing for MSS, and in this case, the resulting MSS (collected by GPS) was used for analysis. When proper testing data was not available, we used the average of the three highest speeds reached in the entire GPS data set of each player (after having manually removed all possible erroneous data > 37 km/h) [11]. This later approach (i.e., using the max speed reached by a player in any possible condition measured by a GPS) is actually how people work in clubs – we therefore believe that, despite the possible underestimation of MSS for some players (which will be never known), it makes the results more ecological and reflect well the real-world scenarios. Following both the research literature [8–10] and actual sports science practice in the field, we marked when near-to-MSS exposures occurred using individual speed thresholds at > 85%, > 90% and > 95% of each player's MSS [11].

Near-to-MSS exposures during turnarounds

To understand the frequency of near-to-MSS events, we labelled all individual player training sequences leading to a match by the turnover value and added an indicator as to whether a near-to-MSS event had occurred or not. We coded the entire individual player training sequences leading to the match (as a block of 2 to 7 days for 3- to 8-d turnarounds) as including (true) and not (false) one or more near-to-MSS exposure using > 85%, > 90% and > 95% of each player's MSS [11]. While other speed thresholds could have been used (e.g., 80% MSS), we replicated those used in a previous study on elite football players using the exact same approach [11]. Moreover, using > 85%, > 90% and > 95% reflects very well the common practices in elite football (Figure 1).

Timing of near-to-MSS exposures during the turnarounds

The timing of near-to-MSS exposures was analyzed in two ways. First, to understand the actual programming of near-to-MSS exposures, the individual player near-to-MSS exposure distribution patterns were coded within each microcycle. Each day was labelled as to whether a near-to-MSS exposure occurred, say 'x' for a day without and 'o' for a day with exposure(s), and the frequency of each of the possible combinations e.g. x/x/x, o/x/x, x/o/x, x/x/o, o/o/x, o/x/o, x/o/o, o/o/o for 4-d turnarounds assessed for each turnaround. Second, since coaches generally split the between-match training cycle into two phases (recovery/compensation and intense work from D+1 until D+3, and match preparation from D-2 to D-1), we also grouped together the first training days of each turnaround up to and including D-3 e.g., for a 7-d turnaround we grouped D-6 to D-3 together as D-3, and D-2 and D-1 were considered as unique days. This grouping allowed us to approximate all turnarounds as a standard 3-day turnaround. Since 3-d turnarounds do not include a D-3, this microcycle was only included in a part of this analysis (Figure 1).

Statistical analysis

Considering all the inclusion/exclusion criteria above, the final analysis was run on a total of 620 players participating in 5052 training session days and 1358 non-international matches for a total of 24486 player-turnarounds (3 to 8 days), and 152 hamstring injuries, with 96 of those occurring during matches, as part of the 36 team-seasons (Figure 1).

Since preliminary analysis did not show any trends suggestive of differences between the different leagues or continents, all data were pooled together to increase the sample size.

Injury rates were estimated as follows: number of non-contact time-loss match injuries following a specific training combination for a given turnaround length/number of observations of that specific training combination for this particular turnaround length × 1000 (e.g., number of match injuries following the o/x/x combinations / the number of o/x/x combinations observed × 1000, or (6/900) × 1000 = 6.06). Results are presented as a mean and 95% confidence intervals (using the exact binomial approach) [18]. Substantial differences were assumed when the CIs did not overlap [19].

RESULTS

Near-to-MSS running bouts occurrences

The number of player-sequences within each turnaround examined where > 85%, > 90% and > 95% MSS exposures occurred (true) or not (false) during the training session days leading to the match are shown in Table 1, 2 and 3, respectively. Overall, the proportion of training sequences with at least one near-to-MSS exposure was clearly lower than without, i.e., 40%, 24%, 10% for > 85, > 90 and > 90% MSS, respectively.

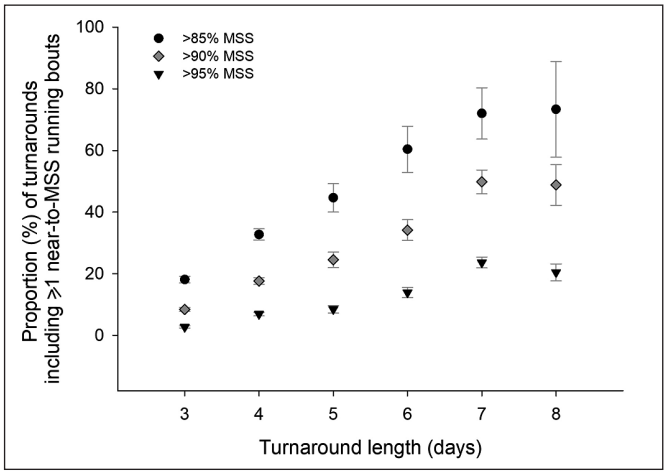


FIG. 2. Proportion of (training) player-sequences including at least one > 85%, > 90% and > 95% MSS running bouts occurrence as a function of the length of the turnaround. Error bars represent 95% confidence intervals.

When looking at the turnaround level, the longer the length of the turnarounds and the lower the speed thresholds, the greater the number (and proportion) of near-to-MSS exposures (Figure 2 and Tables 1–3). For example, when considering > 85% MSS exposures, there were 2 (5-d turnarounds) to 5 × (3-d turnarounds) more sequences without exposures than with. For the longest turnarounds however, sequences with near-to-MSS exposures were 2 (7-d turnaround) to 3 × (8-d turnaround) greater than those without.

Overall occurrence of near-to-MSS running bouts and match hamstring injuries

When looking at all turnarounds pooled, there was no difference in injury rate between training sequences including vs. not including near-to-MSS running exposures, irrespective of the speed threshold considered (Table 1–3). However, when looking within each turnaround, there were no match hamstring injuries when players were exposed to running bouts > 90% MSS (i.e., 5-d turnaround) and > 95% MSS (i.e., 3-, 5- and 6-d turnaround) during the training sessions days leading to matches (Table 3 and Figure 3 lower panel).

In contrast, injury rate was still substantial when considering running bouts > 85%, and when looking at the majority of turnarounds with > 90% MSS exposures (Table 1 and 2, Figure 3 upper and middle panel).

Daily programming of near-to-MSS exposures and match hamstring injuries during 4- to 8-d turnarounds pooled

When looking specifically at the day(s) when > 95% MSS was reached within an average turnaround (i.e., 4- to 8-d turnarounds pooled), there were four main patterns with large sample sizes (n > 200): near-to-MSS occurrence at D-3 and before, n = 990 player-turnarounds and 6 injuries; at D-2, n = 480 and 0 injuries; at D-1, n = 215 and 2 injuries, and no exposure throughout the turnaround, n = 11168 and 46 injuries. The other day-combinations (e.g., occurrences both at D-2 and D-1) had all very low sample sizes (n < 50), for a total of 126 player-turnarounds in total and no injuries; these later combinations were not used for analysis.

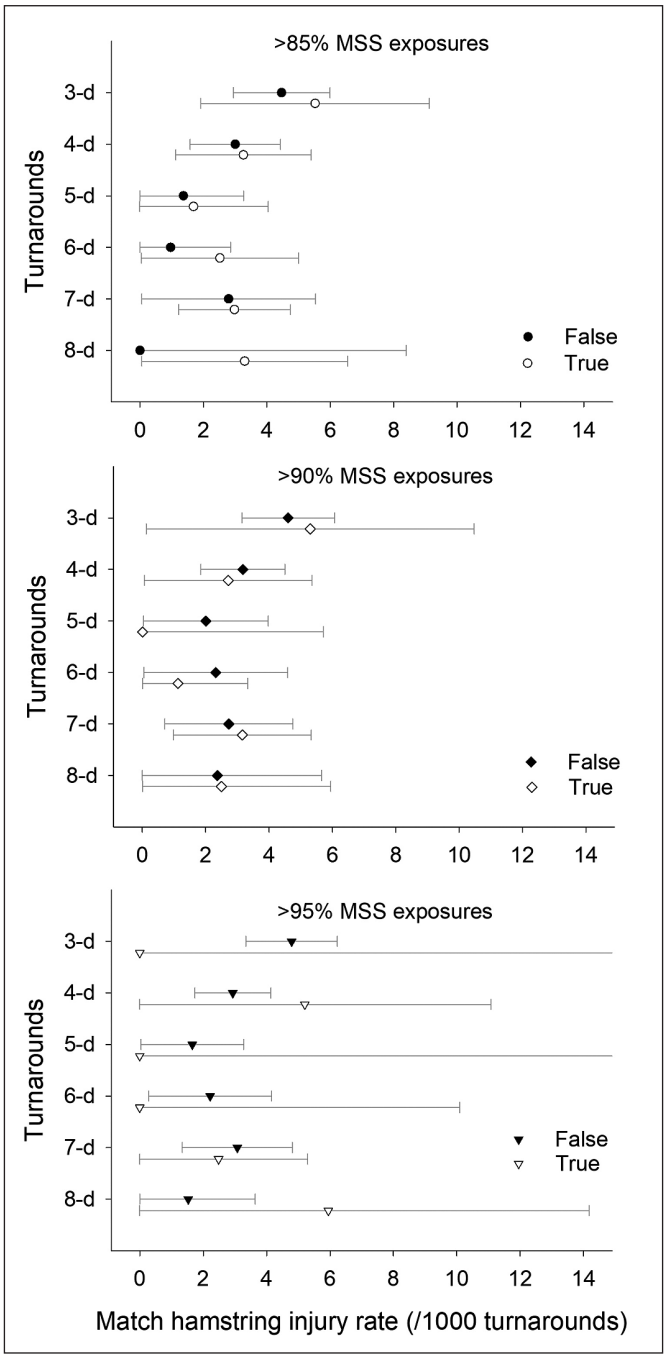


FIG. 3. Match hamstring injury rate (with 95% confidence intervals, and per 1000 turnarounds participation) in players achieving (true) or not (false) > 85% (upper panel), > 90% (middle panel) or > 95% (lower panel) of their maximal sprinting speed (MSS) during the training session days leading to the match, for the different turnarounds examined.

TABLE 1. Number of player-sequences within each turnaround examined where > 85% MSS exposures occurred (true) or not (false) during the training session days leading to the match, number and rate (95% confidence limits, CL) of hamstring injuries during matches.

	Occurrence of > 85% MSS running bouts during the training session days leading to the match	Number of player-sequences	Number of hamstring match injuries	Injury rate/1000 sequences (95% CL)
3 d	False	7389	33	4.5 (2.9–6)
	True	1626	9	5.5 (1.9–9.1)
4 d	False	5663	17	3.0 (1.6–4.4)
	True	2750	9	3.3 (1.1–5.4)
5 d	False	1461	2	1.4 (0–3.3)
	True	1177	2	1.7 (0–4.1)
6 d	False	1037	1	1.0 (0–2.9)
	True	1580	4	2.5 (0.1–5)
7 d	False	1430	4	2.8 (0.1–5.5)
	True	3677	11	3.0 (1.2–4.8)
8 d	False	439	0	0.0 (0–8.4)
	True	1207	4	3.3 (0.1–6.6)
Total	False	17419	57	3.3 (2.4–4.1)
	True	12017	39	3.2 (2.2–4.3)

TABLE 2. Number of player-sequences within each turnaround examined where > 90% MSS exposures occurred (true) or not (false) during the training session days leading to the match, number and rate (95% confidence limits, CL) of hamstring injuries during matches.

	Occurrence of > 90% MSS running bouts during the training session days leading to the match	Number of player-sequences	Number of hamstring match injuries	Injury rate/1000 sequences (95% CL)
3 d	False	8259	38	4.6 (3.1–6.1)
	True	756	4	5.3 (0.1–10.5)
4 d	False	6933	22	3.2 (1.8–4.5)
	True	1480	4	2.7 (0.1–5.3)
5 d	False	1992	4	2 (0–4)
	True	646	0	0 (0–5.7)
6 d	False	1724	4	2.3 (0–4.6)
	True	893	1	1.1 (0–3.3)
7 d	False	2564	7	2.7 (0.7–4.7)
	True	2543	8	3.1 (1–5.3)
8 d	False	843	2	2.4 (0–5.7)
	True	803	2	2.5 (0–5.9)
Total	False	22315	77	3.5 (2.7–4.2)
	True	7121	19	2.7 (1.5–3.9)

TABLE 3. Number of player-sequences within each turnaround examined where > 95% MSS exposures occurred (true) or not (false) during the training session days leading to the match, number and rate (95% confidence limits, CL) of hamstring injuries during matches.

	Occurrence of > 95% MSS running bouts during the training session days leading to the match	Number of player-sequences	Number of hamstring match injuries	Injury rate/1000 sequences (95% CL)
3 d	False	8774	42	4.8 (3.3–6.2)
	True	241	0	0 (0.0–15.2)
4 d	False	7837	23	2.9 (1.7–4.1)
	True	576	3	5.2 (0–11.1)
5 d	False	2416	4	1.7 (0–3.3)
	True	222	0	0 (0.0–16.2)
6 d	False	2254	5	2.2 (0.3–4.2)
	True	363	0	0 (0.0–10.1)
7 d	False	3902	12	3.1 (1.3–4.8)
	True	1205	3	2.5 (0–5.3)
8 d	False	1310	2	1.5 (0–3.6)
	True	336	2	6 (0–14.2)
Total	False	26493	88	3.3 (2.6–4)
	True	2943	8	2.7 (0.8–4.6)

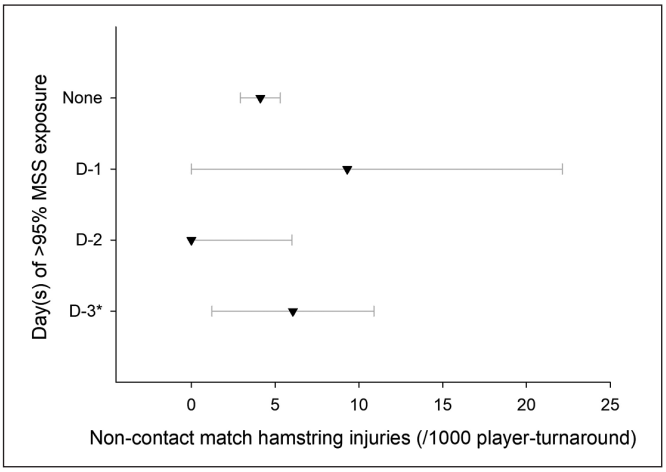


FIG. 4. Match hamstring injury rate (with 95% confidence intervals, and per 1000 player-turnarounds) in relation to the training session day(s) of the turnaround when running bouts > 95% MSS occurred. *Note that D-3 is an aggregation of all training session days of the turnaround before D-3 included (e.g., D-3 summarizes occurrences from D-6 to D-3 for a 7-d turnaround, see methods). Data presented here are from 4- to 8-d turnarounds pooled together; since there is no D-3 data during 3-d turnarounds, data from the entire 3-d turnarounds is excluded from this analysis.

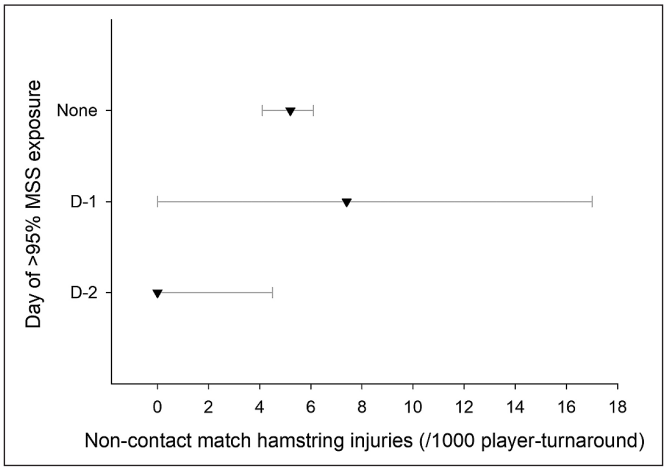


FIG. 5. Match hamstring injury rate (with 95% confidence intervals, and per 1000 player-turnarounds) in relation to near-to-MSS exposure over the last two training day(s) of the turnaround – 3-d to 8-d turnarounds pooled.

When examining the pooled data and comparing these main four patterns, there was no observation of match hamstring injury when > 95% MSS was reached at D-2 – and only for that day (Figure 4). In contrast, injuries still happened when players were not exposed at all, or when these exposures occurred at D-3 and/or earlier within the turnaround. The difference in injury rate between exposures at D-2 vs. D-1 was unclear, likely due to the very low number of injuries for the latter (n = 2).

Daily programming of near-to-MSS exposures and match hamstring injuries during all turnarounds pooled

During 3-d turnarounds (excluded from the above analysis since not including D-3 data), 97% of the player-sequences (n = 5854 player-turnarounds and 42 injuries) did not include 95% MSS exposures, with a hamstring injury rate of 7.1 (6.1–8.3). The numbers of other player-sequences were all below 80, with no injury when > 95%MSS exposures occurred at D-2 or D-1.

When adding the 3-d turnarounds to the previous analysis to increase the number of injuries up to 96 in total (Figure 5, but then removing the D-3 aggregation to be consistent), the trends were similar to those in Figure 4, but there was almost no overlap anymore between the D-2 vs. non-exposure alternatives (Figure 5).

DISCUSSION

This is to our knowledge the first study to describe the occurrence of both non-contact time loss match hamstring injuries and near-to-MSS running bouts within typical turnaround in elite football. The main findings were the following: 1) the large majority of players arrived at the match without having been exposed to near-to-MSS running bouts during the training days of the current turnaround (60% for > 85% MSS, 76% for > 90% MSS and 90% for > 95% MSS), 2) the longer the length of the turnarounds and the lower the speed thresholds, the greater the number (and proportion) of near-to-MSS exposures, 3) for half of the turnarounds examined, there were no match hamstring injuries when players were exposed to running bouts > 95% MSS during training, 4) injuries still occurred during 85% of the turnarounds when there were no or lower relative speed exposures (i.e., > 85 or > 90%) and finally, 5) there were no hamstring injuries when > 95% MSS exposures occurred at D-2, while in contrast, injuries still happened when players were not exposed at all, or when these exposures occurred at D-3 and/or earlier within the turnaround.

Near-to-MSS running bouts occurrences

The most common practice was not to touch near-to-MSS running speeds during training. On average, there were 3 to 10 × more player-turnarounds without near-to-MSS exposures than with, and it was only during the longest turnarounds that these higher running speeds were reached (Figure 1).

The first part of these findings is not surprising and is likely related to the type of drills programmed by most coaches, which do not allow players to reach high speeds [20]. It is now well established that small-side games over small spaces are insufficient in this regard (since players may need to maximally sprint over at least 30 m to reach near-to-MSS speeds [21]), and that often, the only way to get players exposed to near-to-MSS exposures is to either program finishing and transition drills with enough depth [22] and/or individual sprinting drills with or without the ball [23]. The current results (discussed below) lend support to this latter practice.

The influence of the turnaround length on near-to-MSS running bout occurrence is also consistent with the results of our recent survey [12], where the most important drivers for the programming of almost all training contents, and especially those demanding either at the neuromuscular or metabolic level, were reported to be the distance from and to the next match. With not enough time between matches, the emphasis is put on recovery, and practitioners likely consider maximal sprint work too demanding to be performed close to the previous match (the residual fatigue from the previous match may increase injury risk during sprint training itself). In fact, during periods of match congestion, the typical training programming (recovery and easy sessions) does not allow near-to-MSS exposures for starters; those higher-speed exposures may only be possible (and required, see below) for substitutes. When to program those high-speed exposures for subs is another great question for practitioners, and a tentative answer to this will be provided in the last part of the discussion. Finally, these results are also consistent with the common trend found both in the scientific literature [24] and the coaching community, suggesting that 48 h of recovery is generally needed between sprint training sessions/events.

How fast is enough?

While researchers have shown associations between high-speed exposures and injury risk [8–10], there was still a lack of evidence about the minimal intensity required for those runs to be protective. In fact, when it comes to selecting the minimal running velocity that may be associated with reduced hamstring injuries, large variations in relative velocities have been reported, ranging from ≥ 80 [9], to 85 [8] or even 95% of MSS [10]. While the present observational study design precludes the examination of causal relationships, our results show for the first time in a very large sample of elite football players (620 players for a total of 24486 player-turnarounds, Figure 1), that near-to-MSS exposures may need to be performed > 95% MSS during training to be associated with reduced match hamstring injuries (Figure 3). While limited with the present data, the fact that > 95% MSS exposures may be associated with lower injury rates than when only reaching lower relative speeds (85% and 90% MSS), may be related to both higher levels of movements specificity (e.g., leg interaction, elastic energy transfer, reflexes, kinematics, kinetics) [6] and hamstring muscles recruitment that increases exponentially with running speed. In fact, the eccentric (negative) work done at the knee appears to be related to the square of running velocity, which means that toward the attainment of maximal speed (> 95%) the work done is steeply ramping up in a disproportionate manner [25].

Programming near-to-MSS running bouts during the training microcycle

Previous research had suggested the existence of an optimal chronic "dose" in terms of near-to-MSS exposures (i.e., number of weekly exposure [8–10] and/or monthly cumulative distance) [9]. However, this optimal chronic dose is likely specific to each population and context, and it is, therefore, difficult to provide guidelines for all practitioners on the back of those three studies. More importantly, those studies did not provide clear guidelines on how and when to program these near-to-MSS exposures during the weekly microcycle and during turnarounds of different lengths. For these reasons, we believe that our results shed some light on the potential (more) optimal practices in the field.

In this very large data set, there were no match hamstring injuries when near-to-MSS exposures were programmed at D-2. Importantly, this was the case only when near-to-MSS exposures were programmed on that day (Figures 3 and 4). Despite the overlap of the CIs, and acknowledging that descriptive information does not imply causality, this trend suggests that reaching near-to-MSS at D-2 may be the most advantageous strategy with respect to match hamstring injury occurrence.

The actual programming of MSS exposures at D-2 vs. D-3 was actually one of the most debated areas among the practitioners we surveyed [12]. In accordance with the discussion around the alternation of moderate vs. light loads between D-2 and D-1, the sequence order of high-speed running (HSR) and MSS work may have some relevance in the context of injury risk. In fact, since high training loads including HSR and playing over large spaces (which are mainly programmed on D-3, irrespective of the periodization approach [12]) likely induce acute posterior chain fatigue [26], the programming of MSS work the next day (D-2) could expose players to a higher risk of injury during those sprints (assuming that increased neuromuscular fatigue and the changes in mobility/pelvic control that follow such sessions increase injury risk) [27, 28]. For that reason, probably, and in somewhat contradiction with the orientation of the tactical periodization [13] approach that advises planning speed work on D-2 [12], 75% of practitioners reported to program MSS on the same day as HSR (D-3) for both 6- and 7-day turnovers (see Figure 7). This is often achieved during game-play sequences over large spaces [22] and/or through specific speed top-ups post-session when speed targets are not reached [23]. Albeit anecdotal, several practitioners commented in their notes that while they had started to program MSS work at D-2 in the line of the tactical periodization paradigm [13], they ended up changing this specific programming aspect for the above-mentioned reasons [29, 30]. Another important comment in relation to this specific point, is that having 'speed' as the focus of the third acquisition day (following 'strength' and 'endurance' [12] have been sometimes misunderstood: 'speed', as originally introduced, may not necessarily involve MSS work, but could simply refer to the speed of execution, which is often implemented via short attacking transition work and finishing actions.

While the benefit of programming vs. not programming near-to-MSS exposure is straightforward (i.e., preparing muscles to match-specific demands) [5, 6], it remains unclear why exposing players at D-2 may be more appropriate than at D-1 or D-3 and earlier (if this is that clear, considering the CIs overlaps, though). This may be related to the recovery time course of the posterior chain muscles when running near-to-MSS [31]. Exposures at D-1 may not allow those muscles to be completely recovered on match day, and the stimulus (short-term conditioning effect?) may fade away when performed too early in the week (D-3 and earlier), losing its 'protective effect'. Clearly, studies examining this recovery times course in ecological conditions would help better understand this programming aspect. Practically, if D-2 was to be the most appropriate day for near-to-MSS exposures as per the current results (Figure 3 and 4), the programming of the other days of the week may need to be tailored accordingly (i.e., D-4 and D-3), so that players do not reach D-2 with excessive levels of neuromuscular fatigue – not to be at higher risk of hamstring injuries during the exposures themselves. Additionally, while those D-2 exposures may concern the entire squad for long turnarounds (i.e., 6- to 8-d), they may only concern subs for 3- to 5-d turnarounds. In this latter scenario, practitioners reported programming these exposures either on match day immediately post-match, at D+1 or D+2 (in relation to potential days off).[12] The present D-2 practice is then straightforward when that day is either a D+1 (3-d turnaround), or a D+3 (4-d turnaround). For 5-day turnarounds, the option could be to delay this exposure up to D+3/D-2, and/or spread it across multiple days (match day and then again D+3/D-2). As always, players and practitioners' experiences would dictate the possible applications of the present findings in their own context [32].

The lack of clearer differences between the different exposures scenarios (CIs overlap) – despite the very large data set – is likely related to the fact that other factors than the programming of near-to-MSS exposures *per se* may have a greater effect on injury rate, and, in turn, could have diluted/confounded the univariate analysis. This is an important limitation of the present analysis. While we thought to answer the simple question of the programming of near-to-MSS exposures, it is clear that injuries are largely multifactorial in nature [33] and that different chronic training loads and match minutes prior to the turnarounds examined, may also directly affect injury rates. However, we deliberately decided to zoom within each turnaround, since this is the way the very large majority of practitioners operate in the football field, taking and programming one turnaround after the other, with each of them being almost independent of the previous [12]. Additionally, the simultaneous consideration of player profiles (e.g., age, injury history, strength, mobility or flexibility) and other measures of internal training load and responses to load should also improve the analysis – while making the current outputs less straightforward for practitioners. There is in fact a trade-off between the desire for simple questions to have simple answers (e.g., when is it best to sprint?) and more sophisticated analytic approaches that may have more precision but require more effort to interpret in order to provide direct applications

(i.e., results of multivariate analyses can be difficult to translate into simple yes/no answers).

Limitations

In the absence of consistent MSS testing practices across the different teams examined, players' MSS was determined from the available training- and match-related GPS data. While recent results have shown that players may be able to reach their true MSS during matches and some specific training sessions [20], we were not able to verify this at the individual player level. It is therefore possible that inaccurate MSS were used in the analysis, which may have added noise to the results. At least the same (GPS) technology was used across all teams to effectively measure MSS. Importantly, we chose to express injury rate / 1000 turnarounds and not / exposure as it is traditionally done [1, 2]. While it is more intuitive to do so (i.e., exposure to very high-speed running likely is related to the number of hours of training exposure a coach will program), the use of 1000 turnarounds was preferred for the following reasons: 1) exposure duration was not consistently reported across the team, i.e., different ways to report sessions duration (based either on GPS data that may be split differently between practitioners vs. manual entries in teams calendars), and 2) a low number of exposures (e.g., especially for 3-d or 4-d turnarounds; even more when a day off is programmed) can lead to wide variance in the reported rates (potentially very low or very high) with point estimates that are unrepresentative of the true injury rates. Another potential limitation is related to the data used, and the teams it was drawn from i.e., users of the Kitman Labs platform. It is possible that these teams are particularly inclined to embrace evidence-informed practices, and as a result are biased toward the importance of near-to-maximal bouts exposures (as per the literature [8–10]). It is impossible to assess to what extent this is a legitimate concern, but our view is that the cross-section of teams from different leagues across the globe over a number of years makes this less of a concern. Finally, the injury records used for analysis are as good as what practitioners may have registered. Relying on injuries based on practitioners' entries is however common practice [1], and we believe that the value of the information provided, derived from a very large sample size (n = 24486 player-turnarounds), partly outweighs those possible limitations. We will certainly continue to investigate this, and other topics related to planning the microcycle but given the lack of research in this area, we encourage other researchers to think about experimental designs which would provide more insight on how best to adapt the training schedule to the fixture schedule.

Practical applications

While the present observational study design precludes the examination of causal relationships, reaching > 95% of MSS during training may be more protective against non-contact time loss match hamstring injuries than not reaching at least 85% of MSS, or only > 85% or > 90% of MSS. Additionally, programming 95% exposures at D-2 may be the more relevant strategy to decrease the incidence of non-contact match hamstring injuries than no programming exposures at all, or having those exposures at D-3 and/or earlier in the week. If D-2 was to be the most appropriate day for near-to-MSS exposures, the programming of the other days of the week needs to be tailored accordingly (i.e., D-4 and D-3), so that players do not reach D-2 with excessive levels of neuromuscular fatigue – in order not to be at higher risk of hamstring injuries during the exposures themselves.

CONCLUSIONS

Using a very large data set (for a total of 620 players across 5052 training sessions and 36 team-seasons), we showed for the first time that the large majority of players arrived at the match without having been exposed to near-to-MSS running bouts during the training days of the current turnaround. However, while association does not imply causation, match hamstring injuries in elite football were systematically lower when > 95% MSS exposures were programmed at D-2. The present results should nevertheless be taken with caution, and the possibility of false positives should not be disregarded. Future replication studies are required to confirm the present findings on different samples. Whether the current question could one day be answered ecologically using a randomized trial design looks complex at the moment, but this would definitely improve our confidence in the training programming strategy suggested by the present findings.

Acknowledgements

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Conflict of interest statement

The relationship between Kitman Labs and each of its partner organisations is covered by a services contract and data processing addendum which is subject to the relevant regulation (GDPR, HIPAA, HITECH). The specific use of anonymised data for research purposes is agreed upon between the parties, and consent for use in studies of this type is explicitly sought and given. When we process and use data, we protect it, preserve its ownership, and maintain the privacy of the person to who it belongs. Kitman Labs is certified ISO/IEC 27001:2013 (https://www.iso.org/standard/54534.html) compliant.

The authors are all employed by Kitman Labs, a sports performance company used by sports organizations around the world to collect, centralize, and analyse data from multiple sources and aid decision-making (www.kitmanlabs.com). There is no gain for the authors or Kitman Labs, financial or otherwise, as a result of the findings of this study, or would there be if they had been different.

REFERENCES

1. Ekstrand J, Spreco A, Bengtsson H, Bahr R. Injury rates decreased in men's professional football: an 18-year prospective cohort study of almost 12,000 injuries sustained during 1.8 million hours of play. Br J Sports Med. 2021; 55(19):1084–1091.
2. Buchheit M, Eirale C, Simpson BM, et al. Injury rate and prevention in elite football: Let us first search within our own hearts. Br J Sports Med. 2019; 53(21):1327–1328.
3. Buckthorpe M, Wright S, Bruce-Low S, et al. Recommendations for hamstring injury prevention in elite football: Translating research into practice. Br J Sports Med. 2019; 53(7):449–456.
4. Bourne MN, Timmins RG, Opar DA, et al. An evidence-based framework for strengthening exercises to prevent hamstring injury. Sports Med. 2018; 48(2):251–267.
5. Butler S, Running fast: The cause, the cure and a vaccine. BJSM Blog; 19 March, 2019; https://blogs.bmj.com/bjsm/2019/03/19/running-fast-the-cause-the-cure-and-a-vaccine.
6. Edouard P, Mendiguchia J, Guex K, et al. Sprinting: A potential vaccine for hamstring injury? Sport Perform Sci Rep. 2019; (48):v1.
7. van den Tillaar R, Solheim JAB, and Bencke J. Comparison of hamstring muscle activation during high-speed running and various hamstring strengthening exercises. Int J Sports Phys Ther. 2017; 12(5):718–727.
8. Colby MJ, Dawson B, Peeling P, Heasman J, Rogalski B, Drew MK, Stares J. Improvement of Prediction of Noncontact Injury in Elite Australian Footballers With Repeated Exposure to Established High-Risk Workload Scenarios. Int J Sports Physiol Perform. 2018; 13(9):1130–1135.
9. O'Connor F, Thornton HR, Ritchie D, et al. Greater association of relative thresholds than absolute thresholds with noncontact lower-body injury in professional Australian rules footballers: Implications for sprint monitoring. Int J Sports Physiol Perform. 2019; 5(2):204–212.
10. Malone S, Roe M, Doran DA, et al. High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. J Sci Med Sport. 2017; 20:250–4.
11. Buchheit M, Simpson, BM, Hader, K., and Lacome, M. Occurrences of near-to-maximal speed running bouts in elite soccer: insights for training prescription and injury mitigation. Sci Med Football. 2021; 5(2):105–110.
12. Buchheit M, Sandua M, Berndsen J, Shelton, Smith S, Norman D, McHugh D, Hader K. Loading patterns and programming practices in elite football: insights from 100 elite practitioners. Sport Perform Sci Rep. 2021; (153):v1.
13. Delgado Bordonau JL and Mendez Villanueva JA. Tactical Periodization – A Proven Successful Training. SoccerTutor.com Ltd; 2018.
14. Verheijen R. The Original Guide to Football Periodisation Part 1. World Football Academy; 2014.
15. Tarragó JR, Massafret-Marimón ML, Seirul·lo F and Cos F. Entrenamiento en deportes de equipo: el entrenamiento estructurado en el FCB. Apunts. Educacion Fisica y Deportes. 2019; (137):103–114.
16. Bahr R, Clarsen B, Derman W, Dvorak J, Emery CA, Finch CF, Hägglund M, Junge A, Kemp S, Khan KM, Marshall SW, Meeuwisse W, Mountjoy M, Orchard JW, Pluim B, Quarrie KL, Reider B, Schwellnus M, Soligard T, Stokes KA, Timpka T, Verhagen E, Bindra A, Budgett R, Engebretsen L, Erdener U, Chamari K. International Olympic Committee consensus statement: methods for recording and reporting of epidemiological data on injury and illness in sport 2020 (including STROBE Extension for Sport Injury and Illness Surveillance (STROBE-SIIS)). Br J Sports Med. 2020; 54(7):372–389.
17. Winter EM, Maughan RJ. Requirements for ethics approvals. J Sports Sci. 2009; 27(10):985.
18. Wilson EB. "Probable inference, the law of succession, and statistical inference". J Am Stat Assoc. 1927;22 (158): 209–212.
19. Cumming G.- Understanding The New Statistics. Effect Sizes, Confidence Intervals, and Meta-Analysis. Routledge; 2011.
20. Kyprianou E, Di Salvo V, Lolli L, Al Haddad H, Villanueva AM, Gregson W, Weston M. To Measure Peak Velocity in Soccer, Let the Players Sprint. J Strength Cond Res. 2022; 36(1):273–276.
21. Buchheit M, Simpson BM, Peltola E, Mendez-Villanueva A. Assessing maximal sprinting speed in highly trained young soccer players. Int J Sports Physiol Perform. 2012; 7(1):76–8.
22. Asian-Clemente J, Rabano-Munoz A, Requena B, Suarez-Arrones L. High-speed training in a specific context in soccer: transition games. Int J Sports Med. 2022 Sep; 43(10):881–888.
23. Jeffreys I, Huggins S, and Davies N. Delivering a game speed-focused speed and agility development program in an English Premier League soccer academy. Strength Cond J. 2017; 40(3):23–32.
24. Haugen T, Seiler S, Sandbakk Ø, Tønnessen E. The Training and Development of Elite Sprint Performance: an Integration of Scientific and Best Practice Literature. Sports Med Open. 2019 Nov 21; 5(1):44.
25. Schache AG, Blanch PD, Dorn TW, Brown NA, Rosemond D, Pandy MG. Effect of running speed on lower limb joint kinetics. Med Sci Sports Exerc. 2011; 43(7):1260–71.
26. Buchheit M, Lacome M, Cholley Y, Simpson BM. Neuromuscular Responses to Conditioned Soccer Sessions Assessed via GPS-Embedded Accelerometers: Insights Into Tactical Periodization. Int J Sports Physiol Perform. 2018; 13(5):577–583.
27. Verrall GM, Slavotinek JP, Barnes PG, Fon GT, Spriggins AJ. Clinical risk factors for hamstring muscle strain injury: a prospective study with correlation of injury by magnetic resonance imaging. Br J Sports Med. 2001; 35(6):435–9.
28. Hennessey L, Watson AW. Flexibility and posture assessment in relation to hamstring injury. Br J Sports Med. 1993; 27(4):243–6.
29. Kyprianou E. Let's talk about weekly plans in soccer. EK Sports Performance Blog; 8 June 2020; http://www.eksportsperformance.com/ekspjournal//does-practice-only-make-you-better-e4g96.
30. Kyprianou E. Balancing Physical & Tactical Load in Soccer. A practical guide for soccer practitioners. Complementary training. 2019; https://complementarytraining.net/product/balancing-physical-tactical-load-in-soccer/.
31. Rhodes D, McNaughton L, Greig M.. The temporal pattern of recovery in eccentric hamstring strength post-soccer specific fatigue. Res Sports Med. 2019; 27(3):339–350.
32. Buchheit M, Allen SV. To Optimize? First, Empathize. Int J Sports Physiol Perform. 2022; 17(4):505–506.
33. McHugh D & Buchheit, M. Analytics For Sport Performance And Health: A Reality Check. Kitman Labs Website; April 4; 2022. Available from: https://www.kitmanlabs.com/white-papers/analytics-for-sport-performance-and-health-a-reality-check/

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Effects of free play or artificial rules on young soccer players' individual tactical behaviour: a one-by-one analysis

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ABSTRACT: This study assessed the effects of playing freely and introducing artificial rules on individual tactical behaviour during the team-possession game phase in two youth soccer categories. Thirty-two developmental players from U-14 and U-16 teams participated in the study, which consisted of four identical training sessions and two test sessions performed before and after the intervention. Each team was divided into two balanced groups, free-play and conditioned, that faced each other during three eight-a-side games (Gk + 7 vs 7 + Gk) in all training sessions. The free-play groups played freely, while the conditioned ones did so constrained by artificial rules. Individual tactical behaviour was assessed during a non-constrained eight-a-side match by the distance to centroid, spatial exploration index, their entropy measures, and the regularity of each player's displacement on the length and width of the pitch using a local positioning system. In addition to the average outcomes of all the players all together, the one-by-one analysis considered the mean values of each player to appraise individual responses. While the average outcomes of all the players in both groups and categories barely changed (Cohen's $d \leq$ small), with a very high inter-player variability, the one-by-one analysis revealed that the training intervention affected each player's tactical behaviour differently. Introducing artificial rules decreased and raised considerably (Cohen's $d \geq$ moderate) in-width and exploratory regularities of most U-14 and U-16 players, respectively. Therefore, assessing the training effects of game-based interventions from the individual to the whole team may provide unique and meaningful insight regarding the tactical competence of each player.

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INTRODUCTION

Ecological dynamics has become a prominent theoretical approach to understanding, from a functional perspective, how and why team-sports players behave and interact in training and performance scenarios [1, 2]. Rooted in ecological dynamics, the nonlinear pedagogy framework [3–5] endorses the design of representative learning environments that simulate competition through the manipulation of task constraints [6–8]. Coaches can implement task constraints to offer players opportunities for action (viz., affordances) that solve the training problem [7, 9]. Task constraints modify the player relation with *teammates* and *adversaries*, *time*, *space*, and *equipment/mobile* to conduct players' emergent tactical behaviour, their spatiotemporal positioning and organization adapting to the specific structural traits of each sport [10], during practice [11, 12].

Recent systematic reviews and meta-analyses [13, 14] reported that task constraints were habitually manipulated in soccer training because of their relevance and easy manageability, those that alter the playing pitch configuration and the number of players involved being the most investigated. Several studies have assessed the acute effects of modifying the playing space on young soccer players' tactical behaviour and suggested that positioning the goals diagonally [15] or from throw-in line to throw-in line [16], and removing pitch lines (i.e., only corner markings) [17] increased players' dispersion

and impaired synchronization, mostly longitudinal, while adding spatial references such as corridors and sectors helped players to move more regularly but not with greater synchrony [18]. For numerical constraints, it seems that the disequilibrium caused by temporary numerical imbalances [19] or the inclusion of floaters [20] led to players playing wider and slightly prompting their exploratory behaviour. Regarding mobile manipulation, Santos et al. [21] suggested that six-a-side games with a handball and, particularly, rugby balls induced players to explore less and play closer in an unpredictable way. Introducing new artificial rules, coach-made conditions not inherent to the laws of the game are also typical task constraints [6, 13, 14] that may delimit or inhibit specific actions while enhancing or channelling others [7]. For instance, limiting the number of ball touches to one or two during five-a-side games raised players' synchronization, mainly in-width [22].

Despite the fact that several studies have evaluated the acute effects of wide-ranging task constraints on young soccer players' tactical behaviour from pitch-positioning-derived variables [13, 14], research about structured training interventions looking for chronic effects or behavioural adaptations to prove the effectiveness of task constraints in applied settings such as soccer academies is still scarce [7]. Santos et al. [23] and Coutinho et al. [24] designed 40 and 20 constraint-based training sessions of approximately 30 min for young Portuguese soccer players and only for attackers, respectively, under the differential learning approach to foster players' tactical adaptability during small-sided and conditioned games. Both studies compared the chronic effects of traditional training (i.e., control group) with game-based training constrained by the modification of the number of players, playing pitch, number and type of the ball, scoring targets, body restrictions or game rules (i.e., experimental group) and found that central tendency tactical measures barely changed after the differential learning programme, with entropy decrease suggesting a trend in behavioural regularity [23, 24]. More specifically, recent studies assessed the short-term training effects of a single type of task constraint, introducing artificial rules, at different organizational levels [25, 26]. The training intervention applied the nonlinear pedagogy principles of representativeness and constraints manipulation on medium-sided games that faced free-play and conditioned groups of the same team: the first played freely and the second constrained by artificial rules that modified the cooperative motor interactions between teammates. The results indicated that playing under the conditions of artificial rules consolidated collective tactical behaviour during the team-possession game phase [25], while analysing the same intervention at a meso-level [26] revealed that free play could also be valuable to boost team lines' regularity. Given the behavioural differences at macro- [25] and meso-levels [26], assessing the training effects of free play and artificial rules at the micro-level would be pertinent to provide meaningful insights to coaches for optimizing the training strategies at a more detailed level [2, 27].

In fact, Davids et al. [28] underline that the training strategies need to be designed, selected, and implemented expressly for individual learners to lead each of them to seek an appropriate and individualised functional solution to the problem laid out by the training task, rather than automatizing the same actions for all the players. Introducing or even suppressing (i.e., free play) different task rules for each one of the players during the same game-based task may condition their affordances to modulate their tactical response. For instance, focusing on the team-possession game phase, coaches could manipulate the number of touches, the interaction between players or the use of space by well-known and habitually used artificial rules to compel players to spread out and explore more or to look around for more and better opportunities, guiding their individual tactical behaviour. The individualised analysis makes sense as only a few players in the youth categories become professional, increasing the chances to do so step-by-step [29]. The percentage of European players who signed a contract with a professional club that competed in national leagues increased category-by-category: 3.52% from U-12s, 4.13% from U-14s, 6.63% from U-17s, 16.0% from elite U-19s and between 32.1% and 41.8% of the players belonging to a reserve team of elite Spanish soccer clubs [30–33]. Thus, given that developing tactically competent soccer players requires attending to their individual needs and characteristics, such as playing style, position, or maturity [1, 6–8, 28], and many players will probably not continue in the club in the following years [29–33], assessing the chronic effects of game-based interventions (e.g., free play vs artificial rules) on individual tactical behaviour through one-by-one analysis seems pertinent. The one-by-one analysis considers each player separately to appraise their tactical behaviour and determine individual responses to the same training intervention according, for example, to the playing position.

This study aimed to assess the training effects of modified games playing freely and introducing artificial rules on individual tactical behaviour during the team-possession game phase in two youth soccer categories.

MATERIALS AND METHODS

Subjects

Thirty-two Spanish, male youth soccer players from U-14 and U-16 teams of the same club took part in the study. The *a priori* necessary sample size was computed with the G*Power stand-alone power analysis program (version 3.1.9.7 for Windows, Institut für Experimentelle Psychologie, Düsseldorf, Germany) for an effect size of 0.50, an α of 0.05, and a power of 0.80 (1–β) [34]. The total size computed by this method was a minimum of 26 players. The sampling used for the research was non-probability, purposive or convenience sampling and participants were recruited from one of the most representative soccer academies of the region affiliated to a Spanish First Division Club (*LaLiga*). In order not to modify the natural groups for the study, all the players of both teams fully available (i.e., not ill, not injured, nor returning from injury) took part in the intervention (U-14s, $n = 16$; age 13.0 ± 0.40 years; height 1.56 ± 0.07 m; body mass 46.7 ± 5.90 kg; years competing in

soccer: 6 ± 1 years; and U-16s, n = 16; age 15.9 ± 0.40 years; height 1.70 ± 0.07 m; body mass 57.9 ± 8.30 kg; years competing in soccer: 8 ± 1 years). U-14 and U-16 teams trained twice a week (Tuesdays and Thursdays at 18:00) for ~75 min on an outdoor artificial-turf pitch for 32 and 38 weeks a season, respectively, and competed at weekends in official matches (U-14s for 70 and U-16s for 80 min 11-a-side matches). Both teams competed at the highest competition level for their age, and the U-14s were second in the regular league, so they classified for the Champions League, while the U-16s ended up sixth out of 16 in their league. Participants had soccer identified as their specific sport, trained more than 150 min per week, and competed at the highest local-level competition for their age; they were in Tier 2: Trained/Developmental according to the Participant Classification Framework provided by McKay et al. [35].

The parents, coaches, players, and the club were fully informed about the research procedures, and signed written consent forms for the children's participation were gathered. All of the participants and their legal guardians were notified about the risks and benefits, and were told that they could withdraw from the study at any time. All of the procedures were carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki, 2013) and the standards of the Ethics Committee for Research involving Human Beings of the University of the Basque Country (Code M10_2018_178).

Study design

Using a controlled study design, each team was divided into two groups according to the coaches' perception of the players' technical and tactical level and their position [25, 36], pre-intervention values for the pitch-positioning-derived variables being assessed similarly for both groups (see Results): free-play and conditioned groups (i.e., U-14s-free and U-14s-conditioned; U-16s-free and U-16s-conditioned). Also, playing time in the official matches during the intervention period remained similar for both free-play (70% and 74% of the total match minutes for U-14s-free and U-16s-free, respectively) and conditioned (72% and 69% of the total match minutes for U-14s-conditioned and U-16s-conditioned, respectively) groups. The study took place in the final part of the 2018–2019 season (May) and consisted of four identical training sessions carried out twice a week (Tuesdays and Thursdays) on their habitual training pitch (length = 60 m; width = 40 m) from 18:00 to 19:00, with two test sessions of ~30 minutes (from 18:00 to 18:30) performed before (pre-test) and after (post-test) the training intervention.

The four training sessions that comprised the intervention started with an eight-minute warm-up based on the FIFA 11+ protocol [37] and five minutes of the game tail-tag [38] played by all the players together. After four minutes, the free-play and conditioned groups of each competition category faced each other (i.e., U-14s-free vs U-14s-conditioned and U-16s-free vs U-16s-conditioned) during three seven-minute medium-sided games (Gk + 7 vs 7 + Gk) [39] in all training sessions in the same order, with four minutes of ad libitum rest between them. The free-play group played freely without restrictions and without knowing the playing conditions of the conditioned group, which played under the conditions of artificial rules as key task constraints [3, 6]. Each of the three artificial rules employed in each of the three eight-a-side matches [25] reshaped the relevant structural traits [12, 40] of the modified game setting to attempt to constrain players' individual tactical behaviour after the training intervention:

1. Relationship with the equipment/mobile: obligation to touch the ball at least three times before passing or shooting at goal could force players to explore more.
2. Relationship with teammates: the player in possession cannot return the ball to the player who had passed to them, which would commit the rest of the teammates to spread out to offer more passing opportunities.
3. Relationship with the space: after passing the ball back (towards their own goal), the next pass had to be a forward pass, which might enhance the regularity of each player's displacement, especially in-length.

Both free-play and conditioned groups used the same 1-3-3-1 team formation throughout the training intervention with one goalkeeper (Gk), one central defender (CD), two lateral defenders (LD), one central midfielder (CM), two lateral midfielders (LM), and one forward (F), with all the players in their usual playing position. The official game rules, including the offside rule set on the halfway line, were applied during the game. The ball was the standard size (nº 5) and was the same one that was used in official matches by both competition categories. The team coaches presented the training tasks, reminding the free-play group to play freely without restrictions and introducing the artificial rules to the conditioned group. If a player did not respect these rules, then one coach who acted as a referee awarded the opposing team with an indirect free kick from where the offense occurred. Except for this, they remained silent on each lateral line to avoid influencing the participants' behaviour with their comments or corrections during the game [24, 25]. The coaches provided several balls to avoid losing time and controlled the duration of each task.

The test sessions were carried out on the same pitch and at the same hour before (pre-test) and after (post-test) the intervention. As in training, players had a 48-hour recovery between the previous session or match and the test sessions and committed to continuing with their daily activities, abstaining from doing uncommon and too intense exercises during the intervention period. To control the stimulus of the players by a controlled activity, both test sessions started with the FIFA 11+ warm-up programme [37] and a 30-meter sprint. Then, the individual tactical behaviour was assessed during a non-constrained seven-minute eight-a-side match, in which the free-play and conditioned groups of each competition category faced each other. The game rules, team formation and playing positions, ball replacement, and the coach intervention conditions were the

same as those used in the training intervention during the pre-test and the post-test. Similarly as in the intervention, two researchers (AGA and ALA) were present pitch-side from the start to the end of the training and test sessions, and noted all of their observations in a field diary to guarantee the fidelity of the research procedure.

Data collection

Positional data were gathered to assess individual tactical behaviour by a time-motion tracking system using a local positioning system (LPS) (IMU; WIMU PRO, RealTrack Systems, Almeria, Spain) based on ultra-wideband (UWB) technology. The UWB system consists of a reference system and tracking devices that were worn in a special vest by all of the players, who had been previously familiarized with the use of these devices during several training sessions. The reference system is composed of antennae that are transmitters and receivers of the radio-frequency signals [41]. The antennae (mainly the master antenna) computerize the position of the devices that are in the playing area, while the device receives that calculation using time difference of arrival (TDOA) [42, 43]. These lightweight (70 g) inertial devices of $81 \times 45 \times 16$ mm with 2 GB flash memory and five-hour battery life incorporate both GPS (10 Hz) and UWB (18 Hz) sensors, together with triaxial accelerometers (four sensors < 1000 Hz), triaxial gyroscopes (three sensors < 1000 Hz), and triaxial magnetometers (160 Hz) [41, 42]. Six antennae forming a hexagon to better signal emission and reception at a height of three meters and held by a tripod were set up on a training pitch away from metallic materials, with similar environmental conditions on both days (cool temperatures: 15.9°C and 17.3°C; humidity gradients: 60% and 51%; and slow air circulation: 12.3 $^{km}/_{h}$ and 11.8 $^{km}/_{h}$ for pre-test and post-test sessions, respectively) that allow easier positioning [41, 42]. The validity and inter-unit reliability of this equipment for tactical analysis had been confirmed during a continuous test composed of five courses (i.e., perimeter of the pitch course, half-way line, centre circle, perimeter of the penalty area, and semi-circular penalty area) and a small-sided game that emulated real conditions [41], with a mean absolute error of less than 10 cm (*x* coordinate: 9.57 ± 2.66 cm; *y* coordinate: 7.15 ± 2.62 cm) and a typical error of measurement of 1–1.15% for surface area. Furthermore, WIMU PRO had been certified the International Match Standard (IMS) from FIFA and, according to a survey to assess the quality of the data [43] to measure the players' tactical behaviour, data collection was satisfactory (90% score).

The raw data were sampled at 18 Hz and then interpolated to obtain 100 data points per second for better computational time management and easier comparison with existing studies with a similar methodology [26]. Additionally, testing of eight-a-side matches was recorded at 240 frames per second (fps) at FullHD quality (1920×1080 pixels) with two iPhone 7 Plus devices (Apple Inc., Cupertino, Ca, USA) that were located four meters above the playing pitch to differentiate the team-possession and non-possession game phases. The data were downloaded and synchronized with the video using S PRO software (RealTrack Systems, Almeria, Spain) and processed using MATLAB (MATLAB [2018a], The MathWorks Inc., Natick, Ma, USA) following the existing procedures [44].

Pitch-positioning-derived variables

All of the measurements were carried out for the team-possession game phase. The criteria established by Castellano [45] were applied to differentiate ball possession for each team and exclude stoppages in play. Given the difference in length of the several ball possessions, only those that lasted more than five seconds (i.e., 500 data points) were considered for further analysis [46]. Intra- and inter-observer agreement was evaluated using Cohen's kappa statistic to ensure the reliability of data collection and for differentiation of team-possession and non-possession game phases. The same randomly selected match was observed twice by AGA and once by ALA using the LINCE PLUS Research Software for Behaviour Video Analysis [47]. The corresponding calculations were performed in the free software GSEQ5.1 [48, 49]. Satisfactory intra- and inter-observer agreement was obtained for the alignment of ball possessions (intra-observer: 0.93 ± 2 events tolerance, inter-observer: 0.90 ± 2 events tolerance) and the duration of the team-possession game phase (intra-observer: 0.96 ± 2 seconds tolerance, inter-observer: 0.94 ± 2 seconds tolerance) [50].

Individual tactical behaviour was assessed by: 1. the distance of each outfield player to the team centroid (DC – Formula 1); 2. spatial exploration index (SEI – Formula 2) – the distance of each outfield player to their own mean position throughout the game; and 3. the regularity of each outfield player displacement on the length and width of the pitch [27, 51]. To better describe the stochastic and complex nature of the soccer game [27, 51], the outcomes were processed using both central tendency and approximate entropy normalized (ApEn *norm*) measures [46], which were calculated by MATLAB with a vector length (m) of two and a tolerance (r) of $0.2 \times SD$ of the time series to assess the predictability of the individual tactical behaviour (Formula 3). Higher entropy values reflect more unpredictability, while lower values manifest more regularity.

$$DC_{k(i)} = \sqrt{(P_{xk(i)} - C_{x(i)})^2 + (P_{yk(i)} - C_{y(i)})^2}$$

Formula 1 – Distance to centroid (DC) calculation, where *C* represents the centroid or geometrical centre of the team at any given instant *i*, *k* the individual player for whom the DC is being calculated, *Px* and *Py* the players' position coordinates for the × and *y* axis, respectively, at instant *i*.

$$SEI_{k(i)} = \sqrt{\left(P_{xk(i)} - P_{xk(m)}\right)^2 + \left(P_{yk(i)} - P_{yk(m)}\right)^2}$$

Formula 2 – Spatial exploration index (SEI) calculation, where *Px* and *Py* represent the players' position coordinates for the × and *y* axis, respectively, at instant *i* or as a mean (*m*) position, and *k* the individual player for whom the SEI is being calculated.

$$ApEn_{norm} = \frac{ApEn(2, 0.2, N)_{TS}}{\sum_i^{100} ApEn(2, 0.2, N)_{U_i}/100}$$

Formula 3 – Normalized approximate entropy (ApEn *norm*) calculation, where the regularity of the time series TS is normalized using the ratio between the original ApEn and the mean ApEn calculated in 100 random series U_i.

Statistical analysis

Descriptive outcomes of each variable (means ± standard deviations [*SD*]) were computed using the mean value for each ball possession with more than 500 data points (i.e., five seconds). Intra-group and intra-player practical differences were assessed by Cohen's *d* effect size and percentage change from the pre-test to the post-test. The thresholds for effect size (*d*) were 0.25, trivial; 0.50, small; 1.0, moderate; and > 1.0, large [52]. The coefficient of variation (CV % = (SD/mean) × 100) for average outcomes was also calculated to assess inter-player variability. Apart from the average outcomes of all of the players all together, the one-by-one analysis considered the mean value of each player for each ball possession of the team-possession game phase to assess and compare their individual tactical response (means ± *SD*) from the pre-test to the post-test. Statistical procedures were performed with jamovi computer software (The jamovi project [2022], version 2.3.2).

RESULTS

No considerable differences (Cohen's $d \leq$ small) between intervention groups of U-14s (DC $d = 0.26$; DC $_{ApEn\ norm}$ $d = 0.10$; SEI $d = 0.37$; SEI $_{ApEn\ norm}$ $d = 0.10$; length regularity [ApEn *norm*] $d = 0.13$; and width regularity [ApEn *norm*] $d = 0.13$) and U-16s (DC $d = 0.18$;

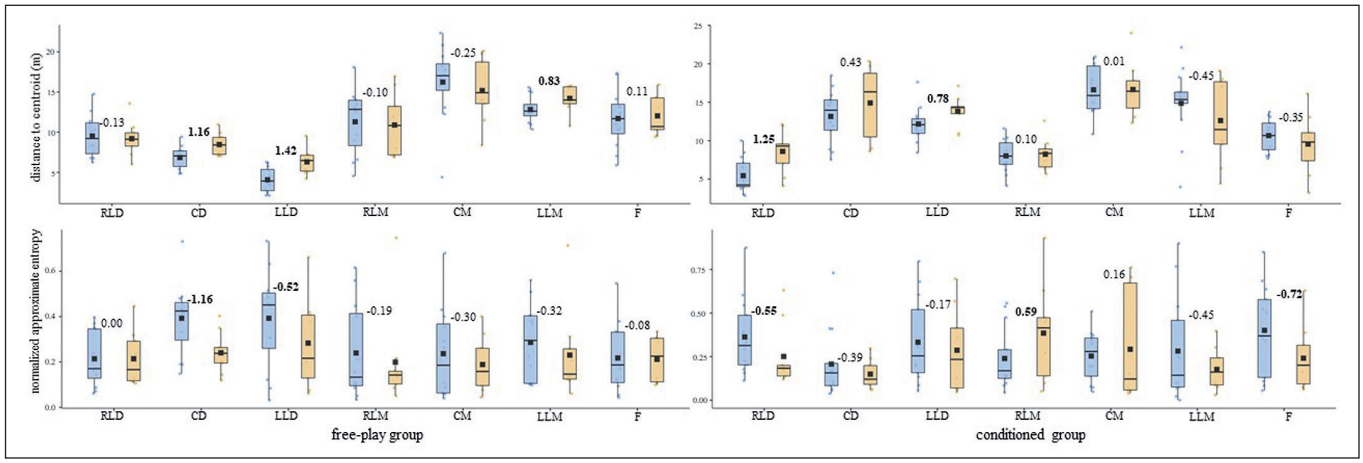


FIG. 1a. U-14s players' distance to centroid central tendency and normalized approximate entropy (arbitrary units) measures for both free-play and conditioned groups. Intra-player comparison (Cohen's *d*) between pre-test (blue) and post-test (orange) boxes, moderate – large effect sizes in bold. RLD = right lateral defender; CD = central defender; LLD = left lateral defender; RLM = right lateral midfielder; CM = central midfielder; LLM = left lateral midfielder; F = forward.

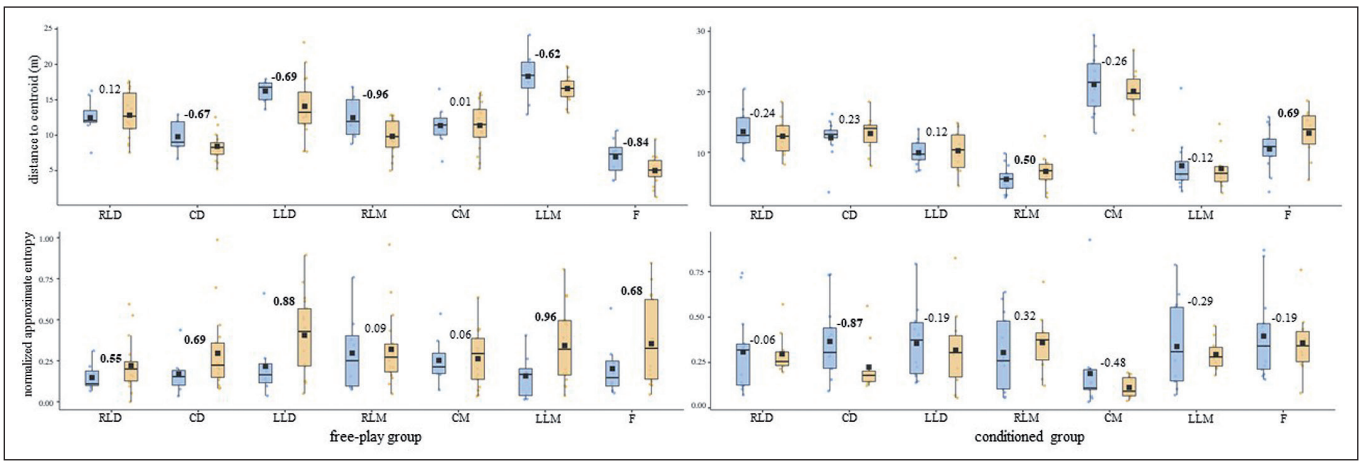


FIG. 1b. U-16s players' distance to centroid central tendency and normalized approximate entropy (arbitrary units) measures for both free-play and conditioned groups. Intra-player comparison (Cohen's *d*) between pre-test (blue) and post-test (orange) boxes, moderate – large effect sizes in bold. RLD = right lateral defender; CD = central defender; LLD = left lateral defender; RLM = right lateral midfielder; CM = central midfielder; LLM = left lateral midfielder; F = forward.

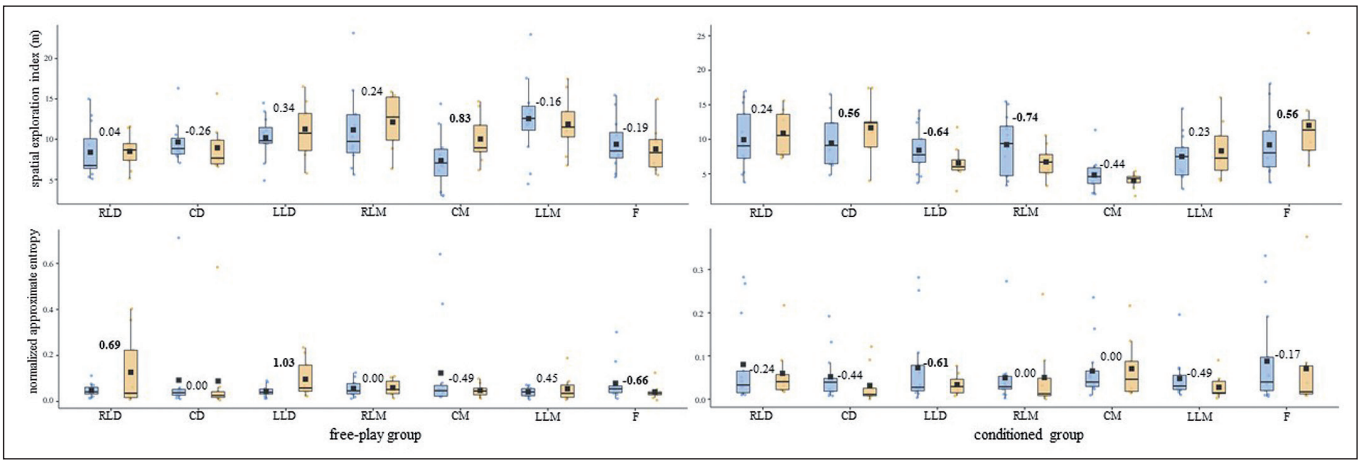


FIG. 2a. U-14s players' spatial exploration index central tendency and normalized approximate entropy (arbitrary units) measures for both free-play and conditioned groups. Intra-player comparison (Cohen's *d*) between pre-test (blue) and post-test (orange) boxes, moderate – large effect sizes in bold. RLD = right lateral defender; CD = central defender; LLD = left lateral defender; RLM = right lateral midfielder; CM = central midfielder; LLM = left lateral midfielder; F = forward.

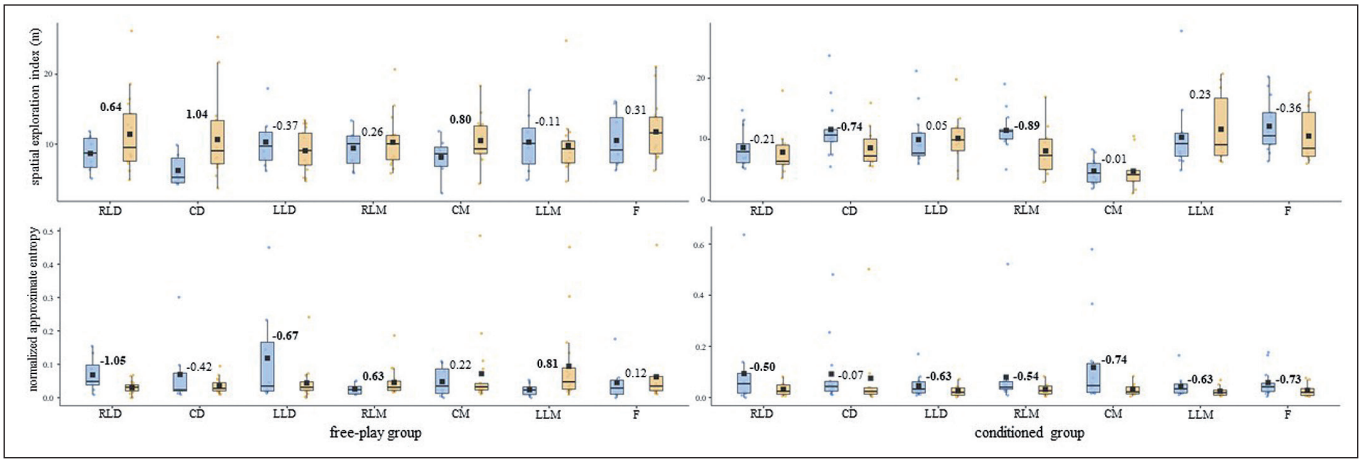


FIG. 2b. U-16s players' spatial exploration index central tendency and normalized approximate entropy (arbitrary units) measures for both free-play and conditioned groups. Intra-player comparison (Cohen's *d*) between pre-test (blue) and post-test (orange) boxes, moderate – large effect sizes in bold. RLD = right lateral defender; CD = central defender; LLD = left lateral defender; RLM = right lateral midfielder; CM = central midfielder; LLM = left lateral midfielder; F = forward.

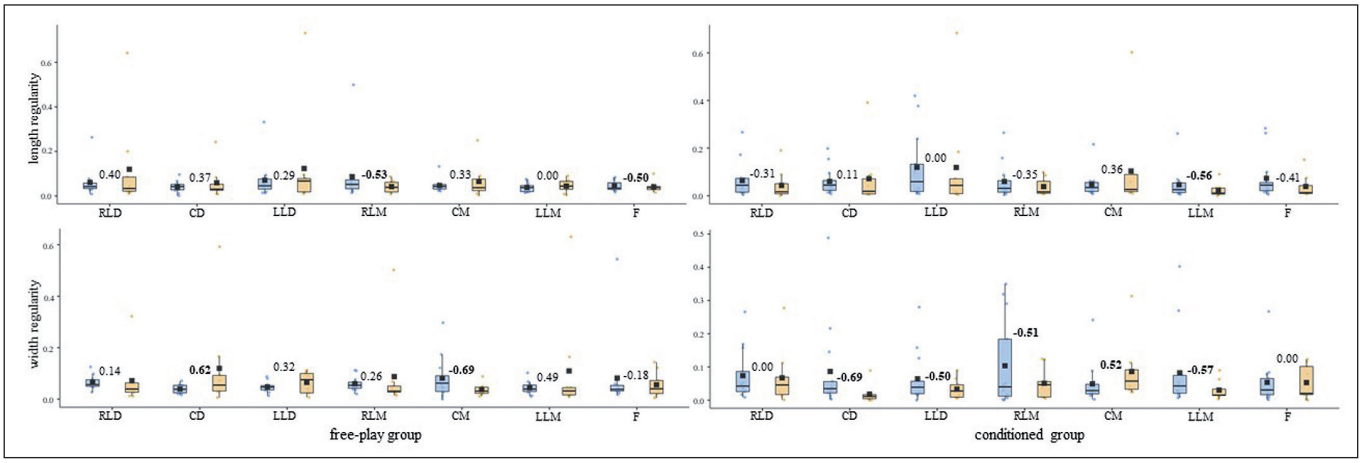


FIG. 3a. U-14s players' displacement regularity (normalized approximate entropy measures [arbitrary units]) on the length and width of the field for both free-play and conditioned groups. Intra-player comparison (Cohen's *d*) between pre-test (blue) and post-test (orange) boxes, moderate – large effect sizes in bold. RLD = right lateral defender; CD = central defender; LLD = left lateral defender; RLM = right lateral midfielder; CM = central midfielder; LLM = left lateral midfielder; F = forward.

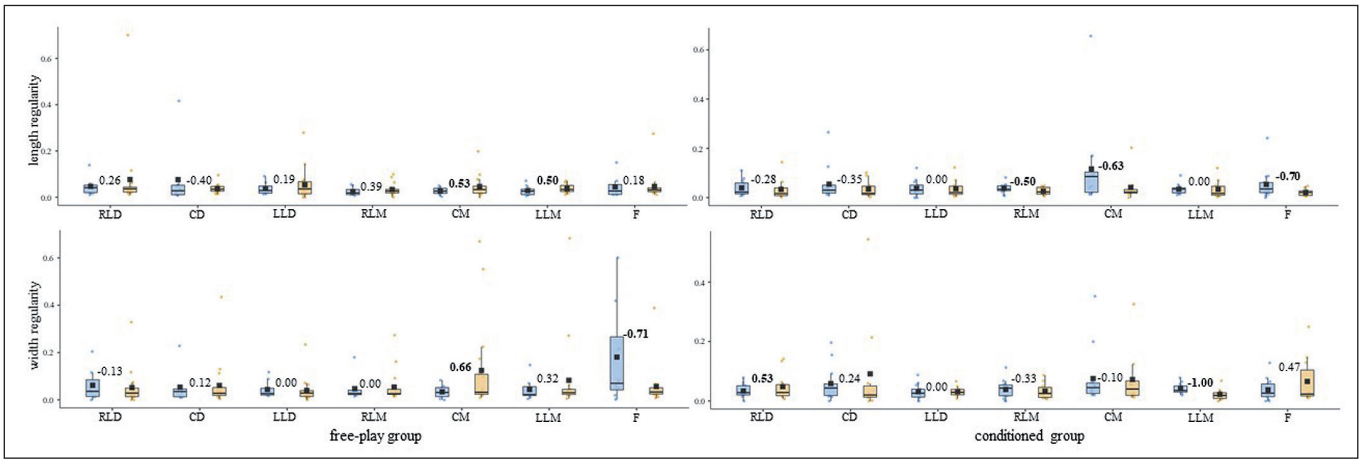


FIG. 3b. U-16s players' displacement regularity (normalized approximate entropy measures [arbitrary units]) on the length and width of the field for both free-play and conditioned groups. Intra-player comparison (Cohen's *d*) between pre-test (blue) and post-test (orange) boxes, moderate – large effect sizes in bold. RLD = right lateral defender; CD = central defender; LLD = left lateral defender; RLM = right lateral midfielder; CM = central midfielder; LLM = left lateral midfielder; F = forward.

TABLE 1. Average outcomes for U-14s' and U-16s' individual tactical behaviour. Descriptive (mean ± *SD*; CV) and intra-group comparison (% change and Cohen's *d*) for both free-play and conditioned groups.

Free-play group	Pre-test		Post-test		Change	Cohen's *d*	
	mean ± SD	CV (%)	mean ± SD	CV (%)	(%)	*d*	Int.
			U-14s				
DC (m)	10.4 ± 4.75	45.7	10.9 ± 3.87	35.5	4.80	0.12	Trivial
DC $_{\text{ApEn norm}}$	0.28 ± 0.19	67.9	0.22 ± 0.15	68.2	-21.4	0.35	Small
SEI (m)	9.81 ± 3.86	39.3	10.2 ± 3.24	31.8	3.98	0.11	Trivial
SEI $_{\text{ApEn norm}}$	0.07 ± 0.11	157	0.07 ± 0.10	143	0.00	0.00	Trivial
Length $_{\text{ApEn norm}}$	0.06 ± 0.07	117	0.07 ± 0.12	171	16.7	0.10	Trivial
Width $_{\text{ApEn norm}}$	0.06 ± 0.07	117	0.08 ± 0.12	150	-33.3	0.20	Trivial
			U-16s				
DC (m)	12.5 ± 4.39	35.1	11.2 ± 4.49	40.1	-10.4	0.29	Small
DC $_{\text{ApEn norm}}$	0.21 ± 0.16	76.2	0.31 ± 0.22	71.0	47.6	0.52	Moderate
SEI (m)	9.07 ± 3.40	37.5	10.5 ± 4.30	41.0	15.8	0.37	Small
SEI $_{\text{ApEn norm}}$	0.06 ± 0.08	133	0.05 ± 0.08	160	-16.7	0.12	Trivial
Length $_{\text{ApEn norm}}$	0.04 ± 0.06	150	0.05 ± 0.07	140	25.00	0.15	Trivial
Width $_{\text{ApEn norm}}$	0.07 ± 0.10	143	0.07 ± 0.12	171	0.00	0.00	Trivial

Conditioned group	Pre-test		Post-test		Change	Cohen's *d*	
	mean ± SD	CV (%)	mean ± SD	CV (%)	(%)	*d*	Int.
			U-14s				
DC (m)	11.6 ± 4.61	39.7	12.1 ± 4.65	38.4	4.31	0.11	Trivial
DC $_{\text{ApEn norm}}$	0.30 ± 0.22	73.3	0.25 ± 0.22	88.0	-16.7	0.23	Trivial
SEI (m)	8.37 ± 3.94	47.1	8.60 ± 4.41	51.3	2.75	0.06	Trivial
SEI $_{\text{ApEn norm}}$	0.06 ± 0.08	133	0.05 ± 0.07	140	-16.7	0.13	Trivial
Length $_{\text{ApEn norm}}$	0.07 ± 0.08	114	0.06 ± 0.12	200	-14.3	0.10	Trivial
Width $_{\text{ApEn norm}}$	0.07 ± 0.10	143	0.05 ± 0.06	120	-28.6	0.24	Trivial
			U-16s				
DC (m)	11.6 ± 5.76	49.7	11.9 ± 5.30	44.5	2.59	0.05	Trivial
DC $_{\text{ApEn norm}}$	0.32 ± 0.22	68.8	0.28 ± 0.16	57.1	-12.5	0.21	Trivial
SEI (m)	9.85 ± 4.65	47.2	8.82 ± 4.61	52.3	-10.5	0.22	Trivial
SEI $_{\text{ApEn norm}}$	0.08 ± 0.12	150	0.04 ± 0.06	150	-50.0	0.42	Small
Length $_{\text{ApEn norm}}$	0.05 ± 0.08	160	0.03 ± 0.04	133	-40.0	0.32	Small
Width $_{\text{ApEn norm}}$	0.05 ± 0.05	100	0.05 ± 0.08	160	0.00	0.00	Trivial

DC = distance to centroid; SEI = spatial exploration index; ApEn *norm* = normalized approximate entropy (arbitrary units); SD = standard deviation; CV = coefficient of variation; Change = percentage change; *d* = Cohen effect size; Int. = effect size' qualitative interpretation.

SEI $d = 0.19$; SEI $_{\text{ApEn norm}}$ $d = 0.20$; length regularity [ApEn *norm*] $d = 0.14$; and width regularity [ApEn *norm*] $d = 0.25$) were apparent in the baseline comparison, except for the DC $_{\text{ApEn norm}}$ ($d = 0.57$) of U-16s players.

In general, the average outcomes of all outfield players of each free-play and conditioned groups for both competition categories (i.e., U-14s and U-16s) barely changed ($d \leq$ small) after the training intervention (Table 1). Inter-player variability was considerable, from 35.1% to 200%, for all the measurements (Table 1).

The one-by-one analysis indicated that the training intervention affected each player's tactical response differently. Altogether, the U-14s' DC and SEI central tendency and ApEn *norm* measures (Figures 1a and 2a) barely changed (d ≤ small) for both free-play and conditioned groups. The U-14s' displacement regularity on the width of the pitch (Figure 3a) decreased considerably (d ≥ moderate) for most of the outfield players ($^4/_7$) who played conditioned by artificial rules during the training intervention.

While most of the U-16s-free players' ($^5/_7$) DC central tendency measures diminished considerably ($d \geq$ moderate), their ApEn *norm* rose ($^5/_7$, $d \geq$ moderate) (Figure 1b). The U-16s-conditioned players' ($^6/_7$) SEI tended considerably ($d \geq$ moderate) toward regularity after the training intervention (Figure 2b). The U-16s' displacement regularity on the length and width of the pitch (Figure 3b) barely changed (d ≤ small) for both free-play and conditioned groups from the pre-test to the post-test.

DISCUSSION

To the best of our knowledge, this is the first study to assess the training effects on individual tactical behaviour from pitch-positioning-derived variables through one-by-one analysis. While the average outcomes of all of the outfield players of each group (i.e., free-play and conditioned groups) for both competition categories (i.e., U-14s and U-16s) all together barely changed ($d \leq$ small) (Table 1), the one-by-one analysis revealed that the training intervention affected each player's tactical behaviour differently (Figures 1, 2, and 3). Attending to these outcomes, together with previous studies that had analysed tactical behaviour at macro- [25] and meso-levels [26], it seems necessary to delve into the different organizational levels of soccer teams to endeavour to comprehend the complex, social, and adaptive nature of the game [2, 27].

The average outcomes of the distinct individual metrics (i.e., DC and SEI central tendency and ApEn *norm* measures and displacement regularity on the length and width of the pitch) that were selected to assess individual tactical behaviour in a non-constrained testing match barely changed ($d \leq$ small) after the short-term training intervention. Similarly, Coutinho et al. [24] found that the average outcomes of DC and SEI central tendency measures and displacement regularity barely changed ($d \leq$ small) after a lengthier (i.e., 10 weeks) constraint-based training programme only for young (i.e., U-15s and U-17s) attackers. At different organizational levels, the previous studies suggest that playing freely or conditioned by artificial rules could impact considerably ($d \geq$ moderate) on the collective tactical variables (i.e., the change in the centroid position, the interpersonal distance between teammates, and surface area central tendency and entropy measures) that are utilized to assess the team [25] and team lines' [26] tactical behaviour. In addition to the different metrics employed to assess tactical behaviour at macro-, meso-, and micro-levels [53], distinct complexity principles such as the emergence phenomenon, self-organization, and adaptation could account for these differences [54, 55]: team and team lines' behaviours emerge from the nonlinear dynamic interactions between players in an unpredictable way and without a blueprint. The players may self-organize to display collective structures and behaviours at larger scales, adapting through learning and cooperation with teammates to reconfigure their tactical behaviour at multiple levels [54, 55]. Therefore, unlike collective tactical behaviour [25, 26], it seems that different game-based interventions that jointly combine several task constraints did not considerably influence players' average individual tactical behaviour (Table 1) [24].

In light of the average outcomes of all of the players and the very high inter-player variability, primarily for entropy measures, that were obtained by this (Table 1) and prior studies [24–26], the one-by-one analysis seems to be essential to deepen the effects of different training strategies on young soccer players' individual tactical behaviour. While the majority of U-14s' DC and SEI central tendency and ApEn *norm* measures (Figures 1a and 2a) barely changed (d ≤ small) after the training intervention, their displacement regularity on the width of the pitch decreased considerably (d ≥ moderate) for most of the conditioned group players ($^4/_7$). This is in line with a team tactical behaviour study [25], in which the collective tactical behaviour tended toward regularity after introducing artificial rules as key task constraints. Meanwhile, even though the majority of the U-16s' displacement regularity (Figure 3b) barely changed (d ≤ small), DC (Figure 1b) and SEI (Figure 2b) one-by-one outcomes considerably changed ($d \geq$ moderate) after the training intervention. It is worth mentioning here that the DC central tendency measures decreased, and their ApEn *norm* increased considerably ($d \geq$ moderate) for most of the players ($^5/_7$ in both cases) who played freely during the four training sessions. Hence, future research could ask whether getting closer to the team centroid raised the players' unpredictability. Regarding the SEI, similarly to the entropy measures of the use of space (i.e., surface area) at a macro-level [25], the ApEn *norm* dropped for six of the seven U-16s-conditioned players. This suggests that introducing artificial rules could boost the exploratory regularity.

Since the adaptations in young soccer players' tactical behaviour depends on the use of three artificial rules during the intervention, changes cannot be attributed to a determinate task condition. So, a broad interpretation of the training effects is required. For practical purposes, just like in lengthier structured constraint-based programmes [24], coaches should not expect considerable behavioural changes in their players' average tactical response after a short-term intervention, with very high inter-player variability. Even so, free play or the combination of three artificial rules impacted each player's

tactical behaviour in a different way, mainly those who played conditioned during the training intervention. Thus, generalizing the effects of game-based interventions to the whole squad would not be suitable [7, 8, 28]. As such, academy heads and youth soccer coaches could take advantage of the one-by-one analysis to supervise the individual's development, attend to their particular needs and characteristics, and adapt and optimize their training strategies.

CONCLUSIONS

This study is the first to assess training effects on the individual tactical behaviour from pitch-positioning-derived variables through one-by-one analysis. This analysis seems to be crucial to study the different organizational levels of soccer teams in depth and comprehend the complex, social, and adaptive nature of the game. Given that the average outcomes of all of the outfield players of both free-play and conditioned groups for both U-14 and U-16 competition categories together barely changed ($d \leq$ small), an individualized analysis could be valuable to complement the players' average measures. Indeed, the one-by-one analysis revealed that the training intervention affected each player's tactical behaviour differently. Therefore, assessing the training effects of game-based interventions from the individual to the whole team may provide unique and meaningful insight regarding the tactical competence of each player.

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Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. Araújo D, Davids K, Hristovski R. The ecological dynamics of decision making in sport. Psychol Sport Exerc. 2006; 7(6):653–76.
2. Travassos B, Davids K, Araújo D, Esteves PT. Performance analysis in team sports: Advances from an ecological dynamics approach. Int J Perform Anal Sport. 2013; 13(1):83–95.
3. Chow JY, Davids K, Button C, Shuttleworth R, Renshaw I, Araújo D. The role of Nonlinear Pedagogy in Physical Education. Rev Educ Res. 2007; 77(3):251–78.
4. Chow JY. Nonlinear learning underpinning pedagogy: Evidence, challenges, and implications. Quest. 2013; 65(4):469–84.
5. Davids K, Chow JY, Shuttleworth R. A Constraints-based framework for Nonlinear Pedagogy in Physical Education. Journal of Physical Education, New Zealand. 2005; 38:17–29.
6. Renshaw I, Araújo D, Button C, Chow JY, Davids K, Moy B. Why the Constraints-Led Approach is not Teaching Games for Understanding: a clarification. Phys Educ Sport Pedagogy. 2016; 21(5):459–80.
7. Renshaw I, Chow JY. A constraint-led approach to sport and physical education pedagogy. Phys Educ Sport Pedagogy. 2019; 24(2):103–16.
8. Correia V, Carvalho J, Araújo D, Pereira E, Davids K. Principles of nonlinear pedagogy in sport practice. Phys Educ Sport Pedagogy. 2019; 24(2):117–32.
9. Silva P, Garganta J, Araújo D, Davids K, Aguiar P. Shared knowledge or shared affordances? Insights from an ecological dynamics approach to team coordination in sports. Sports Medicine. 2013; 43(9):765–72.
10. Goes FR, Meerhoff LA, Bueno MJO, Rodrigues DM, Moura FA, Brink MS, Elferink-Gemser MT, Knobbe AJ, Cunha SA, Torres RS, Lemmink KAPM. Unlocking the potential of big data to support tactical performance analysis in professional soccer: A systematic review. Eur J Sport Sci. 2021; 21(4):481–96.
11. Parlebas P. Elementary mathematical modelization of games and sports. In: Franck R, editor. The Explanatory Power of Models. Dordrecht, Netherlands: Springer; 2002. p. 197–227.
12. Newell KM. Constraints on the development of coordination. In: Wade MG, Whiting HTA, editors. Motor development in children: Aspects of coordination and control. Dordrecht, Netherlands: Martinus Nijhoff; 1986. p. 341–60.
13. Ometto L, Vasconcellos FV, Cunha FA, Teoldo I, Souza CRB, Dutra MB, O'Sullivan M, Davids K. How manipulating task constraints in small-sided and conditioned games shapes emergence of individual and collective tactical behaviours in football: A systematic review. Int J Sports Sci Coach. 2018; 13(6):1200–14.
14. Ramos A, Coutinho P, Leitão JC, Cortinhas A, Davids K, Mesquita I. The constraint-led approach to enhancing team synergies in sport – What do we currently know and how can we move forward? A systematic review and meta-analyses. Psychol Sport Exerc. 2020; 50:101754.
15. Canton A, Torrents C, Gonçalves B, Ric A, Salvioni F, Exel J, Sampaio J. The diagonal positioning of the goals modifies the external training load and the tactical behaviour of young football players. Biol Sport. 2022; 39(1):135–44.
16. Coutinho D, Gonçalves B, Santos S, Travassos B, Wong DP, Sampaio J. Effects of the pitch configuration design on players' physical performance and movement behaviour during soccer small-sided games. Research in Sports Medicine. 2019; 27(3):298–313.
17. Coutinho D, Gonçalves B, Travassos B, Folgado H, Figueira B, Sampaio J. Different marks in the pitch constraint youth players' performances during football small-sided games. Res Q Exerc Sport. 2020; 91(1):15–23.
18. Coutinho D, Gonçalves B, Travassos B, Abade E, Wong DP, Sampaio J. Effects of pitch spatial references on players' positioning and physical performances during football small-sided games. J Sports Sci. 2019; 37(7):741–7.
19. Canton A, Torrents C, Ric A, Gonçalves B, Sampaio J, Hristovski R. Effects of temporary numerical imbalances on collective exploratory behavior of young and professional football players. Front Psychol. 2019; 10:1968.
20. Praça GM, Moreira PED, Rochael M, Barbosa G, Travassos B. Designing facilitated task constraints for different age groups in soccer: The impact of floaters' rules. Int J Sports Sci Coach. 2022; 17(1):46–53.
21. Santos S, Coutinho D, Gonçalves B, Abade E, Pasquarelli B, Sampaio J. Effects of manipulating ball type on youth footballers' performance during small-sided games. Int J Sports Sci Coach. 2020; 15(2):170–83.

22. Coutinho D, Gonçalves B, Santos S, Travassos B, Folgado H, Sampaio J. Exploring how limiting the number of ball touches during small-sided games affects youth football players' performance across different age groups. Int J Sports Sci Coach. 2022; 17(3):545–57.
23. Santos S, Coutinho D, Gonçalves B, Schöllhorn WI, Sampaio J, Leite N. Differential learning as a key training approach to improve creative and tactical behavior in soccer. Res Q Exerc Sport. 2018; 89(1):11–24.
24. Coutinho D, Santos S, Gonçalves B, Travassos B, Wong DP, Schöllhorn WI, Sampaio J. The effects of an enrichment training program for youth football attackers. PLoS One. 2018; 13(6):e0199008.
25. Gonzalez-Artetxe A, Pino-Ortega J, Rico-González M, Los Arcos A. Training effects of artificial rules on youth soccer team tactical behavior. Phys Educ Sport Pedagogy. 2022; 27(5):467–82.
26. Gonzalez-Artetxe A, Los Arcos A, Folgado H, Rico-González M, Pino-Ortega J. Effects of free-play or introducing artificial rules on tactical behavior based on soccer-team lines: A pilot study. Proc Inst Mech Eng P J Sport Eng Technol. 2022; Available from: https://journals.sagepub.com/doi/10.1177/17543371221107179
27. Low B, Coutinho D, Gonçalves B, Rein R, Memmert D, Sampaio J. A systematic review of collective tactical behaviours in football using positional data. Sports Med. 2020; 50:343–85.
28. Davids K, Araújo D, Correia V, Vilar L. How small-sided and conditioned games enhance acquisition of movement and decision-making skills. Exerc Sport Sci Rev. 2013; 41(3):154–61.
29. Bidaurrazaga-Letona I, Lekue JA, Amado M, Gil SM. Progression in youth soccer: Selection and identification in youth Soccer players aged 13–15 years. J Strength Cond Res. 2019; 33(9):2548–58.
30. Los Arcos A, Gonzalez-Artetxe A. Physical fitness performance, playing position and competitive level attained by elite junior soccer players. Kinesiology. 2021; 53(1):56–64.
31. Craig TP, Swinton P. Anthropometric and physical performance profiling does not predict professional contracts awarded in an elite Scottish soccer academy over a 10-year period. Eur J Sport Sci. 2021; 21(8):1101–10.
32. Vega JM, Gonzalez-Artetxe A, Aguinaco JA, Los Arcos A. Assessing the anthropometric profile of Spanish elite reserve soccer players by playing position over a decade. Int J Environ Res Public Health. 2020; 17(15):5446.
33. Castillo D, Los Arcos A, Martínez-Santos R. Aerobic endurance performance does not determine the professional career of elite youth soccer players. Journal of Sports Medicine and Physical Fitness. 2018; 58(4):392–8
34. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007; 39(2):175–91
35. McKay AKA, Stellingwerff T, Smith ES, Martin DT, Mujika I, Goosey-Tolfrey VL, Sheppard J, Burke LM. Defining training and performance caliber: A participant classification framework. Int J Sports Physiol Perform. 2022; 17(2):317–31.
36. Casamichana D, Castellano J. Time-motion, heart rate, perceptual and motor behaviour demands in small-sides soccer games: Effects of pitch size. J Sports Sci. 2010; 28(14):1615–23.
37. Bizzini M, Junge A, Dvorak J. Implementation of the FIFA 11+ football warm up program: How to approach and convince the Football associations to invest in prevention. Br J Sports Med. 2013; 47(12):803–6.
38. Gonzalez-Artetxe A, Pino-Ortega J, Rico-González M, Los Arcos A. Variability of the motor behavior during continued practice of the same motor game: A preliminary study. Sustainability. 2020; 12(22):9731.
39. Sydney MG, Wollin M, Chapman DW, Ball N, Mara JK. Do conditioning focused various-sided training games prepare elite youth male soccer players for the demands of competition? Biol Sport. 2022; 39(4):825–32.
40. Parlebas P. Motor Praxeology: A New Scientific Paradigm. In: Vaczi M, editor. Playing Fields: Power, Practice, and Passion in Sport. Reno, NV: Center for Basque Studies; 2013. p. 127–44.
41. Bastida-Castillo A, Gómez-Carmona CD, De La Cruz Sánchez E, Pino-Ortega J. Comparing accuracy between global positioning systems and ultra-wideband-based position tracking systems used for tactical analyses in soccer. Eur J Sport Sci. 2019; 19(9):1157–65.
42. Clemente FM, Pino-Ortega J, Rico-González M. Local positioning systems. In: Rico-González M, Pino-Ortega J, editors. The Use of Applied Technology in Team Sport. 1st ed. New York: Routledge; 2021. p. 39–51.
43. Rico-González M, Los Arcos A, Rojas-Valverde D, Clemente FM, Pino-Ortega J. A survey to assess the quality of the data obtained by radio-frequency technologies and microelectromechanical systems to measure external workload and collective behavior Variables in team sports. Sensors. 2020; 20(8):2271.
44. Folgado H, Duarte R, Fernandes O, Sampaio J. Competing with lower level opponents decreases intra-team movement synchronization and time-motion demands during pre-season soccer matches. PLoS One. 2014; 9(5):e97145.
45. Castellano J. Análisis de las posesiones de balón en fútbol: frecuencia, duración y transición. Motricidad European Journal of Human Movement. 2008; 21:179–96.
46. Fonseca S, Milho J, Passos P, Araújo D, Davids K. Approximate entropy normalized measures for analyzing social neurobiological systems. J Mot Behav. 2012; 44(3):179–83.
47. Soto A, Camerino O, Iglesias X, Anguera MT, Castañer M. LINCE PLUS: Research Software for Behaviour Video Analysis. Apunts Educación Física y Deportes. 2019; 137:149–53.
48. Bakeman R, Quera V, Gnisci A. Observer agreement for timed-event sequential data: A comparison of time-based and event-based algorithms. Behav Res Methods. 2009; 41(1):137–47.
49. Quera V, Bakeman R, Gnisci A. Observer agreement for event sequences: Methods and software for sequence alignment and reliability estimates. Behav Res Methods. 2007; 39(1):39–49.
50. Fleiss JL, Levin B, Paik MC. Statistical methods for rates and proportions. 3rd ed. Hoboken, NJ: John Wiley & Sons, Inc.; 2003.
51. Coito N, Davids K, Folgado H, Bento T, Travassos B. Capturing and quantifying tactical behaviors in small-sided and conditioned games in soccer: A systematic review. Res Q Exerc Sport. 2022; 93(1):189–203.
52. Rhea MR. Determining the magnitude of treatment effects in strength training research through the use of the effect size. J Strength Cond Res. 2004; 18(4):918–20.
53. Gonzalez-Artetxe A, Los Arcos A. Collective tactical variables. In: Rico-González M, Pino-Ortega J, editors. The Use of Applied Technology in Team Sport. 1st ed. New York: Routledge; 2021. p. 131–45.
54. Pol R, Balagué N, Ric A, Torrents C, Kiely J, Hristovski R. Training or synergizing? Complex systems principles change the understanding of sport processes. Sports Med Open. 2020; 6:28.
55. Strogatz S, Walker S, Yeomans JM, Tarnita C, Arcaute E, de Domenico M, Artime O, Goh KI. Fifty years of 'More is different'. Nature Reviews Physics. 2022. Available from: https://www.nature.com/articles/s42254-022-00483-x

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Eccentric hamstring strength in young athletes is best documented when normalised to body mass: A cross-sectional study with normative data of 590 athletes from different age categories

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ABSTRACT: Despite its widespread use in adults, the Nordic hamstring exercise remains underexplored in athletic youth populations. Further, given the dynamic nature of growth and maturation, comparisons with elite adult populations may be inaccurate. Here we describe absolute and body mass-normalised eccentric hamstring normative values for football, athletics and multi-sport youth populations. 676 routine standardised tests were conducted, including 244 U12–U18 student-athletes (football, athletics, multi-sport) and 346 Qatar Stars League (QSL) football players using the NordBord. The average maximum values for the left and right leg from 3 repetitions were recorded. Significant increases in absolute strength were seen across chronological (e.g., 150 N ± 15 for U12 to 330 N ± 40 for U18) and skeletal (142.9 N ± 13.9 for skeletal age of 12 compared to 336.2 N ± 71.2 for skeletal age of 18) age groups. The differences in values normalised to body mass were smaller at 3.6 N/kg ± 0.25 for the U-13 group, but similar for the U14 to U18 groups (4.5 N/kg ± 0.16, 4.6 N/kg ± 0.11, 4.6 N/kg ± 0.27, 4.7 N/kg ± 0.14, 4.5 N/kg ± 0.18). Students displayed lower absolute strength than the professional football players (272.1 N compared to 297.3 N, $p < 0.0001$) but higher relative strength (4.7 N/kg compared to 4.2 N/kg, $p < 0.0001$). Comparing Nordic hamstring strength values between athletes, and between skeletal and chronological age groups can be done when values are normalised to the athlete's body mass. For the U14s and onwards age categories, body mass normalised values are comparable to professional football players.

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INTRODUCTION

Adolescents undergo a period of rapid growth and development which makes assessment of training-related changes in parameters such as strength difficult to tease out from these normal processes. Between-athlete comparisons are confounded by variations in timing of growth spurts in addition to the longitudinal-within individual differences. Normative eccentric hamstring strength in adult populations has been extensively explored and its association with injury risk mitigation well established [1]. Eccentric hamstring strengthening in youth has been suggested to develop physical qualities of sporting performance as well as reduce injury risk [2]. Further, given that athletic movements for performance in youth mimic their adult counterparts such as deceleration, landing and hopping, exposure to eccentric resistance training is warranted [2]. While its role in injury risk mitigation is well established in adult populations [1], its role in athletic youth populations is not well described. This may in part be due to a lack of normative data for practitioners to base their preparation and intervention decisions on. Understanding any relationships between these strength values and players' chronological age, and skeletal age (for student athletes) as well as body mass will better inform the interpretation of these tests.

The interactions between growth, maturation, and eccentric hamstring muscle strength in football and athletic youth populations are

yet to be fully established. Further, a comprehensive overview assessing eccentric hamstring strength between elite footballers and elite youth athletes is yet to be explored. The inherent complexity and non-linearity of youth athletes' normal physical growth, biological maturation, and behavioural development make it difficult to gauge a true representation of their abilities at any given moment [3]. These complex interactions need to be considered when assessing eccentric hamstring strength at a single time point, or when comparing different measures over time. To better understand the effectiveness of training interventions, any improvements in strength which are attributable to these training effects need to be teased out from those due to physical growth and maturation. [1, 2]

This paper aims to describe normative values of eccentric hamstring strength in well-trained male athletic and football youth populations. Secondly, it aims to describe any relationships between eccentric hamstring strength and body mass, skeletal maturation status, and chronological age. Finally, these data are compared with a sample of professional adult male football players.

MATERIALS AND METHODS

Study design and participants

Student athletes

A cross-sectional cohort study design described growth, maturation, and knee flexor strength prospectively over three seasons. The participants were male full-time student athletes, enrolled in the football, athletics or multi-sports programmes at Aspire Academy, an elite sporting academy in the Doha, Qatar. Testing was completed during the preseason or initial competitive cycle of the 2016/17, 2017/18 and 2018/19 seasons (Figure 1).

A total of 330 male athletes (chronological mean age 15.3 ± 1.7, height 169 ± 11, weight 58.8 ± 14.2, BMI 20.3 ± 3.3) presented for screening across three seasons from 2016 to 2019. The demographic data for this cohort are summarised in Table 1. There were 313 body mass measurements and 306 complete skeletal age measures conducted at the time of eccentric hamstring testing assessments. All athletes needed to be free of injury to the lower limbs and able to participate fully in training at the time of testing.

Qatar Stars League footballers

The comparison adult data are drawn from a previously published study [4] which prospectively examined professional footballers in the Qatar Stars' League over a 4-year period during annual pre-competition medical assessment. In year 2 of this study, all eligible players were tested on the NordBord Nordic hamstring testing device. After exclusion of the players who were injured or refused to consent to the testing, 346 players' results were available for this analysis.

Data collection procedures and statistics

Eccentric knee flexor strength

Athletes performed one set of three maximal repetitions on a device specifically designed to measure maximal force output (N) during the Nordic hamstring exercise [5] using previously described methods.

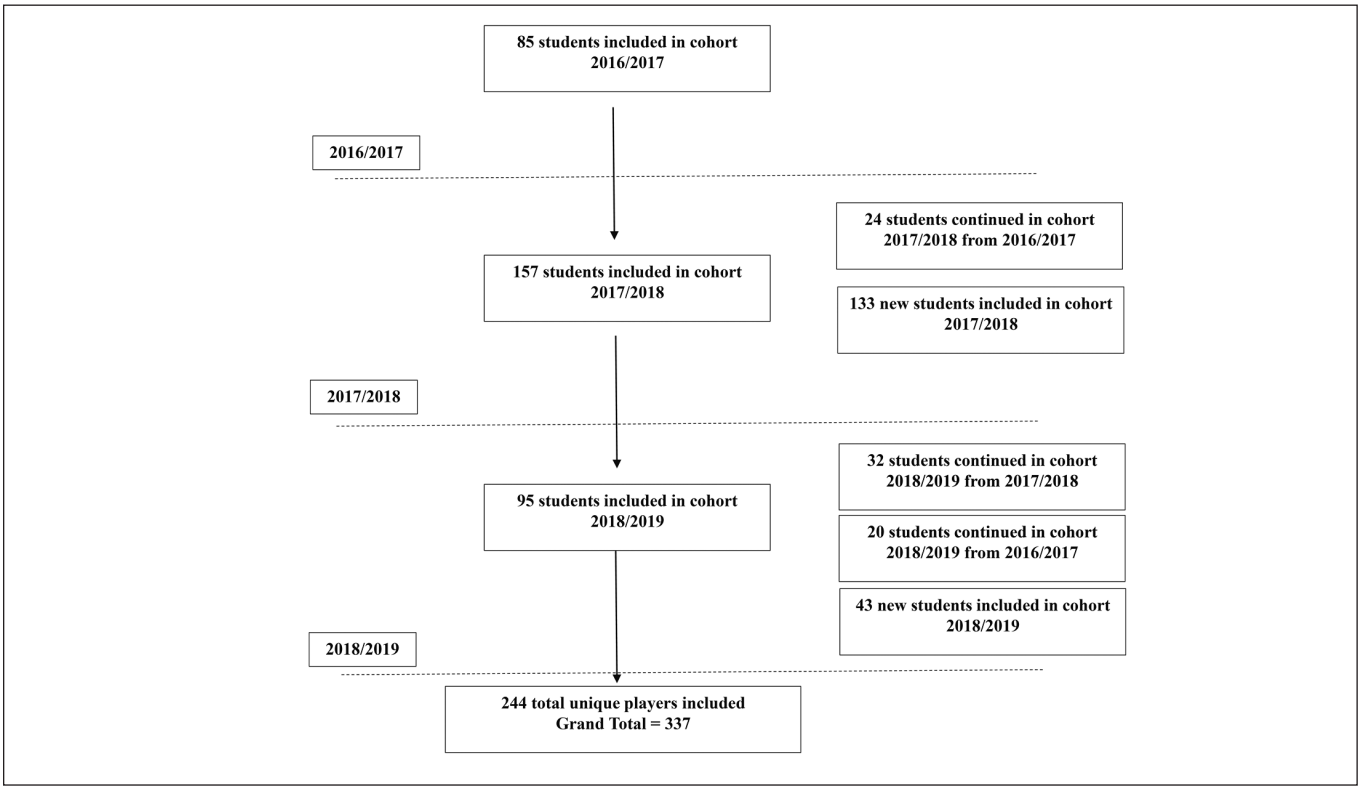


FIG. 1. Flow chart demonstrating the movement of players and repeated measurements during three seasons, 2016–17 to 2018–19 and body mass (kg) for highly trained athletes in sports academy.

TABLE 1. Participant characteristics. Student athletes compete in age categories "U13" to "U20" – Under 13 years of age at the start of the academic year to under 20 years of age respectively. Of these student athletes, 174 played football, 119 competed in athletics, and 46 in multi-sport events. The QSL Adult cohort is the professional football players included in pre-competition medical assessment. Data are presented as mean ± SD. Skeletal age is assessed using the FELS method. No skeletal age data are available for the adult QSL athletes.

Age Group	Chronological Age (Years)	Skeletal Age (Years)	Height (cm)	Weight (kg)	Body Mass Index (kg/m²)
Student athletes (n = 330)	15.2 ± 1.7	16.1 ± 2.0	168.7 ± 10.4	58.0 ± 13.6	20.1 ± 3.3
U13 (n = 38)	12.6 ± 0.46	13.1 ± 1.3	156.7 ± 7.8	46.4 ± 13.6	18.7 ± 3.7
U14 (n = 61)	13.5 ± 0.4	14.4 ± 1.1	160.0 ± 8.4	47.9 ± 11.1	18.5 ± 3.0
U15 (n = 81)	14.9 ± 0.7	15.9 ± 1.6	169.4 ± 8.9	58.3 ± 11.3	20.2 ± 3.2
U16 (n = 31)	15.4 ± 0.4	16.7 ± 1.4	174.1 ± 7.6	58.8 ± 8.7	19.3 ± 1.9
U17 (n = 67)	16.5 ± 0.4	17.6 ± 0.8	174.3 ± 6.0	65.3 ± 8.9	21.5 ± 2.6
U18 (n = 52)	17.5 ± 0.4	17.8 ± 0.8	175.7 ± 8.5	67.6 ± 13.5	21.8 ± 3.3
QSL football (n = 346)	25.9 ± 4.8	N/A	176.6 ± 6.9	72.3 ± 9.3	23.1 ± 2.1

The NordBord (Vald Performance, Australia) has been previously shown to have moderate to high reliability (intraclass correlation coefficient = 0.83–0.90; typical error, 21.7–27.5 N; typical error as a coefficient of variation, 5.8%-8.5%) [5]. Briefly, the athletes were first shown an instructional video and provided a handout in English and Arabic explaining the correct technique during the exercise. Each athlete was positioned kneeling on the device, the ankles secured by individual ankle braces immediately above the lateral malleoli. A submaximal effort was performed for familiarisation and to ensure correct performance. Participants were instructed to gradually lean forward at the slowest possible speed while maximally resisting the fall with both legs and maintaining an upright posture with their spine and pelvis in a neutral position. As the athlete lowered to the ground, uniaxial load cells attached to the ankle braces (Delphi Measurement, Gold Coast, Australia) measured the concomitant maximal force output (N). Each repetition was characterised by a distinct peak in maximum pull force followed by a sharp decline. This rapid reduction in force indicated completion of a repetition, whereby the athlete fails to maintain the resistance required to eccentrically lower their trunk position against the increasing demands of body mass, gravity, and the distance from the line of pull. Verbal encouragement was provided throughout the exercise to ensure maximal effort. The proprietary software provided instantaneous raw data that were then exported into a customised Microsoft Excel spreadsheet (Microsoft, Redmond, USA). The mean of the left and right maximum force (N) was taken to determine a between-limb absolute maximum strength score. An illustrated version of the Nordic hamstring exercise can be seen in Figure 2.



FIG. 2. Nordic hamstring exercise being performed on the NordBord and body mass (kg) for highly trained athletes in sports academy.

Skeletal bone age and anthropometry

Skeletal maturation was assessed at the beginning of each academic year, using X-ray images of the athlete's left hand and wrist complex taken at the Radiology Department at Aspetar Orthopaedic and Sports Medicine Hospital. The images were interpreted and entered into an academy maturation database by the same experienced assessor. Skeletal age was determined using the Fels method, following the procedures outlined by Roche et al. [6]; here a maximal skeletal age of 18.0 indicates full maturity. Anthropometric screenings were conducted by ISAK (International Society for the Advancement of Kinanthropometry) Level 2 certified academy staff at the start and end of each season, which corresponded to the academic year. Measures were taken early in the morning prior to any activities to minimize diurnal variations, following ISAK-recommended procedures, and were uploaded to a central academy anthropometry database, following the procedures previously described [7].

Data analysis

Absolute force data for the left and right limbs were entered in a spreadsheet (Microsoft Excel Microsoft, Redmond, USA) which calculated the average of both legs for the repetition where the highest force was displayed for each leg during the three contractions – the "mean peak force" (average of both limbs' highest score). This value was recorded in both absolute terms (N) and relative to body mass (N/kg). Statistical analysis was conducted in JMP (JMP, Version 16.0 SAS Institute Inc., Cary, NC, 1989–2019). Mixed model regression analysis was conducted considering the fixed effects of sport (Football, Athletics, and Multi-sport) with chronological age group (U13 to U18), and the interaction effects of these two factors for the student athletes (considered as random effects), with post hoc adjustment for multiple comparison (Tukey's HSD).

Ethical approval and consent

This study was part of a larger study on growth, maturation and athletic development for which written informed consent was obtained from the athletes' guardians prior to data collection and ethics approval was granted from the Anti-Doping Lab Qatar Institutional Review Board (IRB Application #E20140000012). The adult data were collected as part of the routine pre-participation periodic health evaluation for football players participating in the Qatar Stars' League and ethical approval for this cohort was obtained from the Shafallah Medical Genetics Centre (institutional review board project number 2012–020).

RESULTS

Student athlete Nordic hamstring strength – absolute and relative values for different age group categories and sports

These analyses were conducted for both absolute and relative Nordic hamstring strength. For absolute strength, a significant effect of age group was found ($p < 0.001$) and a non-significant effect of sport ($p > 0.20$). The interaction effect (sport and age group) was significant ($p < 0.01$). For the Nordic hamstring strength normalised to body mass, there was a significant effect of both chronological age ($p = 0.004$) and an interaction effect of sport and chronological age ($p = 0.0014$) whereas the effect of sport was not significant ($p = 0.7112$). Post hoc testing however revealed that of the possible 210 pair-wise comparisons (age group and sport), 21 were statistically significant after adjusting for multiple comparison (Tukey's HSD), Appendix 5, Figure 4. Post hoc multiple comparison of the different student athlete age group categories for the relative Nordic hamstring strength revealed significant differences only for the comparison between the U13 years age group and the 15 years (difference = -1.0 N/kg [-1.7 to -0.2] $p = 0.005$), and the U13 to the U17 years age groups (difference = -1.1 N/kg [-1.9 to -0.3] $p = 0.002$). For each of these models, the residuals were analysed for normality by a combination of inspection of frequency histograms and residual quantile-quantile plots, and Shapiro-Wilk tests.

Nordic strength compared to chronological and skeletal age

Figure 3 and Table 2 show the absolute and relative values of Nordic hamstring strength for the different age and sport categories respectively. Comparing the adult (Qatar Stars' League players) to the student athlete age groups, significant differences were found for absolute strength with the U13, U14, U17, and U18 age categories (Figure 3, Appendix 1). By contrast, comparison of the normalised Nordic hamstring strength only showed significant differences for the 13 years age group compared to the 15 and 17 years' categories (Figure 3, Appendix 2).

Figures 4 and 5 show these same absolute and relative Nordic strength values compared to skeletal age and chronological age for the student athletes and QSL football players respectively.

DISCUSSION

This cross-sectional study of highly trained male youth athletes showed a clear pattern of increasing strength with chronological and skeletal age. However, the more important clinical finding is the more consistent relationship between body mass and maximum eccentric Nordic strength across these chronological and skeletal ages, particularly once these athletes were above the age of 13. This information can be used by physical preparation and rehabilitation practitioners as benchmarks for their adolescent male cohorts independent of their size and age. While this was a cross-sectional study, the stability of this finding across ages suggests that longitudinal progress needs to be assessed using the body mass-normalised values lest the apparent maturation effect be mistaken for relative improvement in strength.

These data suggest that clinicians should consider body mass as a critical factor in the interpretation of absolute eccentric hamstring strength. Increased body mass and/or longer lower leg lever distances can influence eccentric hamstring strength results during the Nordic exercise [8]. Specifically, heavier and older players have been shown to outperform their younger, lighter counterparts [8]. Body mass was found to be largely responsible for observed age-related increases in absolute Nordic hamstring strength [9]. A large body of evidence suggests that performing the Nordic hamstring exercise as part of a prevention programme is an effective way to reduce this injury's burden [1]. These current data may complement this knowledge by providing practitioners with strength training targets for those adolescents beginning resistance training.

The student athletes' average normative score was 4.74 N/kg (95% confidence interval: 4.64 to 4.86) whereas the QSL players' average was 4.16 N/kg (4.06 to 4.27). Soccer players have been shown to achieve eccentric hamstring strength (N) scores of 4x body mass (kg) +26.1 N; for example a 50 kg athlete would have a predictive score of: 4×50 kg +26.1 = 226.1 N [8]. This value is comparable with the mean absolute strength of 277 N described in the current research. Roe et al. [10] examined eccentric knee flexor strength profiles of 341 elite Gaelic football players, 105 of whom were U17 or below, and found body mass to have moderate-to-large

TABLE 2. Absolute and relative strength values of the Nordic hamstring exercise by sports category

Group	Absolute Maximal Eccentric Nordic Strength (Mean ± SD, N)	Relative Maximal Eccentric Nordic Strength (Mean ± SD, N·kg−1)
Football (n=174)	**276.29 ± 74.76**	**4.95 ± 0.95**
Athletics (n=123)	**289.73 ± 94.60**	**4.62 ± 1.01**
Sprints (n=27)	347.00 ± 83.54	5.07 ± 1.10
Endurance (n=40)	283.85 ± 75.20	4.90 ± 0.86
Jumps (n=15)	320.17 ± 74.36	4.58 ± 0.87
Throws (n=5)	417.70 ± 83.92	4.14 ± 0.85
Development (n=28)	234.93 ± 74.16	4.18 ± 0.91
Foundation (n=8)	180.69 ± 98.19	3.58 ± 0.86
Multi-Sports (n=40)	**240.74 ± 77.64**	**4.30 ± 1.21**
Fencing (n=16)	226.42 ± 71.54	4.13 ± 1.16
Gymnastics (n=6)	209.18 ± 57.05	3.69 ± 0.98
Squash (n=12)	303.46 ± 75.22	5.17 ± 1.12
Table Tennis (n=6)	189.71 ± 41.07	3.58 ± 1.02
Total (n=337)	**276.97 ± 83.92**	**4.74 ± 1.03**

associations (r = 0.47) with maximum force in youth. In this study, relative maximum force was found to be 4.4 N/kg across all players. Bourne et al. [11] reported eccentric knee flexor strength in elite rugby union players of 3.65 ± 0.71 N/kg [11]. Further, they found sub-elite and U19 players to be significantly stronger than elite players, which is consistent with our cohort. Again, in uninjured elite Australian footballers, in-season relative eccentric hamstring strength scores were found to be 4.09 ± 1.01 N/kg [12]. Together these findings suggest that long-term tracking of these body mass normalised Nordic values can begin in early adolescence – we suggest after the age of 13 – and progress throughout an athlete's career to adulthood; however, this would require verification with longitudinal studies.

Eccentric hamstring strength training in youth has been advocated as important in developing physical qualities that underpin performance and reduce injury risk [2, 9]. Furthermore, muscular strength in youth is strongly associated with a multitude of physical qualities including running speed, power, agility and endurance performance [13] Eccentric hamstring strength training complements the Youth Physical Development model to facilitate appropriate neural and structural adaptations [14, 15]. Despite the clinical indication for this exercise, performance and rehabilitation staff must consider the unique journey each athlete follows. It is important to recognise and embrace the inherent complexity and non-linearity of athlete development rather than age-related prescription-based methods [3]. The Nordic hamstring exercise in male youth footballers has been established as a reliable measure of bilateral hamstring peak force across maturation stages [16]. Individual differences in growth and maturation may contribute to competitive inequity and increased risk of injury [17]. Our findings highlight the fact that there are moderate associations between skeletal age and chronological age with eccentric hamstring strength in absolute terms but not when body mass is accounted for. Similarly, non-linear relationships between Nordic strength and age have been found in highly trained youth footballers [9]. Interestingly, abrupt changes were found in the U16 age group in absolute terms. This was ascribed to the pubertal growth spurt and accompanying increase in serum androgen hormones [9]. Drury et al. (2019) explored the influence of maturation status on eccentric hamstring strength improvements by implementing a 6-week Nordic hamstring exercise intervention study. Small and moderate increases (10% and 16%) in relative eccentric hamstring strength were observed in the pre-peak height velocity (PHV) and mid/post PHV groups respectively. Based on these findings, the authors suggest ingraining relative strength as a foundation for absolute strength in less mature individuals [2]. This considered, appropriate training relative to a child's chosen activity, before and during maturation, enables combinatory and consolidatory factors that

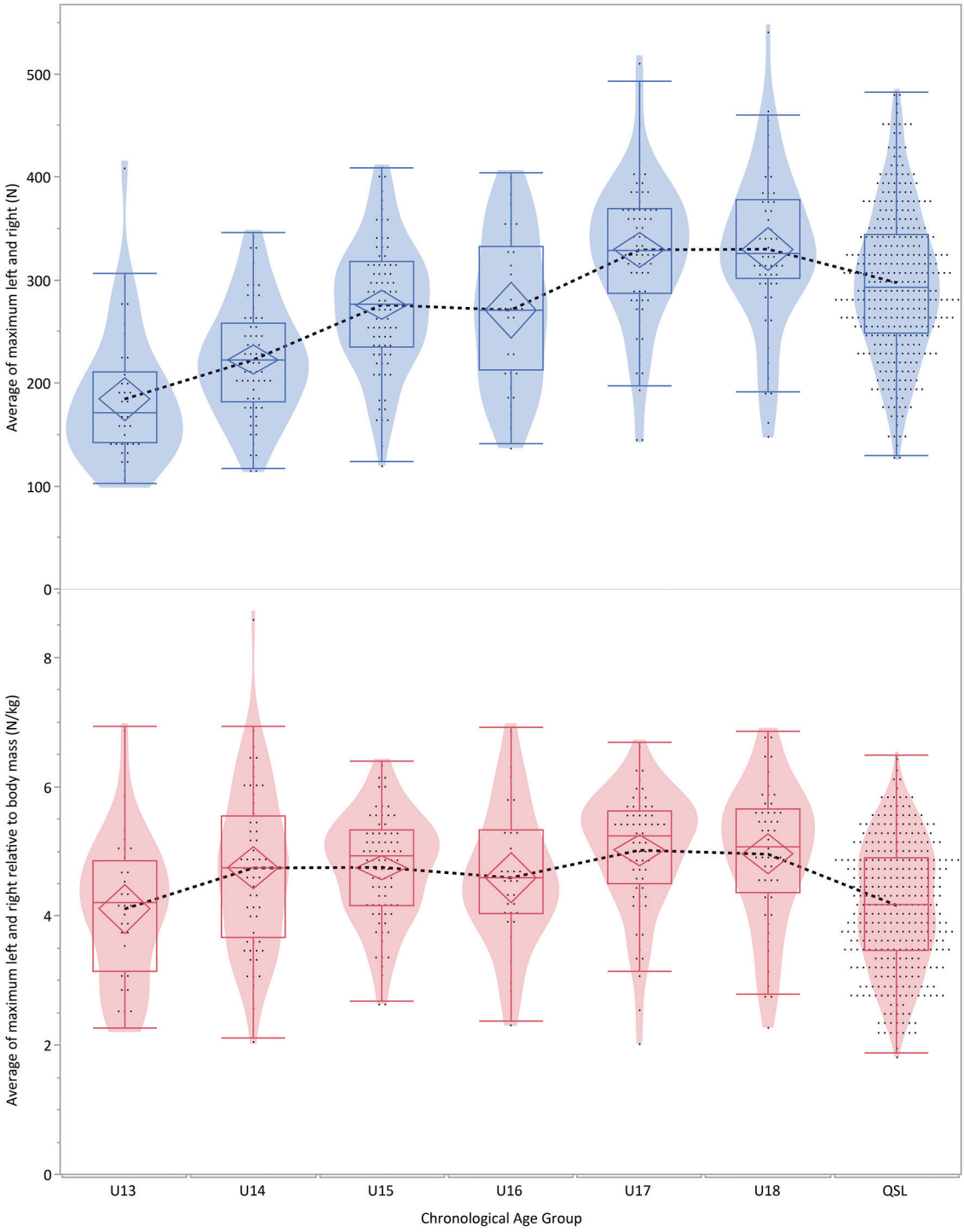


FIG. 3. Relative (N/kg) and absolute strength values for the different age groups. Note that the "QSL" category indicates all the Qatar Stars' League players, and the U13 to U20 categories indicate the Aspire Academy student athletes' age group categories. Confidence diamond within the boxplot describes the 95% confidence limit of the mean, contours represent the distribution of the individual points (dots) for each observation. Dotted line connects the mean values of the groups.

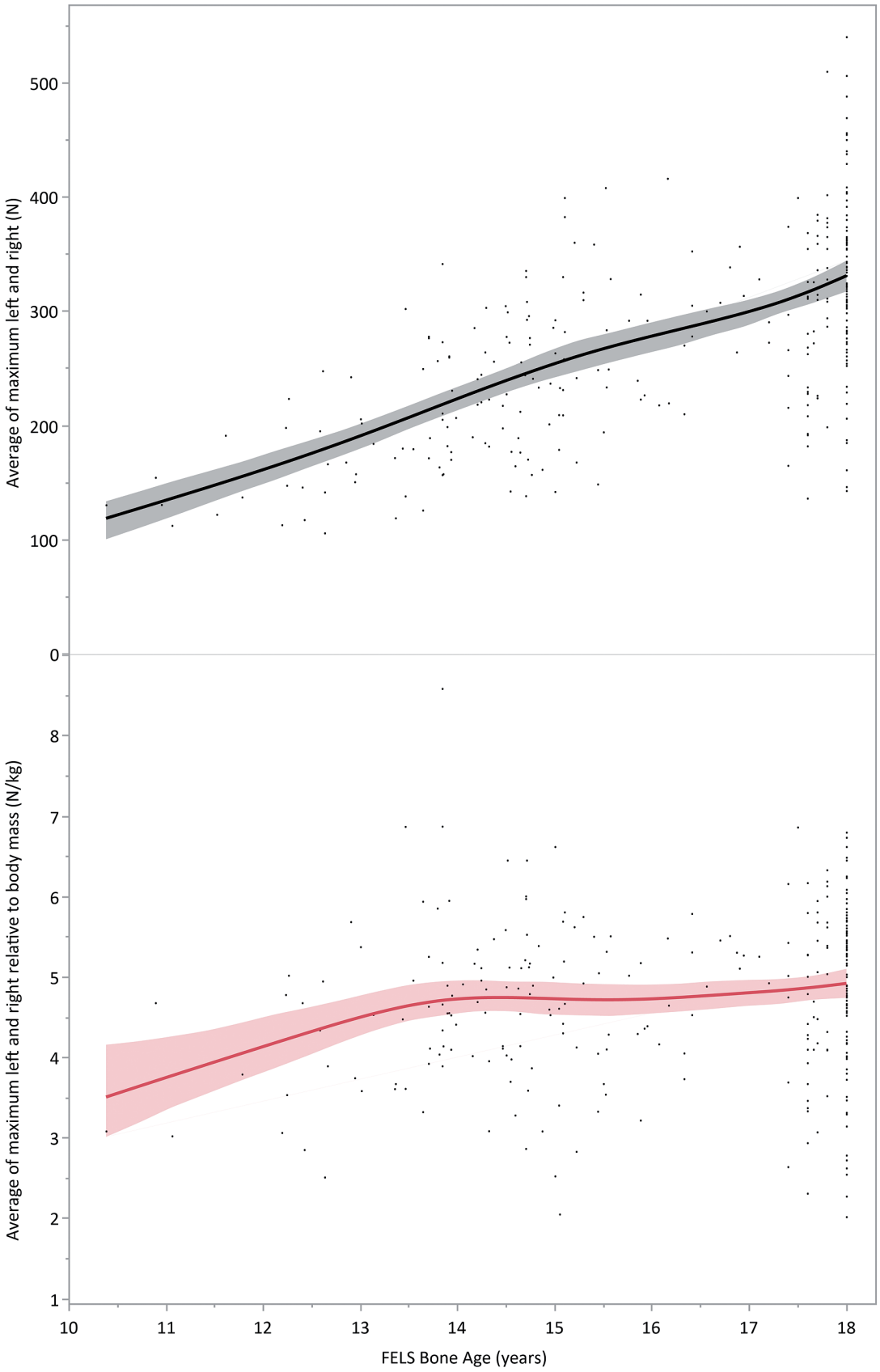


FIG. 4. Absolute and relative Nordic hamstring strength values compared to skeletal age as estimated by the Fels method. There is a moderate positive (r = 0.65 [0.57 to 0.71]) significant ($p < 0.0001$) correlation between Fels skeletal age and absolute (N) strength, but only a weak positive (r = 0.18 [0.06 to 0.29]) significant (p = 0.003) correlation between relative strength (N/kg) and skeletal age.

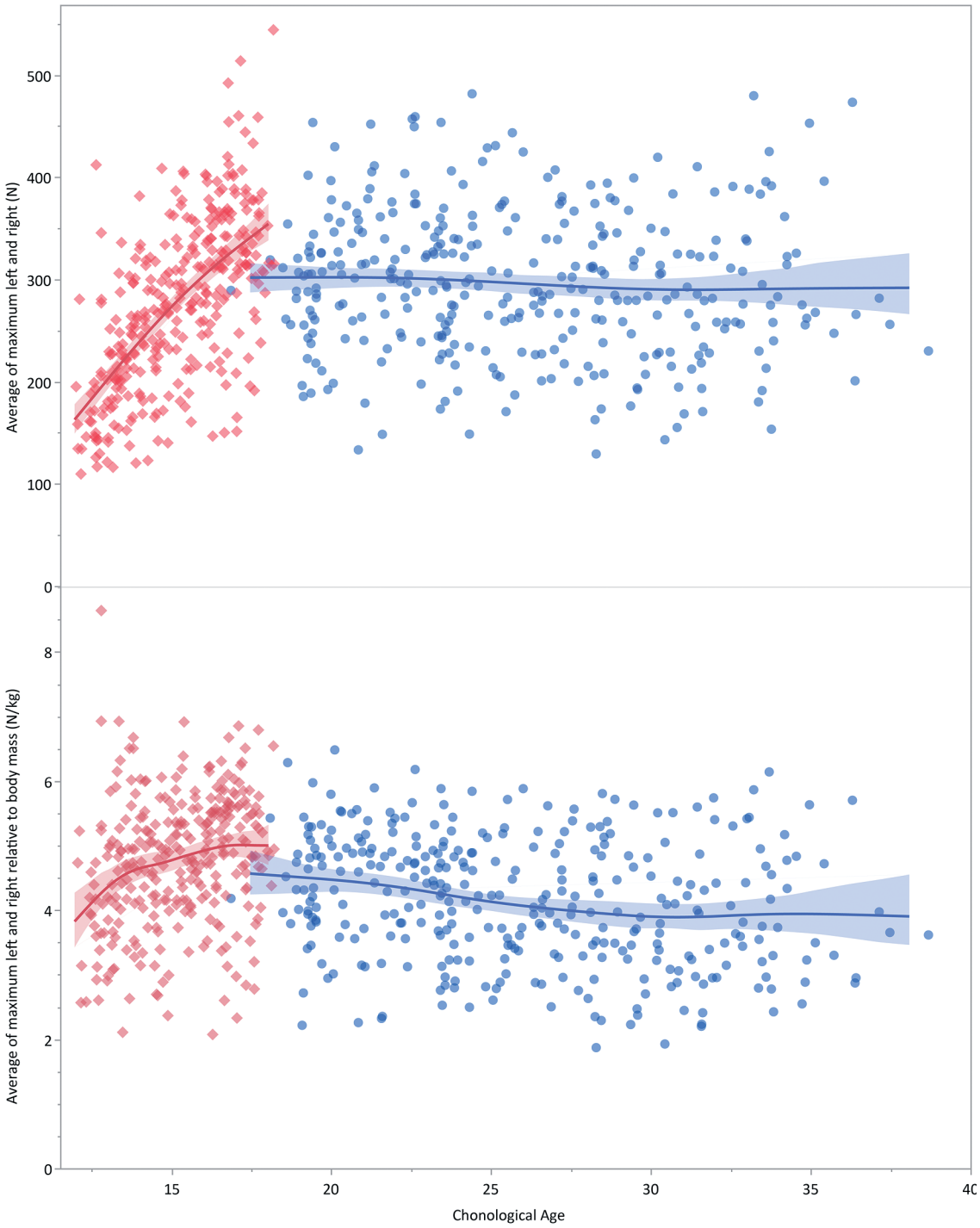


FIG. 5. Absolute (N, upper panel) and relative (N/kg, lower panel) average maximum Nordic hamstring strength compared to age for both the student athletes (red diamonds, red line of best fit with confidence interval) and the QSL football players (blue circles, blue line). There is a moderate positive ($r = 0.64$ [0.57 to 0.70]) significant ($p < 0.0001$) correlation of absolute strength and age for the student athletes but not for the QSL footballers ($r = 0.06$ [-0.17 to 0.04], $p = 0.2365$). For the relative strengths, there is a weak positive ($r = 0.25$ [0.14 to 0.36]) significant ($p < 0.0001$) correlation for the student athletes, and a weak negative ($r = -0.21$ [-0.31 to -0.11)] significant ($p < 0.0001$) correlation for the QSL football players.

support motor skill performance during post-pubertal training years driven primarily via increases in testosterone, growth hormone and insulin-like growth factor [18]. Future research may consider the effect of hormonal as well as physical (i.e. body size) changes to tease out any individual effects.

Limitations and future research

Given the limited understanding of eccentric hamstring strength in youth sporting populations, further exploration is warranted particularly in other cohorts including youth female athletes and other ethnicities. In this cohort, the lever arm was not measured and may represent an extra independent variable to consider in youth athletes. The Nordic hamstring exercise requires a level of technical competence and a capacity to tolerate a high loading stimulus, which limits these findings to athletes who have been given appropriate technical instruction. The cross-sectional nature of this study prevents definitive statements about the longitudinal stability of these measures during maturation irrespective of the apparent stability of these data. Accordingly, long-term data examining individual variation are suggested for future research. Finally, while the performance of the Nordic hamstring exercise is associated with a reduction in hamstring injury in adults, there are essentially no similar data for adolescent athletes. Recommending the measurement of this strength in the absence of such data must be considered preliminary until this research is conducted.

CONCLUSIONS

Adolescent male athletes show increases in the absolute strength displayed during the Nordic hamstring exercise as chronological and especially skeletal age increases; however, when normalised to body mass these strengths are quite stable at approximately 4.7 N/kg once these adolescent boys were over the age of 13 years.

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Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. van Dyk N, Behan FP, Whiteley R. Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. Br J Sports Med. 2019; 53(21):1362–70.
2. Drury B, Ratel S, Clark CCT, Fernandes JFT, Moran J, Behm DG. Eccentric Resistance Training in Youth: Perspectives for Long-Term Athletic Development. J Funct Morphol Kinesiol. 2019; 4(4).
3. Bergeron MF, Mountjoy M, Armstrong N, Chia M, Cote J, Emery CA, Faigenbaum A, Hall G, Jr., Kriemler S, Leglise M, Malina RM, Pensgaard AM, Sanchez A, Soligard T, Sundgot-Borgen J, van Mechelen W, Weissensteiner JR, Engebretsen L. International Olympic Committee consensus statement on youth athletic development. Br J Sports Med. 2015; 49(13):843–51.
4. van Dyk N, Bahr R, Whiteley R, Tol JL, Kumar BD, Hamilton B, Farooq A, Witvrouw E. Hamstring and Quadriceps Isokinetic Strength Deficits Are Weak Risk Factors for Hamstring Strain Injuries: A 4-Year Cohort Study. Am J Sports Med. 2016; 44(7):1789–95.
5. Opar DA, Piatkowski T, Williams MD, Shield AJ. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. J Orthop Sports Phys Ther. 2013; 43(9):636–40.
6. Roche AF, Thissen D, Chumlea W. Assessing the skeletal maturity of the hand-wrist: Fels method: Thomas; 1988.
7. Wik EH, Martinez-Silvan D, Farooq A, Cardinale M, Johnson A, Bahr R. Skeletal maturation and growth rates are related to bone and growth plate injuries in adolescent athletics. Scand J Med Sci Sports. 2020; 30(5):894–903.
8. Buchheit M, Cholley Y, Nagel M, Poulos N. The Effect of Body Mass on Eccentric Knee-Flexor Strength Assessed With an Instrumented Nordic Hamstring Device (Nordbord) in Football Players. Int J Sports Physiol Perform. 2016; 11(6):721–6.
9. Markovic G, Sarabon N, Boban F, Zoric I, Jelcic M, Sos K, Scappaticci M. Nordic Hamstring Strength of Highly Trained Youth Football Players and Its Relation to Sprint Performance. J Strength Cond Res. 2020; 34(3):800–7.
10. Roe M, Malone S, Delahunt E, Collins K, Gissane C, Persson UM, Murphy JC, Blake C. Eccentric knee flexor strength profiles of 341 elite male academy and senior Gaelic football players: Do body mass and previous hamstring injury impact performance? Phys Ther Sport. 2018; 31:68–74.
11. Bourne MN, Opar DA, Williams MD, Shield AJ. Eccentric Knee Flexor Strength and Risk of Hamstring Injuries in Rugby Union: A Prospective Study. Am J Sports Med. 2015; 43(11):2663–70.
12. Opar D, Drezner J, Shield A, Williams M, Webner D, Sennett B, Kapur R, Cohen M, Ulager J, Cafengiu A, Cronholm PF. Acute injuries in track and field athletes: a 3-year observational study at the Penn Relays Carnival with epidemiology and medical coverage implications. Am J Sports Med. 2015; 43(4):816–22.
13. Lloyd RS, Faigenbaum AD, Stone MH, Oliver JL, Jeffreys I, Moody JA, Brewer C, Pierce KC, McCambridge TM, Howard R, Herrington L, Hainline B, Micheli LJ, Jaques R, Kraemer WJ, McBride MG, Best TM, Chu DA, Alvar BA, Myer GD. Position statement on youth resistance training: the 2014 International Consensus. Br J Sports Med. 2014; 48(7):498–505.
14. Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, Micheli LJ, Myer GD, Oliver JL. National Strength and Conditioning Association Position Statement on Long-Term Athletic Development. J Strength Cond Res. 2016; 30(6):1491–509.
15. Lloyd RS, Oliver JL. The youth physical development model: A new approach to long-term athletic development. Strength & Conditioning Journal. 2012; 34(3):61–72.
16. Fernandes JFT, Moran J, Clarke H, Drury B. The influence of maturation on the reliability of the Nordic hamstring exercise in male youth footballers. Translational Sport Medicine. 2020; 3(2):148–53.

17. Cumming SP, Lloyd RS, Oliver JL, Eisenmann JC, Malina RM. Bio-banding in sport: applications to competition, talent identification, and strength and conditioning of youth athletes. Strength & Conditioning Journal. 2017; 39(2):34–47.

18. Malina RM. Top 10 research questions related to growth and maturation of relevance to physical activity, performance, and fitness. Res Q Exerc Sport. 2014; 85(2):157–73.

APPENDIX 1. All pairwise comparisons of the different age groups for the absolute values of Nordic hamstring strength showing the mean, standard error of the difference, and the lower and upper 95% confidence limits. Significant ($p < 0.05$) differences are highlighted in red font (post hoc adjustment for multiple comparison using Tukey's HSD)

Tukey HSD All Pairwise Comparisons
Quantile = 2.86867, Adjusted DF = 293.2, Adjustment = Tukey-Kramer
All Pairwise Differences

Chronological Age Group	Chronological Age Group	Difference	Std Error	t Ratio	Prob > |t|	Lower 95%	Upper 95%
U13	U14	-39.812	19.88504	-2.00	0.3436	-96.856	17.2314
U13	U15	-92.807	18.79877	-4.94	< .0001*	-146.734	-38.8792
U13	U16	-109.499	22.59550	-4.85	< .0001*	-174.318	-44.6797
U13	U17	-143.100	19.20479	-7.45	< .0001*	-198.192	-88.0076
U13	U18	-152.554	21.16543	-7.21	< .0001*	-213.271	-91.8375
U14	U15	-52.994	12.21499	-4.34	0.0003*	-88.035	-17.9536
U14	U16	-69.686	17.92088	-3.89	0.0017*	-121.096	-18.2774
U14	U17	-103.288	13.51347	-7.64	< .0001*	-142.053	-64.5219
U14	U18	-112.742	16.18616	-6.97	< .0001*	-159.175	-66.3091
U15	U16	-16.692	15.69550	-1.06	0.8954	-61.717	28.3332
U15	U17	-50.293	11.08316	-4.54	0.0001*	-82.087	-18.4992
U15	U18	-59.747	14.33989	-4.17	0.0006*	-100.884	-18.6110
U16	U17	-33.601	15.97462	-2.10	0.2884	-79.427	12.2249
U16	U18	-43.055	19.03310	-2.26	0.2131	-97.655	11.5443
U17	U18	-9.454	14.40274	-0.66	0.9864	-50.771	31.8624

APPENDIX 2. All pairwise comparisons of the different age groups for the relative values of Nordic hamstring strength showing the mean, standard error of the difference, and the lower and upper 95% confidence limits. Significant ($p < 0.05$) differences are highlighted in red font (post hoc adjustment for multiple comparison using Tukey's HSD)

Tukey HSD All Pairwise Comparisons
Quantile = 2.86946, Adjusted DF = 281.5, Adjustment = Tukey-Kramer
All Pairwise Differences

Chronological Age Group	Chronological Age Group	Difference	Std Error	t Ratio	Prob > |t|	Lower 95%	Upper 95%
U13	U14	-0.83261	0.2953740	-2.82	0.0574	-1.68018	0.01495
U13	U15	-1.00024	0.2781175	-3.60	0.0051*	-1.79828	-0.20219
U13	U16	-1.01200	0.3695513	-2.74	0.0710	-2.07241	0.04841
U13	U17	-1.10295	0.2864349	-3.85	0.0020*	-1.92487	-0.28104
U13	U18	-0.84518	0.3121202	-2.71	0.0768	-1.74080	0.05044
U14	U15	-0.16763	0.1903528	-0.88	0.9509	-0.71384	0.37858
U14	U16	-0.17939	0.3119213	-0.58	0.9926	-1.07444	0.71566
U14	U17	-0.27034	0.2072105	-1.30	0.7823	-0.86493	0.32424
U14	U18	-0.01257	0.2413914	-0.05	1.0000	-0.70523	0.68010
U15	U16	-0.01176	0.2884429	-0.04	1.0000	-0.83944	0.81591
U15	U17	-0.10272	0.1753471	-0.59	0.9919	-0.60587	0.40043
U15	U18	0.15506	0.2157032	0.72	0.9795	-0.46389	0.77401
U16	U17	-0.09095	0.2947299	-0.31	0.9996	-0.93667	0.75476
U16	U18	0.16682	0.3257376	0.51	0.9957	-0.76787	1.10151
U17	U18	0.25778	0.2223961	1.16	0.8558	-0.38038	0.89593

APPENDIX 3. All pairwise comparisons for the different skeletal age groups for the student athletes for absolute Nordic hamstring strength. Significant differences are noted in the column "Prob > |t|" with an asterisk and a coloured font.

FELS Bone Age Group	FELS Bone Age Group	Difference	Std Error	t Ratio	Prob > |t|	Lower 95%	Upper 95%
10	11	-2.188	49.29283	-0.04	1.0000	-156.243	151.868
10	12	-29.533	40.81834	-0.72	0.9984	-157.103	98.037
10	13	-64.229	39.08058	-1.64	0.7799	-186.368	57.910
10	14	-96.338	38.51122	-2.50	0.2355	-216.698	24.021
10	15	-129.486	38.82598	-3.34	0.0265*	-250.829	-8.142
10	16	-157.938	41.06059	-3.85	0.0046*	-286.265	-29.610
10	17	-160.318	38.26461	-4.19	0.0012*	-279.907	-40.729
10	18	-193.303	37.81667	-5.11	< .0001*	-311.491	-75.114
11	12	-27.346	36.31838	-0.75	0.9979	-140.852	86.160
11	13	-62.042	34.35375	-1.81	0.6783	-169.408	45.324
11	14	-94.151	33.70463	-2.79	0.1218	-199.488	11.187
11	15	-127.298	34.06384	-3.74	0.0068*	-233.758	-20.838
11	16	-155.750	36.59043	-4.26	0.0009*	-270.106	-41.394
11	17	-158.131	33.42258	-4.73	0.0001*	-262.587	-53.675
11	18	-191.115	32.90880	-5.81	< .0001*	-293.965	-88.265
12	13	-34.696	20.40917	-1.70	0.7462	-98.481	29.089
12	14	-66.805	19.29654	-3.46	0.0176*	-127.112	-6.497
12	15	-99.952	19.91731	-5.02	< .0001*	-162.200	-37.705
12	16	-128.404	23.98362	-5.35	< .0001*	-203.360	-53.448
12	17	-130.785	18.79955	-6.96	< .0001*	-189.539	-72.030
12	18	-163.769	17.87017	-9.16	< .0001*	-219.619	-107.919
13	14	-32.109	15.28109	-2.10	0.4745	-79.867	15.649
13	15	-65.257	16.05785	-4.06	0.0020*	-115.442	-15.071
13	16	-93.708	20.88945	-4.49	0.0004*	-158.994	-28.422
13	17	-96.089	14.64849	-6.56	< .0001*	-141.870	-50.308
13	18	-129.073	13.43496	-9.61	< .0001*	-171.062	-87.085
14	15	-33.148	14.61768	-2.27	0.3654	-78.832	12.537
14	16	-61.599	19.80382	-3.11	0.0522	-123.493	0.294
14	17	-63.980	13.05375	-4.90	< .0001*	-104.777	-23.183
14	18	-96.964	11.67563	-8.30	< .0001*	-133.454	-60.474
15	16	-28.452	20.40917	-1.39	0.8995	-92.237	35.333
15	17	-30.832	13.95504	-2.21	0.4023	-74.446	12.781
15	18	-63.817	12.67530	-5.03	< .0001*	-103.431	-24.203
16	17	-2.381	19.31988	-0.12	1.0000	-62.761	58.000
16	18	-35.365	18.41678	-1.92	0.6003	-92.923	22.193
17	18	-32.984	10.83452	-3.04	0.0629	-66.846	0.877

APPENDIX 4. All pairwise comparisons of relative Nordic hamstring strength for the different skeletal age groups. No significant differences were found for any between-group comparisons.

FELS Bone Age Group	FELS Bone Age Group	Difference	Std Error	t Ratio	Prob > |t|	Lower 95%	Upper 95%
10	11	0.47335	0.9687062	0.49	0.9999	-2.55567	3.502366
10	12	-0.20649	0.7398616	-0.28	1.0000	-2.51994	2.106965
10	13	-0.76756	0.7074430	-1.08	0.9760	-2.97965	1.444518
10	14	-0.82032	0.7007274	-1.17	0.9620	-3.01140	1.370768
10	15	-0.60721	0.7054303	-0.86	0.9947	-2.81300	1.598585
10	16	-1.06531	0.7322731	-1.45	0.8751	-3.35503	1.224416
10	17	-0.86670	0.6980271	-1.24	0.9464	-3.04934	1.315940
10	18	-0.99327	0.6922274	-1.43	0.8834	-3.15777	1.171239
11	12	-0.67983	0.7398616	-0.92	0.9918	-2.99328	1.633619
11	13	-1.24091	0.7074430	-1.75	0.7122	-3.45299	0.971173
11	14	-1.29366	0.7007274	-1.85	0.6512	-3.48475	0.897422
11	15	-1.08055	0.7054303	-1.53	0.8397	-3.28634	1.125239
11	16	-1.53865	0.7322731	-2.10	0.4747	-3.82838	0.751070
11	17	-1.34005	0.6980271	-1.92	0.6007	-3.52269	0.842595
11	18	-1.46661	0.6922274	-2.12	0.4628	-3.63112	0.697893
12	13	-0.56108	0.3308762	-1.70	0.7488	-1.59569	0.473529
12	14	-0.61383	0.3162631	-1.94	0.5860	-1.60274	0.375084
12	15	-0.40072	0.3265508	-1.23	0.9499	-1.42180	0.620364
12	16	-0.85882	0.3810870	-2.25	0.3743	-2.05043	0.332789
12	17	-0.66021	0.3102343	-2.13	0.4564	-1.63028	0.309849
12	18	-0.78678	0.2969549	-2.65	0.1715	-1.71532	0.141759
13	14	-0.05275	0.2304404	-0.23	1.0000	-0.77331	0.667806
13	15	0.16036	0.2443682	0.66	0.9992	-0.60375	0.924468
13	16	-0.29774	0.3135406	-0.95	0.9898	-1.27814	0.682658
13	17	-0.09914	0.2220939	-0.45	1.0000	-0.79359	0.595323
13	18	-0.22570	0.2031320	-1.11	0.9722	-0.86087	0.409465
14	15	0.21311	0.2241856	0.95	0.9897	-0.48789	0.914111
14	16	-0.24499	0.2980789	-0.82	0.9961	-1.17705	0.687063
14	17	-0.04638	0.1996724	-0.23	1.0000	-0.67073	0.577966
14	18	-0.17295	0.1783422	-0.97	0.9883	-0.73060	0.384703
15	16	-0.45810	0.3089726	-1.48	0.8628	-1.42422	0.508015
15	17	-0.25950	0.2155971	-1.20	0.9552	-0.93364	0.414649
15	18	-0.38606	0.1960077	-1.97	0.5659	-0.99895	0.226829
16	17	0.19861	0.2916744	0.68	0.9990	-0.71342	1.110636
16	18	0.07204	0.2775083	0.26	1.0000	-0.79569	0.939774
17	18	-0.12657	0.1674183	-0.76	0.9979	-0.65006	0.396929

APPENDIX 5. All pairwise comparisons of relative Nordic hamstring strength for the student athletes – age and sport, with post-hoc adjustment (Tukey HSD) for multiple comparison. Significant effects are highlighted in the Prob > |t| column with an asterisk and coloured font.

Tukey HSD All Pairwise Comparisons
Quantile = 3.52198, Adjusted DF = 278.9, Adjustment = Tukey-Kramer
All Pairwise Differences

SPORT 2	Chronological Age Group	SPORT 2	Chronological Age Group	Difference	Std Error	t Ratio	Prob > |t|	Lower 95%	Upper 95%
Athletics	U13	Athletics	U14	-0.01462	0.4174617	-0.04	1.0000	-1.48491	1.45568
Athletics	U13	Athletics	U15	-0.69500	0.3555572	-1.95	0.8876	-1.94727	0.55726
Athletics	U13	Athletics	U16	-0.67331	0.3574688	-1.88	0.9156	-1.93231	0.58569
Athletics	U13	Athletics	U17	-1.36840	0.3529221	-3.88	0.0153*	-2.61139	-0.12542
Athletics	U13	Athletics	U18	-1.54723	0.3693259	-4.19	0.0048*	-2.84799	-0.24647
Athletics	U13	Football	U13	-0.83713	0.3607736	-2.32	0.6678	-2.10777	0.43351
Athletics	U13	Football	U14	-1.18520	0.3344155	-3.54	0.0467*	-2.36300	-0.00739
Athletics	U13	Football	U15	-1.27168	0.3332591	-3.82	0.0190*	-2.44541	-0.09794
Athletics	U13	Football	U16	-0.41366	0.7029482	-0.59	1.0000	-2.88943	2.06211
Athletics	U13	Football	U17	-1.38900	0.3461831	-4.01	0.0094*	-2.60825	-0.16975
Athletics	U13	Football	U18	-1.30046	0.3497937	-3.72	0.0265*	-2.53243	-0.06849
Athletics	U13	Multi-sport	U13	1.09518	0.7296358	1.50	0.9900	-1.47459	3.66494
Athletics	U13	Multi-sport	U14	-1.03998	0.4496943	-2.31	0.6735	-2.62379	0.54384
Athletics	U13	Multi-sport	U15	-0.77599	0.3889837	-1.99	0.8694	-2.14598	0.59400
Athletics	U13	Multi-sport	U16	-1.69099	0.5473588	-3.09	0.1676	-3.61878	0.23680
Athletics	U13	Multi-sport	U17	-0.29342	0.4317714	-0.68	1.0000	-1.81411	1.22728
Athletics	U13	Multi-sport	U18	0.57020	0.5572685	1.02	0.9999	-1.39249	2.53289
Athletics	U14	Athletics	U15	-0.68039	0.3346714	-2.03	0.8506	-1.85909	0.49832
Athletics	U14	Athletics	U16	-0.65869	0.3512654	-1.88	0.9186	-1.89584	0.57846
Athletics	U14	Athletics	U17	-1.35379	0.3482578	-3.89	0.0148*	-2.58034	-0.12723
Athletics	U14	Athletics	U18	-1.53262	0.3649971	-4.20	0.0046*	-2.81813	-0.24710
Athletics	U14	Football	U13	-0.82252	0.3563366	-2.31	0.6767	-2.07753	0.43249
Athletics	U14	Football	U14	-1.17058	0.3296238	-3.55	0.0456*	-2.33151	-0.00965
Athletics	U14	Football	U15	-1.25706	0.3284506	-3.83	0.0182*	-2.41386	-0.10026
Athletics	U14	Football	U16	-0.39904	0.7006813	-0.57	1.0000	-2.86683	2.06875
Athletics	U14	Football	U17	-1.37439	0.3415566	-4.02	0.0090*	-2.57734	-0.17143
Athletics	U14	Football	U18	-1.28584	0.3452156	-3.72	0.0259*	-2.50169	-0.07000
Athletics	U14	Multi-sport	U13	1.10979	0.7274521	1.53	0.9881	-1.45228	3.67187
Athletics	U14	Multi-sport	U14	-1.02536	0.4461425	-2.30	0.6839	-2.59667	0.54594
Athletics	U14	Multi-sport	U15	-0.76137	0.3848720	-1.98	0.8771	-2.11689	0.59414
Athletics	U14	Multi-sport	U16	-1.67637	0.5444445	-3.08	0.1719	-3.59390	0.24115
Athletics	U14	Multi-sport	U17	-0.27880	0.4280709	-0.65	1.0000	-1.78646	1.22886
Athletics	U14	Multi-sport	U18	0.58482	0.5544063	1.05	0.9999	-1.36779	2.53743
Athletics	U15	Athletics	U16	0.02169	0.2584407	0.08	1.0000	-0.88853	0.93192
Athletics	U15	Athletics	U17	-0.67340	0.2691777	-2.50	0.5311	-1.62144	0.27464
Athletics	U15	Athletics	U18	-0.85223	0.2919248	-2.92	0.2489	-1.88039	0.17592
Athletics	U15	Football	U13	-0.14213	0.2812871	-0.51	1.0000	-1.13282	0.84856
Athletics	U15	Football	U14	-0.49019	0.2465735	-1.99	0.8726	-1.35862	0.37823
Athletics	U15	Football	U15	-0.57667	0.2450029	-2.35	0.6432	-1.43957	0.28622

SPORT 2	Chronological Age Group	SPORT 2	Chronological Age Group	Difference	Std Error	t Ratio	Prob > |t|	Lower 95%	Upper 95%
Athletics	U15	Football	U16	0.28134	0.6656583	0.42	1.0000	-2.06309	2.62578
Athletics	U15	Football	U17	-0.69400	0.2623119	-2.65	0.4239	-1.61786	0.22986
Athletics	U15	Football	U18	-0.60546	0.2670588	-2.27	0.7061	-1.54603	0.33512
Athletics	U15	Multi-sport	U13	1.79018	0.6937818	2.58	0.4718	-0.65331	4.23367
Athletics	U15	Multi-sport	U14	-0.34498	0.3888313	-0.89	1.0000	-1.71443	1.02448
Athletics	U15	Multi-sport	U15	-0.08099	0.3166593	-0.26	1.0000	-1.19626	1.03428
Athletics	U15	Multi-sport	U16	-0.99599	0.4985644	-2.00	0.8680	-2.75192	0.75995
Athletics	U15	Multi-sport	U17	0.40159	0.3679556	1.09	0.9998	-0.89435	1.69752
Athletics	U15	Multi-sport	U18	1.26520	0.5094242	2.48	0.5449	-0.52898	3.05939
Athletics	U16	Athletics	U17	-0.69509	0.2547918	-2.73	0.3662	-1.59246	0.20228
Athletics	U16	Athletics	U18	-0.87392	0.2912006	-3.00	0.2070	-1.89953	0.15168
Athletics	U16	Football	U13	-0.16382	0.2836996	-0.58	1.0000	-1.16301	0.83536
Athletics	U16	Football	U14	-0.51189	0.2493221	-2.05	0.8401	-1.39000	0.36622
Athletics	U16	Football	U15	-0.59837	0.2477690	-2.42	0.5971	-1.47100	0.27427
Athletics	U16	Football	U16	0.25965	0.6666813	0.39	1.0000	-2.08839	2.60769
Athletics	U16	Football	U17	-0.71569	0.2648973	-2.70	0.3843	-1.64866	0.21727
Athletics	U16	Football	U18	-0.62715	0.2695987	-2.33	0.6635	-1.57667	0.32237
Athletics	U16	Multi-sport	U13	1.76849	0.6947634	2.55	0.4980	-0.67846	4.21543
Athletics	U16	Multi-sport	U14	-0.36667	0.3905801	-0.94	1.0000	-1.74228	1.00895
Athletics	U16	Multi-sport	U15	-0.10268	0.3188042	-0.32	1.0000	-1.22550	1.02014
Athletics	U16	Multi-sport	U16	-1.01768	0.4999295	-2.04	0.8492	-2.77842	0.74306
Athletics	U16	Multi-sport	U17	0.37989	0.3698031	1.03	0.9999	-0.92255	1.68233
Athletics	U16	Multi-sport	U18	1.24351	0.5107602	2.43	0.5822	-0.55538	3.04240
Athletics	U17	Athletics	U18	-0.17883	0.2586926	-0.69	1.0000	-1.08994	0.73228
Athletics	U17	Football	U13	0.53127	0.2779487	1.91	0.9053	-0.44766	1.51020
Athletics	U17	Football	U14	0.18321	0.2427583	0.75	1.0000	-0.67178	1.03820
Athletics	U17	Football	U15	0.09673	0.2411629	0.40	1.0000	-0.75264	0.94610
Athletics	U17	Football	U16	0.95474	0.6642545	1.44	0.9938	-1.38475	3.29424
Athletics	U17	Football	U17	-0.02060	0.2587289	-0.08	1.0000	-0.93184	0.89064
Athletics	U17	Football	U18	0.06794	0.2635403	0.26	1.0000	-0.86024	0.99613
Athletics	U17	Multi-sport	U13	2.46358	0.6924350	3.56	0.0447*	0.02483	4.90232
Athletics	U17	Multi-sport	U14	0.32842	0.3864231	0.85	1.0000	-1.03255	1.68940
Athletics	U17	Multi-sport	U15	0.59241	0.3136976	1.89	0.9139	-0.51243	1.69725
Athletics	U17	Multi-sport	U16	-0.32259	0.4966886	-0.65	1.0000	-2.07192	1.42674
Athletics	U17	Multi-sport	U17	1.07499	0.3654099	2.94	0.2369	-0.21198	2.36195
Athletics	U17	Multi-sport	U18	1.93860	0.5075885	3.82	0.0188*	0.15088	3.72632
Athletics	U18	Football	U13	0.71010	0.2985014	2.38	0.6244	-0.34122	1.76142
Athletics	U18	Football	U14	0.36204	0.2660436	1.36	0.9967	-0.57496	1.29904
Athletics	U18	Football	U15	0.27556	0.2645886	1.04	0.9999	-0.65632	1.20743
Athletics	U18	Football	U16	1.13357	0.6731134	1.68	0.9682	-1.23712	3.50427
Athletics	U18	Football	U17	0.15823	0.2806924	0.56	1.0000	-0.83036	1.14683
Athletics	U18	Football	U18	0.24678	0.2851335	0.87	1.0000	-0.75746	1.25101
Athletics	U18	Multi-sport	U13	2.64241	0.7009378	3.77	0.0222*	0.17372	5.11110
Athletics	U18	Multi-sport	U14	0.50726	0.4014604	1.26	0.9986	-0.90668	1.92119
Athletics	U18	Multi-sport	U15	0.77124	0.3320449	2.32	0.6661	-0.39821	1.94070

SPORT 2	Chronological Age Group	SPORT 2	Chronological Age Group	Difference	Std Error	t Ratio	Prob > |t|	Lower 95%	Upper 95%
Athletics	U18	Multi-sport	U16	-0.14376	0.5084753	-0.28	1.0000	-1.93460	1.64709
Athletics	U18	Multi-sport	U17	1.25382	0.3812768	3.29	0.0994	-0.08903	2.59667
Athletics	U18	Multi-sport	U18	2.11743	0.5191278	4.08	0.0073*	0.28908	3.94579
Football	U13	Football	U14	-0.34806	0.2319494	-1.50	0.9900	-1.16498	0.46886
Football	U13	Football	U15	-0.43454	0.2519972	-1.72	0.9604	-1.32207	0.45299
Football	U13	Football	U16	0.42347	0.6684425	0.63	1.0000	-1.93077	2.77772
Football	U13	Football	U17	-0.55187	0.2692804	-2.05	0.8420	-1.50027	0.39653
Football	U13	Football	U18	-0.46333	0.2736955	-1.69	0.9666	-1.42728	0.50063
Football	U13	Multi-sport	U13	1.93231	0.6964696	2.77	0.3355	-0.52064	4.38526
Football	U13	Multi-sport	U14	-0.20284	0.3936070	-0.52	1.0000	-1.58912	1.18343
Football	U13	Multi-sport	U15	0.06114	0.3225055	0.19	1.0000	-1.07472	1.19700
Football	U13	Multi-sport	U16	-0.85386	0.5022979	-1.70	0.9653	-2.62294	0.91523
Football	U13	Multi-sport	U17	0.54372	0.3729987	1.46	0.9927	-0.76998	1.85741
Football	U13	Multi-sport	U18	1.40733	0.5130787	2.74	0.3563	-0.39972	3.21439
Football	U14	Football	U15	-0.08648	0.2098376	-0.41	1.0000	-0.82552	0.65257
Football	U14	Football	U16	0.77154	0.6544613	1.18	0.9994	-1.53346	3.07654
Football	U14	Football	U17	-0.20381	0.2322766	-0.88	1.0000	-1.02188	0.61427
Football	U14	Football	U18	-0.11526	0.2364071	-0.49	1.0000	-0.94788	0.71736
Football	U14	Multi-sport	U13	2.28037	0.6831881	3.34	0.0865	-0.12580	4.68655
Football	U14	Multi-sport	U14	0.14522	0.3695978	0.39	1.0000	-1.15650	1.44694
Football	U14	Multi-sport	U15	0.40921	0.2927215	1.40	0.9954	-0.62175	1.44017
Football	U14	Multi-sport	U16	-0.50579	0.4837140	-1.05	0.9999	-2.20943	1.19784
Football	U14	Multi-sport	U17	0.89178	0.3475689	2.57	0.4827	-0.33235	2.11591
Football	U14	Multi-sport	U18	1.75540	0.4948998	3.55	0.0462*	0.01237	3.49843
Football	U15	Football	U16	0.85802	0.6481493	1.32	0.9976	-1.42475	3.14079
Football	U15	Football	U17	-0.11733	0.2106229	-0.56	1.0000	-0.85914	0.62448
Football	U15	Football	U18	-0.02878	0.2216538	-0.13	1.0000	-0.80944	0.75188
Football	U15	Multi-sport	U13	2.36685	0.6826228	3.47	0.0591	-0.03733	4.77104
Football	U15	Multi-sport	U14	0.23170	0.3685519	0.63	1.0000	-1.06634	1.52973
Football	U15	Multi-sport	U15	0.49568	0.2913998	1.70	0.9651	-0.53062	1.52199
Football	U15	Multi-sport	U16	-0.41931	0.4829153	-0.87	1.0000	-2.12013	1.28151
Football	U15	Multi-sport	U17	0.97826	0.3464564	2.82	0.3044	-0.24195	2.19847
Football	U15	Multi-sport	U18	1.84188	0.4941191	3.73	0.0257*	0.10160	3.58216
Football	U16	Football	U17	-0.97534	0.6529113	-1.49	0.9905	-3.27489	1.32420
Football	U16	Football	U18	-0.88680	0.6614025	-1.34	0.9972	-3.21625	1.44265
Football	U16	Multi-sport	U13	1.50884	0.9214382	1.64	0.9757	-1.73645	4.75413
Football	U16	Multi-sport	U14	-0.62632	0.7203506	-0.87	1.0000	-3.16338	1.91074
Football	U16	Multi-sport	U15	-0.36233	0.6840967	-0.53	1.0000	-2.77171	2.04705
Football	U16	Multi-sport	U16	-1.27733	0.7850361	-1.63	0.9771	-4.04221	1.48755
Football	U16	Multi-sport	U17	0.12024	0.7093001	0.17	1.0000	-2.37790	2.61839
Football	U16	Multi-sport	U18	0.98386	0.7919774	1.24	0.9989	-1.80547	3.77319
Football	U17	Football	U18	0.08854	0.2422806	0.37	1.0000	-0.76476	0.94185
Football	U17	Multi-sport	U13	2.48418	0.6890247	3.61	0.0384*	0.05745	4.91091
Football	U17	Multi-sport	U14	0.34902	0.3802783	0.92	1.0000	-0.99031	1.68836
Football	U17	Multi-sport	U15	0.61301	0.3060963	2.00	0.8657	-0.46505	1.69108

SPORT 2	Chronological Age Group	SPORT 2	Chronological Age Group	Difference	Std Error	t Ratio	Prob > |t|	Lower 95%	Upper 95%
Football	U17	Multi-sport	U16	-0.30199	0.4919230	-0.61	1.0000	-2.03453	1.43056
Football	U17	Multi-sport	U17	1.09559	0.3589055	3.05	0.1833	-0.16847	2.35964
Football	U17	Multi-sport	U18	1.95920	0.5029263	3.90	0.0143*	0.18791	3.73050
Football	U18	Multi-sport	U13	2.39564	0.6908457	3.47	0.0591	-0.03751	4.82878
Football	U18	Multi-sport	U14	0.26048	0.3835681	0.68	1.0000	-1.09044	1.61140
Football	U18	Multi-sport	U15	0.52447	0.3101738	1.69	0.9670	-0.56796	1.61690
Football	U18	Multi-sport	U16	-0.39053	0.4944706	-0.79	1.0000	-2.13205	1.35099
Football	U18	Multi-sport	U17	1.00704	0.3623893	2.78	0.3326	-0.26929	2.28337
Football	U18	Multi-sport	U18	1.87066	0.5054183	3.70	0.0281*	0.09058	3.65073
Multi-sport	U13	Multi-sport	U14	-2.13515	0.7464162	-2.86	0.2822	-4.76402	0.49371
Multi-sport	U13	Multi-sport	U15	-1.87117	0.7114918	-2.63	0.4353	-4.37703	0.63469
Multi-sport	U13	Multi-sport	U16	-2.78617	0.8090203	-3.44	0.0635	-5.63552	0.06319
Multi-sport	U13	Multi-sport	U17	-1.38859	0.7357573	-1.89	0.9143	-3.97992	1.20273
Multi-sport	U13	Multi-sport	U18	-0.52498	0.8157576	-0.64	1.0000	-3.39806	2.34811
Multi-sport	U14	Multi-sport	U15	0.26399	0.4123967	0.64	1.0000	-1.18847	1.71644
Multi-sport	U14	Multi-sport	U16	-0.65101	0.5691634	-1.14	0.9996	-2.65560	1.35357
Multi-sport	U14	Multi-sport	U17	0.74656	0.4595539	1.62	0.9775	-0.87198	2.36510
Multi-sport	U14	Multi-sport	U18	1.61018	0.5790657	2.78	0.3315	-0.42928	3.64964
Multi-sport	U15	Multi-sport	U16	-0.91500	0.5117659	-1.79	0.9454	-2.71743	0.88743
Multi-sport	U15	Multi-sport	U17	0.48257	0.3998759	1.21	0.9992	-0.92578	1.89093
Multi-sport	U15	Multi-sport	U18	1.34619	0.5332920	2.52	0.5140	-0.53205	3.22444
Multi-sport	U16	Multi-sport	U17	1.39757	0.5390543	2.59	0.4627	-0.50097	3.29611
Multi-sport	U16	Multi-sport	U18	2.26119	0.6577946	3.44	0.0647	-0.05555	4.57793
Multi-sport	U17	Multi-sport	U18	0.86362	0.5652598	1.53	0.9879	-1.12722	2.85445

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Does player age influence match physical performance? A longitudinal four-season analysis in Spanish Soccer LaLiga

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ABSTRACT: This study aims to analyse the evolution of match running performance in relation to the age distribution of professional soccer players using a large-scale analysis. An explorational-longitudinal and retrospective study was designed and a total of 36,883 individual match observations were collected on outfield players competing across four consecutive Spanish LaLiga seasons (from 2015/16 to 2018/19), using an optical tracking system (ChyronHego). Soccer players were divided into 3 age groups: young (18–24 years old), middle-aged (25–30 years old), and seniors (31–41 years old). Relative total distance (TD/min), distance covered at 21–24 $km \cdot h^{-1}$ (HIRD/min), and > 24 $km \cdot h^{-1}$ per minute (VHIRD/min) were analysed; also, the number of efforts at 21–24 $km \cdot h^{-1}$ (Sp21) and > 24 $km \cdot h^{-1}$ (Sp24) were taken into consideration. Seasons were divided into four phases (P): P1 (matches 1–10), P2 (11–19), P3 (20–29), and P4 (30–38). The results showed that young players covered significantly greater TD, HIRD and VHIRD than the rest of the players ($p < .05$) in all season phases. In addition, TD significantly decreased along season phases in all player age group ($p < .01$). Crucially, young players performed significantly greater numbers of Sp21 and Sp24 than the rest of the players ($p < .05$) in all season phases. In addition, Sp21 and SP24 significantly decreased in middle-aged ($p < .01$) and senior players ($p < .05$) across the seasons. This study demonstrated that players' match running performance decreases with increasing years, especially in high-intensity running distances.

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INTRODUCTION

Soccer players' external load during competition has been widely studied [1]. External load, mainly explored through the analysis of match running performance, has been linked to different contextual-related variables such as the competitive standard and the country of the competition (First Spanish Division vs. Second Spanish Division: [2]; FA Premier League, Championship, vs. League One: [3]; three competitive leagues in Norway: [4]). Playing formation [5], playing style [6] and playing position [6, 7] have also been shown to impact running performance by means of the interplay between physical and tactical demands. Other contextual-related variables such as fixture congestion [8], match location, and match status [9], or even the recent pandemic lockdown [10], have also been related to soccer players' external load.

The influence of age is another variable related to the extensive body of research analysing match running performance [11]. It is well known that the aging process influences athletes' physical and competitive performance [12], but there is slight evidence from examining the effects of age on competitive match performance in professional soccer players. For instance, a study that analysed match running performance of Spanish First and Second division players in the 2017/18 season, using a computerized tracking system, reported that professional soccer players aged ≥ 30 years exhibited less total distance (TD) covered and reduced distance covered at different velocities (medium-speed: 14–21 $km \cdot h^{-1}$; high-speed running [HSR]: 21 $km \cdot h^{-1}$; very HSR: 21–24 $km \cdot h^{-1}$, sprinting speed: > 24 $km \cdot h^{-1}$) compared with younger players (< 30 years) [13]. Similarly, a recent study focused on the same season reported that players under 25.2 years showed lower variability for high-intensity activities (21–24 $km \cdot h^{-1}$ and > 24 $km \cdot h^{-1}$) in comparison with players over 33.1 years [14]. In addition, Lorenzo-Martínez et al. [15] found that soccer players aged between 31 and 38 years who competed in the First Spanish Division performed a significantly lower total number of

accelerations and decelerations in comparison with younger players. However, these types of research have only considered a transversal perspective and they have not analysed the influence of age on match running performance across the years.

Considering a longitudinal perspective, recent research has shown that in elite soccer players the TD and high-intensity running distance significantly decreased each year that they got older [16]. However, this research only analysed TD and high-intensity running distance, necessitating a deeper analysis about match physical demands. In the same vein, Errekagori et al. [11] analysed the last eight seasons (from 2011–12 to 2018–19) in the Spanish Football First Division, reporting a descending trend in TD covered by soccer teams, although only TD was considered as a physical variable and age groups were not analysed. A study based on the Chinese Soccer Super League reported a significant decrease in the running performance of players, especially for high-intensity running [17]. Another similar study focused on the first German league (Bundesliga) during three seasons (2012/13–2015/16) evaluated the effects of age in match running performance, showing a significantly lower performance in professional soccer players aged > 30 years in the TD covered, the number of fast runs, and the number of sprints compared with younger players (≤ 30 years; [18]). Taken together, these results along with previous research point to a significant decrease in physical performance observed beyond the third decade of life in athletic populations [19–21]. However, the physical performance evolution across the season phases considering different age groups has not been analysed and a deeper analysis based on high-intensity running distance is also necessary. This fact is highly relevant taking into consideration that the current soccer game is evolving towards shorter, higher intensity play periods where players cover higher sprinting distances and perform more sprints and explosive actions [22–24], placing subsequently higher physical demands on the players over the temporal course of the season [25].

Thus, we consider of special interest the study of the evolution of match running performance within the season in relation to the age distribution of the players. It would also be interesting to know how physical performance changes over the years, since there are fewer studies carried out on the age effect over the seasons and these studies have only focused on analysing differences between age groups, without considering the evolution within each age group. In order to accomplish these goals, we conducted a large-scale analysis of match running performance of soccer players who competed in the First Spanish soccer league (LaLiga) across four consecutive seasons (from 2015/16 to 2018/19), also analysing the evolution of physical performance across the different phases of each season.

MATERIALS AND METHODS

Sample and procedure

The sample was composed of 36,883 individual match observations of 1,037 professional soccer players who competed in the First Division of the Spanish soccer league (LaLiga) across four seasons (from 2015/16 to 2018/19; n = 1,985 matches). All players who participated in matches (starters and non-starters) were included. Goalkeepers and players who played less than 10 minutes during the matches were excluded because it was observed that average values obtained from these players were higher than the team average [26]. Thus, 4,252 recordings were excluded due to inclusion criteria, issues related to repeated signal loss by the system, or adverse weather conditions during the match that hindered accurate data collection. Data were provided to the authors by LaLiga, and the study received ethical approval from the University of Extremadura; Vice-Rectorate of Research, Transfer and Innovation – Delegation of the Bioethics and Biosafety Commission (Protocol number: 239/2019).

Variables

Players' age. Two variables were used to analyse this construct from two different perspectives: 1) Players' age group: according to previous studies [13, 14], soccer players were divided into 3 age groups: young (18–24 years old), middle-aged (25–30 years old), and seniors (31–41 years old); 2) Centred players' age: a continuous variable was generated to explore the longitudinal age effects across the four seasons (i.e., age group-mean centred; the players' age in each season was centred to the players' age group mean in each season).
Match running performance. The relative distance covered by the teams was analysed by Mediacoach at different speed ranges [23, 27]: distance covered between 21 and 24 $km \cdot h^{-1}$ (i.e., HIRD/min = high-intensity running distance per minute) and distance covered at more than 24 $km \cdot h^{-1}$ (i.e., VHIRD/min = very high-intensity running distance per minute). The relative TD variable corresponds to the summation of all the distances covered by the players per minute. Likewise, the number of high-intensity efforts performed per minute was also divided into two speed ranges: the number of very high-intensity running efforts between 21 and 24 $km \cdot h^{-1}$ (i.e., Sp21) and the number of sprints at speeds above 24 $km \cdot h^{-1}$ (i.e., Sp24). Absolute values of match running performance variables were normalized to relative values per unit of time to consider the possible differences in the total playing time of soccer matches. All the efforts that implied a minimum movement of one metre, which was maintained for a 1-second minimum, were recorded. Any recording at a speed of over 80% of the value of that category (i.e., > 24 $km \cdot h^{-1}$) was considered as a single register.

These data were obtained using an optical tracking system (ChyronHego; TRACAB, New York, US). This multi-camera tracking system consists of 8 super 4K high dynamic range cameras based on a positioning system (Tracab – ChyronHego VTS) that film from several angles and analyse X and Y positions of each player, thus providing real-time three-dimensional tracking. This instrument is also based on the correction of the semi-automatic VTS (the manual part of the process). The validity and reliability of the Tracab video-tracking system have been analysed, reporting average measurement errors of 2% for the total TD [2, 28]. In addition, recent studies have previously tested the agreement between the Mediacoach system

and GPS devices [27]. Specifically, the magnitude of the intraclass correlation coefficients (ICC) was higher than .90.

Season phases. All matches of each round of the four seasons were recorded. Similar to previous research [25, 29], every season was split into four blocks of matches. Specifically, according to the number of matches per season, every season was split into four phases: matches 1–10 (i.e., Phase 1 = P1), matches 11–19 (i.e., Phase 2 = P2), matches 20–29 (i.e., Phase 3 = P3), and matches 30–38 (i.e., Phase 4 = P4).

Statistical analysis

All statistical analyses were performed using R-studio [30]. Taking into account the characteristics of the sample, organized hierarchically, nested in groups, and with a longitudinal structure, we considered that the best procedure to analyse the data is through linear mixed models (LMM).

LMM have demonstrated their ability to cope with unbalanced and repeated-measures data [31]. For instance, variables about distances covered in matches are nested into players (i.e., each player has a record for every match they have participated in, and each match has observations of several players). Players, in turn, are also nested into different teams every season. Thus, the cross-classified multilevel models are suitable for data structures that are not purely hierarchical. Consequently, a general multilevel-modelling strategy was applied where fixed and random effects in different steps were included [31].

First, unconditional models were analysed exclusively including dependent variables (i.e., distance covered variables), to determine whether the grouping variables at Levels 2 and 3 (i.e., Players and Teams) significantly affect the intercept of each dependent variable (intercepts represent the estimated mean of each variable). Only at Level 2 (players) did relevant values of variability appear, verified from the intraclass correlation coefficient (ICC) with scores greater than 10% [31]. Subsequently, different models were performed for each of the dependent variables, introducing as fixed effects the players' age, firstly centred for each player, and later age group and season phases. Following the procedure proposed by Heck and Thomas [31], models with different random effects (intercepts and slope) were created for each variable. Model comparison for each step was done using the Akaike information criterion (AIC; [32]) and a chi-square likelihood ratio test [33], where a lower value represented a better fitting model.

Final models, presented in Tables 2 and 3, were chosen according to better fit values of AIC, chi-square likelihood ratio test, and the significant effect of the variables. We used maximum likelihood (ML) estimation for model comparison, and, for the final model of each distance variable, we refitted the best model using restricted maximum likelihood (REML) estimation. The intercept represents the predicted value of the dependent variable when all the independent variables have a value of 0. The slope indicates the steepness of the regression line between dependent and independent variables (i.e., physical demands and player's age centred). We reported marginal and conditional R^2 metrics for each LMM to provide some measure of effect sizes [34]. The level of significance was set to $p < .05$.

RESULTS

Players, matches, and minutes distribution

Table 1 displays the matches' and minutes' mean distribution of all the players who participated in the study. A large number of individual match observations were registered in G2 (19,177). In general, the players of G1 played fewer matches and minutes than the players of G2 and G3 across the four seasons, whereas the players of G3 played more matches (except for season 15/16) and minutes than the players of G1 and G2 across the four seasons.

Age differences in match running performance

Regarding match running performance, Table 2 displays the intercepts and slopes of TD, HIRD, and VHIRD across the years according to age group in different season phases. The intercept represents the estimated mean of each variable when the players' age centred variable has a value of 0. In general, young players covered significantly greater TD, HIRD, and VHIRD than the rest of the players ($p < .05$) in all the season phases. The senior players covered the lowest values ($p < .05$). In addition, all players covered significantly less TD, HIRD, and VHIRD in P1 compared to the rest of the season phases ($p < .05$), with young players covering higher values.

TABLE 1. Mean of number of matches and minutes played per season and group

Season	G1 (n = 7,399)		G2 (n = 19,177)		G3 (n = 10,397)	
	Matches	Minutes	Matches	Minutes	Matches	Minutes
15/16	13.10	58.88	21.09	71.23	20.32	73.35
16/17	14.24	61.17	19.69	71.62	20.11	74.70
17/18	12.59	59.33	19.80	72.08	20.59	75.94
18/19	14.69	64.42	21.11	72.10	21.11	74.13

Note. G1 = between 18–24 years old; G2 = between 25–30 years old; G3 = between 31–41 years old.

TABLE 2. Player´s match TD, HIRD and VHIRD according to different age groups depending on season phases

Variables		TD (m/min.)						HIRD (m/min.)						VHIRD (m/min.)					
		Intercept (SE)	DG	DP	Slope (SE)	DG	DP	Intercept (SE)	DG	DP	Slope (SE)	DG	DP	Intercept (SE)	DG	DP	Slope (SE)	DG	DP
P1	G1	114.1 (.51)	bc	23	-.67 (.23)**		34	3.57 (.06)	bc	234	.00 (.04)	b		3.63 (.08)	bc	234	.03 (.05)	bc	
	G2	111.8 (.42)	ac	234	-.94 (.28)***		24	3.31 (.07)	ac	234	-.09 (.08)***	a	234	3.25 (.09)	ac	234	-.10 (.05)***	a	2
	G3	109.6 (.39)	ab	234	-.98 (.23)***		2	2.92 (.05)	ab	234	-.07 (.08)**			2.60 (.01)	ab	234	-.08 (.04)**	a	
P2	G1	114.7 (.51)	bc	14	-.95 (.23)***	bc	34	3.80 (.06)	bc	14	.01 (.04)			3.81 (.08)	bc	1	.03 (.05)		
	G2	113.2 (.47)	ac	134	-.45 (.18)***	a	134	3.54 (.08)	ac	14	-.01 (.08)		1	3.45 (.06)	ac	14	-.02 (.02)	a	1
	G3	111.1 (.59)	ab	14	-.52 (.15)***		13	3.14 (.06)	ab	14	-.02 (.08)			2.73 (.09)	ab	1	-.03 (.02)		
P3	G1	114.7 (.51)	bc	14	-1.75 (.23)***	bc	12	3.82 (.06)	bc	14	-.04 (.04)	b		3.82 (.08)	bc	1	.05 (.04)	bc	
	G2	112.8 (.41)	ac	124	-.94 (.11)***	a	24	3.51 (.08)	ac	14	-.02 (.08)		1	3.42 (.06)	ac	1	-.06 (.01)**	a	
	G3	111.3 (.59)	ab	14	-.88 (.15)***	a	2	3.13 (.06)	ab	14	-.05 (.02)*			2.77 (.09)	ab	1	-.05 (.03)*	a	
P4	G1	114.0 (.50)	bc	23	-2.08 (.23)***	bc	12	3.69 (.06)	bc	123	-.00 (.04)			3.83 (.08)	bc	1	-.04 (.04)		
	G2	112.2 (1.18)	ac	123	-1.21 (.11)***	ac	123	3.41 (.04)	ac	123	.01 (.08)	c	1	3.40 (.07)	ac	12	-.05 (.02)*		
	G3	110.5 (1.39)	ab	123	-.77 (.14)***	ab		3.06 (.05)	ab	123	-.05 (.08)*	b		2.75 (.09)	ab	1	-.04 (.02)		

Note. *p < .05, **p < .01, ***p < .001. SE = Standard Error; TD/min. = Total distance covered per minute; HIRD/min. = High intensity running distance covered per minute; VHIRD/min. = Very high intensity running distance covered per minute; G1 = 18–24 years old; G2 = 25–30 years old; G3 = 31–41 years old; P1 = Season Phase 1; P2 = Season Phase 2; P3 = Season Phase 3; P4 = Season Phase 4; a = significant differences compared with G1; b = significant differences compared with G2; c = significant differences compared with G3; 1, 2, 3 and 4 = significant differences compared with P1, P2, P3 and P4, respectively.

The slopes represent the relationship between match running performance and the players' age-centred variable (i.e., evolution of match running performance over the years). Concretely, TD significantly decreased over the years in all player age groups (p < .01), but this trend was greater across the seasons in young players. According to season phases, TD covered by young players in P1 decreased less than in the rest of the season phases, where the decrease was significantly greater (p < .001). TD covered by senior players decreased less, that is, it remained stable across season phases. In addition, HIRD significantly decreased in middle-aged (p < .001) and senior players (p < .01) in P1, and in senior players in P3 (p < .05) and P4 (p < .05). Finally, VHIRD significantly decreased in middle-aged (p < .001) and senior players (p < .01) in P1, in middle-aged (p < .01) and senior players (p < .05) in P3, and in middle-aged players (p < .05) in P4. We highlight that HIRD and VHIRD covered by young players did not decrease over the years, except in the end season phases.

Concerning the number of very high-intensity running efforts, Table 3 displays the intercepts and slopes of Sp21 and Sp24 performed per minute according to age groups in different season phases. In general, young players performed significantly more Sp21 and Sp24 than the rest of the players (p < .05) in all the season phases. The senior players performed the lowest number of Sp21 and Sp24 (p < .05). In addition, all players performed significantly fewer Sp21 and Sp24 in P1 compared to the rest of the season phases (p < .05). Regarding the slopes (i.e., evolution of the number of very high-intensity running efforts across the years), Sp21 significantly decreased in middle-aged (p < .01) and senior players (p < .05) in P1, and in senior players in P3 (p < .05) and P4 (p < .01). Finally, Sp24 significantly decreased in middle-aged (p < .001) and senior players (p < .001) in P1 and P2 (both p < .05), in senior players in P3 (p < .05), and in middle-aged (p < .001) and senior players (p < .001) in P4. We note that in young players the number of Sp21 performed did not decrease as much as that of Sp24.

Finally, an overview of match movement profiles according to different age groups depending on season phases is presented in Table 4. In general, young players covered greater TD, HIRD and VHIRD than the rest of the players in all the season phases. Meanwhile, the senior players covered the lowest values in TD, HIRD and VHIRD. Concerning the number of very high-intensity running efforts, young players performed more Sp21 and Sp24 than the rest of the players in all the season phases, whereas senior players performed the lowest number of Sp21 and Sp24. In addition, match running performance (i.e., TD, HIRD, VHIRD, SP21 and SP24) was lower in P1 compared to the rest of the season phases. On the other hand, match movement profiles considering the time (in minutes) played by soccer players were also analysed (See Supplementary Table).

TABLE 3. Number of Sp21 and Sp24 performed according to different age groups depending on season phases

Variables		Sp21 (nº/min.)						Sp24 (nº/min.)					
		Intercept (SE)	DG	DP	Slope	DG	DP	Intercept (SE)	DG	DP	Slope	DG	DP
P1	G1	.32 (.01)	bc	234	-.00 (.00)	b		.20 (.00)	bc	234	-.00 (.00)	b	
	G2	.29 (.01)	ac	234	-.01 (.00)***	a	234	.18 (.01)	ac	234	-.01 (.00)***	a	234
	G3	.26 (.01)	ab	234	-.01 (.00)**			.15 (.01)	ab	234	-.01 (.01)***		
P2	G1	.34 (.01)	bc	14	-.00 (.00)			.21 (.00)	bc	14	-.00 (.00)		
	G2	.31 (.01)	ac	134	-.00 (.00)		1	.19 (.01)	ac	14	-.00 (.00)*		1
	G3	.27 (.01)	ab	14	-.00 (.00)			.16 (.01)	ab	1	-.00 (.01)*		
P3	G1	.36 (.01)	bc	14	.00 (.00)			.21 (.00)	bc	1	.00 (.00)		
	G2	.29 (.01)	ac	124	-.00 (.00)		1	.19 (.01)	ac	14	-.01 (.00)***	a	1
	G3	.27 (.01)	ab	14	-.00 (.00)*			.16 (.01)	ab	1	-.00 (.01)***		
P4	G1	.32 (.01)	bc	123	-.00 (.00)			.20 (.00)	bc	12	-.00 (.00)	b	
	G2	.30 (.01)	ac	123	.00 (.00)	c	1	.19 (.01)	ac	123	-.00(.00)***	a	1
	G3	.26 (.01)	ab	123	-.01 (.00)**	b		.15 (.01)	ab	1	-.01 (.01)***		

Note. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$. SE = Standard Error; Sp21/min. = Sprints at very high intensity running covered per minute; Sp24/min. = Sprints at more than 24 $km \times h^{-1}$ covered per minute; G1 = 18–24 years old; G2 = 25–30 years old; G3 = 31–41 years old; P1 = Season Phase 1; P2 = Season Phase 2; P3 = Season Phase 3; P4 = Season Phase 4; a = significant differences compared with G1; b = significant differences compared with G2; c = significant differences compared with G3; 1, 2, 3 and 4 = significant differences compared with P1, P2, P3 and P4, respectively.

TABLE 4. Match movement profiles (in meters) according to different age groups depending on season phases

Season phases	Age group	TD (m)	HIRD (m)	VHIRD (m)	Sp21 (nº)	Sp24 (nº)
		Intercept (SE)	Intercept (SE)	Intercept (SE)	Intercept (SE)	Intercept (SE)
P1	G1	10,386 (912)	285.94 (100.07)	298.15 (154.60)	25.22 (8.20)	16.08 (7.10)
	G2	10,373 (929)	271.48 (102.33)	259.93 (142.35)	23.95 (8.45)	14.53 (7.11)
	G3	10,065 (921)	258.31 (99.66)	234.44 (127.76)	22.67 (8.28)	13.31 (6.40)
P2	G1	10,535 (939)	304.78 (98.35)	315.65 (157.35)	26.81 (8.23)	17.15 (7.54)
	G2	10,484 (887)	294.73 (107.55)	282.82 (151.11)	25.88 (8.93)	15.76 (7.46)
	G3	10,201 (951)	280.37 (99.25)	247.75 (129.15)	24.49 (8.17)	14.12 (6.54)
P3	G1	10,540 (927)	310.33 (104.19)	318.67 (168.41)	27.31 (8.55)	17.18 (7.69)
	G2	10,469 (899)	291.01 (107.03)	284.30 (147.52)	25.62 (8.80)	15.74 (7.24)
	G3	10,168 (944)	272.62 (100.89)	250.92 (135.28)	23.83 (8.30)	14.08 (6.69)
P4	G1	10,425 (922)	295.59 (99.83)	314.36 (156.21)	26.03 (8.26)	16.82 (7.19)
	G2	10,419 (922)	286.66 (106.61)	280.11 (148.85)	25.22 (8.84)	15.53 (7.40)
	G3	10,162 (948)	266.48 (101.36)	243.15 (131.05)	23.26 (8.32)	13.70 (6.53)

Note. SE = Standard Error; TD = Total distance; HIRD = High intensity running distance; VHIRD = Very high intensity running distance; Sp21 = Number of sprints at very high intensity running; Sp24 = Number of sprints at more than 24 $km \times h^{-1}$; G1 = 18–24 years old; G2 = 25–30 years old; G3 = 31–41 years old; P1 = Season Phase 1; P2 = Season Phase 2; P3 = Season Phase 3; P4 = Season Phase 4.

DISCUSSION

The main objective of the present study is to explore the evolution of match running performance throughout the season depending on players' age, including, as a novel approach, a longitudinal follow-up during four consecutive seasons. The main findings of the study revealed that TD significantly decreased over the years in all the players' age groups, although the number of high-intensity efforts performed by young soccer players remained stable and increased compared to the rest of the players. Also, match running performance (distances covered and number of high-intensity efforts performed per minute) in P1 was lower compared to the rest of the season phases.

Concerning the intercepts, our results showed that younger soccer players covered significantly greater TD, HIRD, and VHIRD and performed a significantly greater number of Sp21 and Sp24 than the other two groups (i.e., middle-aged and senior soccer players) across all season phases. These results are consistent with those previously reported in the first German league, where professional soccer players aged > 30 years showed a significantly lower performance in the TD covered, distance covered at high intensity, and the number of sprints compared with younger players [18]. Similar results were also found in the First Spanish Division. Rey et al. [13] reported that professional soccer players aged > 30 years covered significantly lower TD, distances covered at medium and high-intensity, maximum running speed, and number of high-intensity efforts compared to younger soccer players. Specifically, in elite soccer players the TD, distances covered at high intensity and number of high-intensity efforts significantly decrease each year that they get older [16]. Although acceleration and deceleration match performance were not analysed in this study, Lorenzo-Martínez et al. [15] also found that soccer players aged 31–38 years who competed in the First Spanish Division performed a significantly lower total number of accelerations and decelerations in comparison with younger players.

Regarding how the different age group players run, our results revealed that the TD covered by young soccer players (< 24 y.o.) was higher than the rest of the soccer players and it remained stable throughout the different season phases (i.e., P2, P3, and P4), whereas the TD covered by the two older age groups was lower and their TD increased as the season progressed. A possible explanation may be the fact that young soccer players played fewer matches and minutes (see Table 1) than older soccer players and covered more distance at high intensity than the rest of the players, who were more experienced in pacing their efforts [34]. When the intensity of distance covered was analysed in depth, our findings showed that young players covered greater distances at a high intensity (HIRD and VHIRD) in all the season phases (i.e., P2, P3, and P4) compared to the early season (i.e., P1). These young players are not usually part of the starter team and often play in the last part of the matches, when other players are under match-derived fatigue conditions. This situation allows young players to cover greater relative distances per minute at all running intensities than the older players, who have been forced to dosage their effort for more time during the match [35, 36].

Focusing on the evolution of match running performance throughout the season, this study showed that TD, HIRD, and VHIRD, as well as the number of high-intensity efforts, were greater during the middle season compared to the rest of season phases. Research has explored physical performance in other European leagues, reaching similar conclusions. Two longitudinal studies from the Italian Serie-A reported increases in TD and distances covered at high velocities (HIRD and VHIRD) at the end season [37, 38]. Another longitudinal study (from 2014 to 2017) from the German Bundesliga indicated across-season (P1–P4) reductions in TD covered at low intensity (below 11 $km \cdot h^{-1}$) but increases in distances covered at higher intensities toward the end season (P4–P6; [19]). Similar results were presented by Ponce-Bordon et al. [29], who found that soccer players covered significantly greater distances and completed a higher number of sprints in mid season. This increase in the players' capacity of effort (greater TD covered and at higher intensities) as the season progresses may be related to the improvement of the players' performance due to the specific adaptations derived from training and competitions [25, 39]. Conversely, a recent study of the English Championship (EC, Second Division) identified the opposite pattern of results, showing decreases in HIRD and VHIRD and the number of sprints, over the four season phases [40]. It should be noted that the aforementioned studies proposed a longitudinal analysis of the evolution of the match running performance indicators across the season without considering the players' age. Interestingly, our results showed a reduction in the TD covered in the young players' group as the season progresses. At the end season, the higher pressure demands to win may imply that younger players with less experience play fewer minutes as starters but relatively more at the end of the match and, therefore, with higher intensity per minute in comparison to the groups of older players [35].

One of the more significant findings to emerge from this study is the longitudinal changes in match running performance in all the four seasons analysed. It is noteworthy that taking the early season as a reference (i.e., Phase 1 of 2015/16 season), the TD showed a decrease throughout all the seasons, similar to the results of a previous study which analysed the Spanish LaLiga Santander across 8 seasons [11]. Concretely, young soccer players covered fewer metres per minute each season, whereas this trend was lower in the older age groups. Indeed, considering the following season phases, the trend became more negative, showing that, over the years, young players covered less distance as the season progressed. Taken together, these results suggest that young players across the season (from P1 to P4) and over the seasons (from 2015/16 to 18/19) could optimize their physical performance by covering less distance at lower intensities but more distance at higher velocities. This fact may be facilitated by a greater game understanding as they mature as professional players [18]. Similarly, in middle-aged and older players the TD covered

significantly decreased as the season progressed but the effect of the age group throughout the four seasons was significantly lower than in younger players. That is, older players maintain their physical performance throughout the season and over various consecutive seasons. This pattern of more stable physical performance throughout the years in older players could be explained by their greater expertise, which would entail greater self-knowledge of their physical, technical, and tactical capacities, as well as their ability to apply them in the best way due to their better knowledge of the game and its demands [18]. Finally, and regarding the differences in distance covered at high intensity, the effect of age is completely different, showing greater distance covered at high intensity over the seasons in younger players and less distance covered at high intensity (HIRD and VHIRD) over the seasons in older players. Lorenzo-Martínez et al. [14] found that younger players were more stable, maintaining the ability to perform high-intensity running and sprinting in comparison with older players. Our findings have shown that older players tend to reduce their ability to repeat high-intensity efforts over the years, due to different factors, such as their age-related decrease in strength [41] or diminishing soccer-specific physical abilities [16].

Limitations and Future Directions

The present study has several limitations that should be considered. Firstly, future studies on match running performance should be analysed according to players' playing position and the type of participation in the match (starters vs. non-starters, entire game, 1st or 2nd half, last quarter of the match, etc.), given that younger players may participate more in the last minutes of the match, and this could modify the profile of their efforts and intensities of running. Secondly, this study did not consider some contextual-related variables, such as the opponent quality, game model, and fixture congestion, which may influence players' match running performance.

CONCLUSIONS

The current study represents the first longitudinal research to explore the evolution of match running performance depending on the age of soccer players who competed in four consecutive seasons. Firstly, young soccer players covered significantly greater distances at all intensities than the older groups, so these players showed a better physical performance independently of the season phase (P1–P4). Secondly, young players increased distances at a high intensity as the season progressed. This age group plays fewer matches and minutes, so this situation makes it easier for younger players to perform greater relative distances per minute at all running intensities than older players. Finally, in middle-aged and older players the distances covered at high intensity significantly decreased across the seasons. Therefore, soccer coaches should take into consideration that the evolution of match running performance over the season is especially influenced by the player's age. This should be considered when adjusting competition minutes, selecting the distribution of players depending on the anticipated match physical demands, and especially when adapting physical training regimes to the evolution of players' match running performance.

Practical applications

This study provides very useful knowledge to soccer coaches when adjusting competition minutes, selecting the distribution of players depending on the anticipated match physical demands. Therefore, coaches could select younger soccer players at the early season due to better physical performance. Moreover, match running performance significantly changes in the different phases of the season and, more importantly, these changes are highly influenced by the players' age. Therefore, our results could help strength and conditioning coaches, especially when adapting physical training regimes to the evolution of players' match running performance according to the season phases to avoid overuse and optimize their physical performance.

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Disclosure of interest

The authors report no conflict of interest.

REFERENCES

1. Paul DJ, Bradley PS, Nassis GP. Factors affecting match running performance of elite soccer players: Shedding some light on the complexity. Int J Sports Physiol Perform. 2015; 10(4):516–9. https://doi.org/10.1123/ijspp.2015-0029
2. Pons E, García-Calvo T, Cos F, Resta R, Blanco H, López del Campo R, et al. Integrating video tracking and GPS to quantify accelerations and decelerations in elite soccer. Sci Reports. 2021; 11:1–10. https://doi.org/10.1038/s41598-021-97903-2
3. Bradley P, Carling C, Gomez Diaz A, Hood P, Barnes C, Ade J, et al. Match performance and physical capacity of players in the top three competitive standards of English professional soccer. Hum Mov Sci. 2013; 32(4):808–21. http://dx.doi.org/10.1016/j.humov.2013.06.002
4. Sæterbakken A, Haug V, Fransson D, Grendstad HN, Gundersen HS, Moe VF, et al. Match running performance on three different competitive standards in Norwegian soccer. Sports Med Int Open. 2019; 3(3):82–8. http://doi.org/10.1055/a-0943-3682
5. Bradley P, Carling C, Archer D, Roberts J, Dodds A, di Mascio M, et al. The effect of playing formation on high-intensity running and technical profiles in English FA premier League soccer matches. J Sports Sci. 2011; 29(8):821–30. https://doi.org/10.1080/02640414.2011.561868
6. Bush MD, Archer DT, Hogg R, Bradley PS. Factors influencing physical and technical variability in the english

premier league. Int J Sports Physiol Perform. 2015; 10(7):865–72. https://doi.org/10.1123/ijspp.2014-0484
7. Andrzejewski M, Konefał M, Chmura P, Kowalczuk E, Chmura J. Match outcome and distances covered at various speeds in match play by elite German soccer players. Int J Perform Anal Sport. 2016; 16(3):817–28. https://doi.org/10.1080/24748668.2016.11868930
8. Julian R, Page RM, Harper LD. The effect of fixture congestion on performance during professional male soccer match-play: A systematic critical review with meta-analysis. Sports Med. 2021 Feb 17; 51(2):255–73. https://doi.org/10.1007/s40279-020-01359-9
9. Castellano J, Blanco-Villaseñor A, Álvarez D. Contextual variables and time-motion analysis in soccer. Int J Sports Med. 2011; 32(6):415–21. http://dx.doi.org/10.1055/s-0031-1271771
10. Radzimiński Ł, Lorenzo-Martinez M, Konefał M, Chmura P, Andrzejewski M, Jastrzębski Z, et al. Changes of physical match performance after the COVID-19 lockdown in professional soccer players according to their playing position. Biol Sport. 2022; 40(1):1087–1094. https://doi.org/10.5114/biolsport.2022.114281
11. Errekagorri I, Castellano J, Echeazarra I, López-Del Campo R, Resta R. A longitudinal analysis of technical-tactical and physical performance of the teams in the Spanish LaLiga Santander: An eight-season study. Biol Sport. 2022; 39(2):389–96. https://doi.org/10.5114/biolsport.2022.105331
12. Tønnessen E, Hem E, Leirstein S, Haugen T, Seiler S. Maximal aerobic power characteristics of male professional soccer players, 1989–2012. Int J Sports Physiol Perform. 2013 May; 8(3):323–9. https://doi.org/10.1123/ijspp.8.3.323
13. Rey E, Costa P, Corredoira F, Sal A. Effects of age on physical match performance in professional soccer players. J Strength Cond Res. 2019; 00(00):1–6. 10.1519/jsc.0000000000003244
14. Lorenzo-Martínez M, Rey E, Padrón-Cabo A. The effect of age on between-match physical performance variability in professional soccer players. Res Sports Med. 2019; 00(00):1–9. https://doi.org/10.1080/15438627.2019.1680985
15. Lorenzo-Martínez M, Corredoira FJ, Lago-Peñas C, Campo RLD, Nevado-Garrosa F, Rey E. Effects of age on match-related acceleration and deceleration efforts in elite soccer players. Int J Sports Med. 2021; 42(14):1274–80. https://doi.org/10.1055/a-1337-2961
16. Rey E, Lorenzo-Martínez M, López-Del Campo R, Resta R, Lago-Peñas C. No sport for old players. A longitudinal study of aging effects on match performance in elite soccer. J Sci Med Sport. 2022; 25(6):535–9. https://doi.org/10.1016/j.jsams.2022.03.004
17. Zhou C, Lorenzo A, Gómez MÁ, Palao JM. Players' match demands according to age and playing position in professional male soccer players. Int J Perform Anal Sport. 2020; 20(3):389–405. https://doi.org/10.1080/24748668.2020.1753979
18. Sal de Rellán-Guerra A, Rey E, Kalén A, Lago-Peñas C. Age-related physical and technical match performance changes in elite soccer players. Scan J Med & Sci Sports. 2019 Sep 6; 29(9):1421–7. https://doi.org/10.1111/sms.13463
19. Botek M, Krejčí J, McKune AJ, Klimešová I. Somatic, endurance performance and heart rate variability profiles of professional soccer players grouped according to age. J Hum Kinet. 2016 Dec 1; 54(1):65–74. https://doi.org/10.1515/hukin-2016-0035
20. Haugen TA, Solberg PA, Foster C, Morán-Navarro R, Breitschädel F, Hopkins WG. Peak age and performance progression in world-class track-and-field athletes. Int J Sports Physiol Perform. 2018; 13(9):1122–9. https://doi.org/10.1123/ijspp.2017-0682
21. Hawkins SA, Wiswell RA. Rate and mechanism of maximal oxygen consumption decline with aging. Sports Med. 2003; 33(12):877–88. https://doi.org/10.2165/00007256-200333120-00002
22. Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The evolution of physical and technical performance parameters in the English Premier League. Int J Sports Med. 2014; 35(13):1095–100. https://doi.org/10.1055/s-0034-1375695
23. Pons E, Ponce-Bordón JC, Díaz-García J, del Campo RL, Resta R, Peirau X, et al. A longitudinal exploration of match running performance during a football match in the Spanish LaLiga: A four-season study. Int J Environ Res Public Health. 2021; 18(3):1–10. https://doi.org/10.3390/ijerph18031133
24. Wallace JL, Norton KI. Evolution of World Cup soccer final games 1966–2010: Game structure, speed and play patterns. J Sci Med Sport. 2014; 17(2):223–8. http://dx.doi.org/10.1016/j.jsams.2013.03.016
25. Chmura P, Konefał M, Wong DP, Figueiredo AJ, Kowalczuk E, Rokita A, et al. Players' physical performance decreased after two-thirds of the season: Results of 3 consecutive seasons in the German first bundesliga. Int J Environ Res Public Health. 2019; 16(11):1–9. https://doi.org/10.3390/ijerph16112044
26. Rampinini E, Martin M, Bosio A, Donghi F, Carlomagno D, Riggio M, et al. Impact of COVID-19 lockdown on professional soccer players' match physical activities. Sci Med Footb. 2021; 5:1–9. https://doi.org/10.1080/24733938.2021.1995033
27. Pons E, García-Calvo T, Resta R, Blanco H, López del Campo R, Díaz García J, et al. A comparison of a GPS device and a multi-camera video technology during official soccer matches: Agreement between systems. Plos One. 2019; 14(8). https://doi.org/10.1371/journal.pone.0220729
28. Felipe JL, Garcia-Unanue J, Viejo-Romero D, Navandar A, Sánchez-Sánchez J. Validation of a video-based performance analysis system (Mediacoach®) to analyze the physical demands during matches in LaLiga. Sensors. 2019; 19(19):4–13. https://doi.org/10.3390/s19194113
29. Ponce-Bordón JC, García-Calvo T, Candela-Guardiola JM, Serpiello FR, del Campo RL, Resta R, et al. The relationship between running distance and coaches' perception of team performance in professional soccer player during multiple seasons. Sci Reports. 2022 Dec 27; 12(1):1454. https://doi.org/10.1038/s41598-022-05519-x
30. R-Studio Team. RStudio: Integrated Development for R. RStudio, editor. Boston; 2020.
31. Heck RH, Thomas SL. An introduction to multilevel modeling techniques: MLM and SEM approaches using Mplus. Routledge, editor. 2015.
32. Akaike H. A new look at the Statistical Model Identification. IEEE Transactions on Autom Control. 1974; 19(6):716–23.
33. Field A. Discovering statistics using IBM SPSS statistics. 4th Edition. SAGE Editorial, editor. New York; 2013.
34. Nakagawa S, Schielzeth H. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods Ecol Evol. 2013; 4(2):133–42. https://doi.org/10.1111/j.2041-210x.2012.00261.x
35. Lorenzo-Martínez M, Padrón-Cabo A, Rey E, Memmert D. Analysis of physical and technical performance of substitute players in professional soccer. Res Q Exerc Sport. 2020; 00(00):1–8. https://doi.org/10.1080/02701367.2020.1755414
36. Giménez J V, Leicht AS, Gomez MA. Physical performance differences between starter and non-starter players during professional soccer friendly matches. J Hum Kinet. 2019; 69(1):283–91. https://doi.org/10.2478/hukin-2019-0018
37. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer

players with special reference to development of fatigue. J Sports Sci. 2003; 21(7):519–28. https://doi.org/10.1080/0264041031000071182
38. Rampinini E, Coutts A, Castagna C, Sassi R, Impellizzeri F. Variation in top level soccer match performance. Int J Sports Med. 2007; 28(12):1018–24. http://www.thieme-connect.de/DOI/DOI?10.1055/s-2007-965158
39. Meckel Y, Doron O, Eliakim E, Eliakim A. Seasonal variations in physical fitness and performance indices of elite soccer players. Sports. 2018; 6(1):14. https://doi.org/10.3390/sports6010014
40. Springham M, Williams S, Waldron M, Burgess D, Newton RU. Large reductions in match play physical performance variables across a professional football season with control for situational and contextual variables. Front Sports Act Living. 2020; 2:1–11. https://doi.org/10.3389/fspor.2020.570937
41. Ganse B, Ganse U, Dahl J, Degens H. Linear decrease in athletic performance during the human life span. Front Physiol. 2018; 9:1–13. https://doi.org/10.3389/fphys.2018.01100

SUPPLEMENTARY TABLE

Table S1. Match movement profiles (in meters) according to different age groups depending on season phases considering time played by soccer players

Season phases	Age group	TD (m)	HIRD (m)	VHIRD (m)	Sp21 (nº)	Sp24 (nº)
		Intercept (SE)	Intercept (SE)	Intercept (SE)	Intercept (SE)	Intercept (SE)
P1	G1	7,614 (3,289)	222.97 (114.48)	231.55 (150.65)	19.74 (9.80)	12.57 (7.36)
	G2	8,471 (2,976)	234.22 (111.87)	227.24 (141.18)	20.62 (9.49)	12.65 (7.24)
	G3	8,438 (2,747)	223.05 (107.89)	202.00 (127.28)	19.57 (9.14)	11.47 (6.60)
P2	G1	7,908 (3,339)	243.23 (119.95)	251.57 (158.70)	21.40 (10.32)	13.69 (7.92)
	G2	8,628 (3,005)	253.98 (120.43)	244.50 (153.30)	22.25 (10.24)	13.57 (7.76)
	G3	8,697 (2,714)	245.89 (112.87)	218.77 (131.33)	21.43 (9.51)	12.45 (6.87)
P3	G1	7,822 (3,409)	242.76 (124.38)	248.29 (166.63)	21.34 (10.66)	13.42 (8.17)
	G2	8,634 (2,953)	253.33 (118.86)	245.97 (148.55)	22.24 (10.09)	13.62 (7.54)
	G3	8,493 (2,792)	236.89 (113.16)	215.02 (135.57)	20.65 (9.50)	12.08 (6.92)
P4	G1	7,887 (3,290)	236.94 (118.37)	248.96 (156.07)	20.81 (10.11)	13.29 (7.62)
	G2	8,575 (2,938)	246.37 (117.35)	240.93 (148.14)	21.59 (9.94)	13.31 (7.56)
	G3	8,405 (2,898)	229.30 (112.19)	209.31 (132.56)	19.96 (9.45)	11.77 (6.83)

Note. The time (in minutes) played by soccer players was considered for this analysis. SE = Standard Error; TD = Total distance; HIRD = High intensity running distance; VHIRD = Very high intensity running distance; Sp21 = Number of sprints at very high intensity running; Sp24 = Number of sprints at more than 24 km $\times$ h^{-1}; G1 = 18–24 years old; G2 = 25–30 years old; G3 = 31–41 years old; P1 = Season Phase 1; P2 = Season Phase 2; P3 = Season Phase 3; P4 = Season Phase 4.

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Internal workload in elite female football players during the whole in-season: starters vs non-starters

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ABSTRACT: The aim of this study was to quantify weekly internal workload across the in-season and compare the workload variables between starter and non-starter Spanish female first league (Liga Iberdrola) football players. Twenty-six participants belonging to the same team (age, height, and mass: 25.4 ± 6.1 years, 167.4 ± 4.8 cm and 57.96 ± 6.28 kg, respectively) participated in this study. Training loads (TL) and match loads (ML) were assessed through breath-cardiovascular (RPE_{breath}), leg-musculature (RPE_{leg}) and cognitive (RPE_{cog}) rating of perceived exertion ($RPE_{0–10}$) for each training session and match during the in-season phase (35 weeks). Session-RPE (sRPE) was calculated by multiplying each RPE value by session duration (minutes). From these, total weekly TL (weekly TL+ML), weekly TL, weekly ML, chronic workload, acute:chronic workload ratio, training monotony, and training strain were calculated. Linear mixed models were used to assess differences for each dependent variable, with playing time (starter vs non-starter players) used as a fixed factor, and athlete, week, and team as random factors. The results showed that total weekly TL (d = 1.23–2.04), weekly ML (d = 4.65–5.31), training monotony (d = 0.48–1.66) and training strain (d = 0.24–1.82) for RPE_{breath}, RPE_{leg} and RPE_{cog} were higher for starters in comparison with non-starters (p = 0.01). Coaches involved in elite female football should consider implementing differential sRPE monitoring strategies to optimize the weekly load distribution for starters and non-starters and to introduce compensatory strategies to equalise players' total weekly load.

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INTRODUCTION

Women's football (soccer) has changed exponentially, imposing greater match load (ML) and training load (TL) demands [1]. In terms of absolute external load, the total distance covered in a match increased from ~8.5 [2] to ~10 km [3, 4], with 1,326 to 1,641 activity pattern changes, requiring decelerations, accelerations, sprinting or jumping [2]. Elite female football players cover a relative total distance up to 104.4 $m \cdot min^{-1}$, of which 11.4 ± 4.3 $m \cdot min^{-1}$ is at high intensity (> 15 $km \cdot h^{-1}$), 5.1 ± 2.4 $m \cdot min^{-1}$ at very high intensity (≥ 18 $km \cdot h^{-1}$) and 2.45 ± 0.8 $m \cdot min^{-1}$ while sprinting (≥ 21 $km \cdot h^{-1}$) [5].

To cope with these match demands and to provide an adequate training stimulus which optimizes performance and minimizes the risk of injuries [6, 7], the assessment of TL and ML becomes crucial. In these terms, the assessment of TL and ML through ratings of perceived effort (RPE) has proved to be a valid measure of training load due to its relationships with internal and external load measures [8]. It was also identified as a useful time and cost-effective measure to understand the internal response to workload stimuli. Session ratings of perceived exertion (sRPE) have previously been widely used as a marker of internal training load [1]. However, it has previously been suggested that a general RPE is too simplistic to

HIGHLIGHTS

- The monitoring of differential sRPE (i.e. RPE_{breath}, RPE_{leg} and $RPE_{cognitive}$) has shown higher internal weekly loads, match load, monotony and strain for starter compared to non-starter players.
- On MD+1 non-starter players experienced higher differential sRPE than starters due to the nature of the compensation session. However, the total weekly load was higher for starters as they presented higher TL on MD-4, MD-3, MD-2 and during the match.
- As higher internal weekly load was experienced by starters, coaches may adjust the weekly training loads for non-starters to optimize load distribution for all players.

identify all the subjective sensations perceived during the exercise (i.e., cardiorespiratory sensations, muscular exertion, joint and skin sensation, perception of effort, fatigue, heat or pain), leading to low-reliability measures in team sports due to the intermittent nature of their physical actions [8, 9]. To overcome these constraints, differential ratings of perceived exertion (dRPE) – which integrate the cardiorespiratory system (RPE_{breath}), neuromuscular system (RPE_{leg}) and the cognitive RPE (RPE_{cog}) [10] – have emerged as a viable alternative for measuring internal loads.

In team sports such as rugby, basketball and American football [11–13], TL and ML are widely monitored through RPE across the microcycle and the different phases of the season, with an association between workload and injury risk. For example, Malone et al. (2017) found that Gaelic football players were at increased risk of injury with a weekly cumulative TL between ≥ 1,500 and ≤ 2,120 arbitrary units (AU), with further increases in TL or large weekly changes in TL leading to a greater increase in injury risk. However, to our knowledge, there are no published data regarding weekly internal TL and ML in highly competitive female football players across extended periods of time (whole in-season).

As playing time is considered an important factor to programme the weekly workload, coaches usually plan a lower TL for starters and a greater TL for non-starters in the training session after the match day (MD+1). Indeed, on MD+1 it is common that players who performed > 60 minutes of competition (starters) complete a recovery training session, while those with < 60 minutes of competition (non-starters) complete a compensatory session [14]. Despite the compensatory sessions, non-starter male football players performed with considerably lower TL compared to starters, contributing to a lower total weekly TL for non-starters [15]. Specifically, very large (d = 2.0–3.4) differences between starters and non-starters were observed at high-intensity running zones in English Premier League players [16]. In this

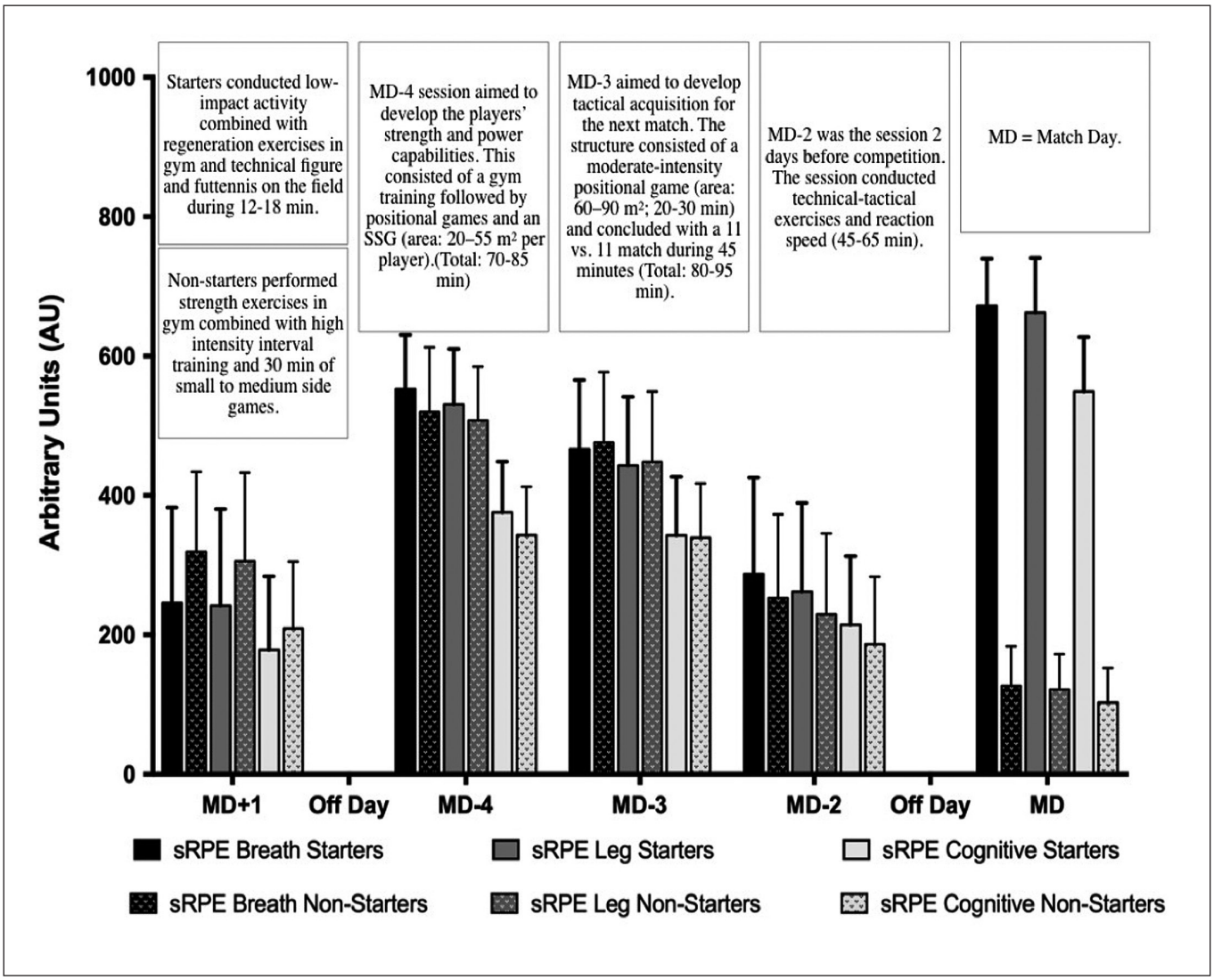


FIG. 1. Distribution of differential sRPE and training description over a typical microcycle.

sense, consideration of players as starters and non-starters is of key importance for optimal monitoring of total weekly load and fluctuations (spikes) in TL, thus helping to optimize the player's physical fitness and avoid increasing injury risk. Moreover, the acute:chronic workload ratio (ACWR), calculated as the ratio between acute (accumulated workload during the last 7 days) and chronic (mean load over the previous 3 to 6 weeks) workloads, has been identified as an index of player preparedness and suggested as a valuable monitoring variable [17, 18]. Nonetheless, the validity of ACWR in some sports and populations is still under discussion [19]. Indeed, the ACWR and longitudinal description of the differential sRPE in highly competitive female football players during the in-season is under-researched.

Due to its ease of application, its low cost and its practicality for monitoring the internal training load, the aims of the current investigation were to quantify the weekly internal workload across the in-season and compare several workload variables between starter and non-starter elite female football players. Based on previous literature [15], we hypothesize significant differences in internal load between starters and non-starters.

MATERIALS AND METHODS

To fulfil the research aim, and to identify the possible differences between starters and non-starters, differentiated sRPE monitoring of the internal load was carried out during the 2018/2019 season in an elite female football team using a descriptive-comparative design. During all weeks of the competitive period, weekly load, consisting of TL and ML, was monitored for RPE_{breath}, RPE_{leg} and RPE_{cog} during field-based training.

Subjects

Initially, 26 elite female football players belonging to the same team of the first women's Spanish League with a mean (± SD) age, height, and body mass of 25.4 ± 6.1 years, 167.4 ± 4.8 cm and 57.96 ± 6.28 kg, respectively, with 1–14 years of elite competitive experience, participated in this study. To be eligible, players had to meet the following requirements: 1) complete the whole training session, 2) no long-term injuries (> 6 months) and 3) complete > 90% of the sessions with the first team. Players were analysed as starters (completed > 60 minutes of competition in MD; mean (± SD) = 86.12 ± 8.69) and non-starters (completed < 60 minutes of competition in MD; mean (± SD) = 25.28 ± 15.83). From the 26 participants initially enrolled in the study, seven players were removed from the study due to severe injury (n = 1), completion of < 10 training sessions (n = 1), or involvement in the second team (n = 5). 19 players, excluding goalkeepers, were included for analysis (defenders = 6; midfielders = 7; attackers = 6). During the preseason, all players were informed about the aim and procedures of the study in accordance with the Declaration of Helsinki and provided informed consent. Ethical approval was obtained from Autonomous University, Madrid. Approval number: CEI-124-2528.

Design

Player workload was assessed in each training session and match during the in-season (35 weeks, September 2018 to May 2019), comprising 3,197 observations during training sessions and 576 during matches. Across the in-season, players performed 30 league matches and 2 national cup (Queen's cup) matches, without international matches. The typical weekly training and competition structure across the in-season is depicted in Figure 1, with four sessions with one match per week.

The dependent variables analysed in this study were total weekly TL, weekly TL, weekly ML, ACWR, chronic workload, training monotony, and training strain [20]. Data were compared between starters (number of cases = 2.188) and non-starters (number of cases = 1.585).

TABLE 1. Description of the dependent variables analysed

Dependent variables	Description
Total Weekly Load	Weekly TL+ Weekly ML
Weekly TL	Sum of workload from each training session in a week
Weekly ML	Sum of match workload in a week
Chronic Weekly Load	Total weekly load of the last four weeks
Acute:Chronic Workload Ratio	Total weekly load / chronic weekly load
Monotony	Mean total weekly load / SD total weekly load
Strain	Total weekly load * monotony

TL = training load; ML = match load; SD = standard deviation.

These dependent variables were calculated for $sRPE_{breath}$, $sRPE_{leg}$ and $sRPE_{cog}$.

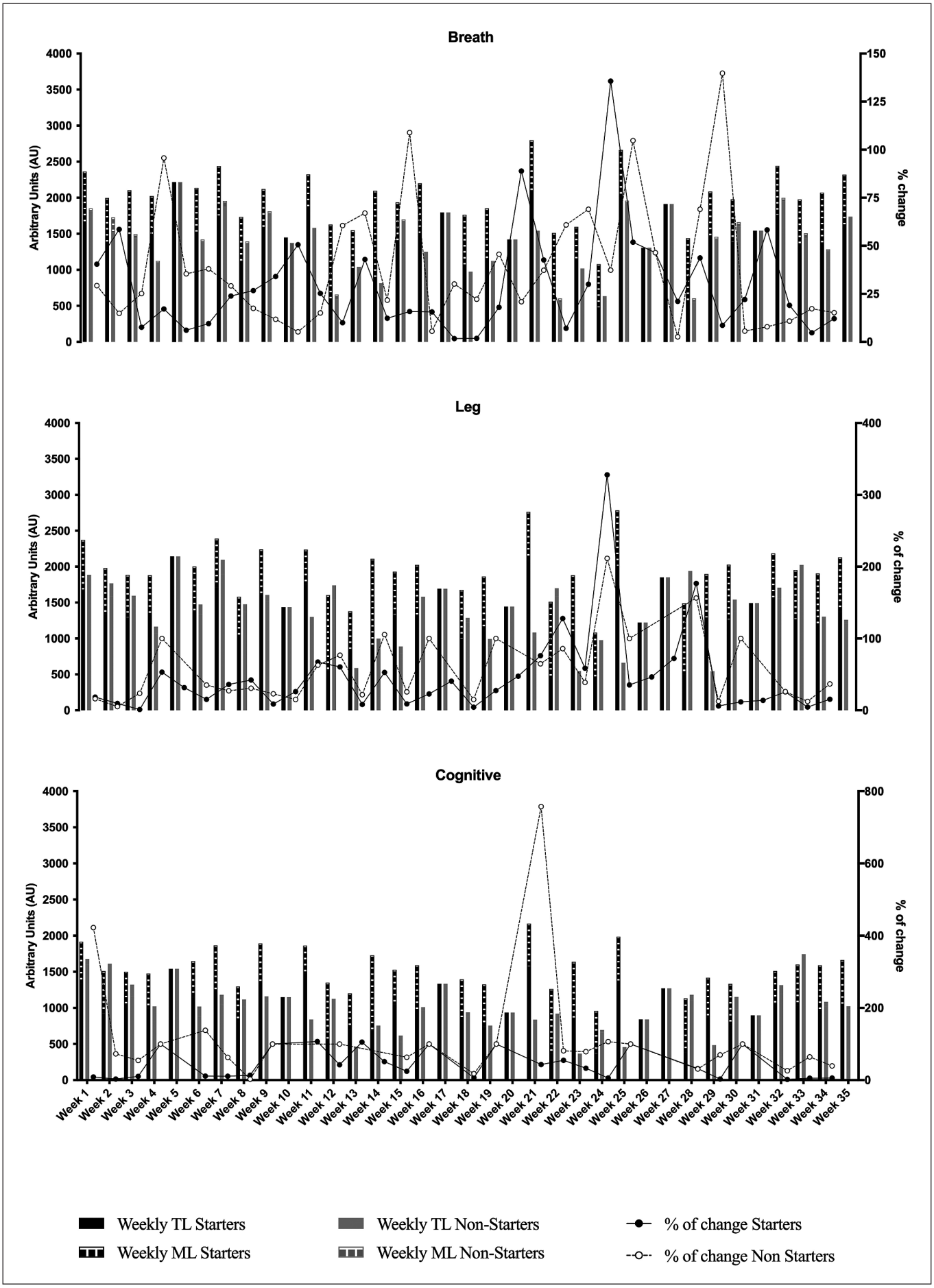


FIG. 2. Distribution of differential sRPE for TL, ML and weekly change over the season.

Procedures

Internal player workload was measured through session RPE (sRPE) for each scale $sRPE_{breath}$, $sRPE_{leg}$ and $sRPE_{cog}$, calculated as each RPE value multiplied by session duration (minutes), for each training session (including the recovery period between exercises) and match (excluding warm-up) [9, 21]. Players filled a questionnaire composed of three questions: i) How hard was your session on your heart/chest? (i.e., RPE_{breath}), ii) How hard was your session on your legs? (i.e., RPE_{leg}), iii) How difficult was your session for decision making? (RPE_{cog}). Data were provided using their personal mobile phone with responses stored using cloud-based software (Google Forms, CA, United States of America). The 10-point RPE Borg scale was applied 15–30 minutes after training sessions and matches [22]. This online data collection approach has shown a stronger association with the heart rate-based training impulse (TRIMP) compared to a paper-pencil method [23], suggesting sRPE as a valid indicator of global internal load in soccer [24]. All players were familiarized with the RPE_{breath}, RPE_{leg} and RPE_{cog} during six weeks of pre-season training sessions and friendly matches. The descriptions of the dependent variables for sRPEbreath, $sRPE_{leg}$ and $sRPE_{cog}$ (AU) are displayed in Table 1.

Statistical analysis

Data are presented as mean ± standard deviation (SD) and confidence intervals (95%). Sample size was estimated using free software (G* Power v3.1). An a priori sample size for two independent groups revealed a minimum of 7 participants in each group given a Cohen's d of 2.04, giving a power of 0.974. Data were analysed using factorial linear mixed modelling using the software IBM SPSS Statistics v26.0 software (IBM Corp., Armonk, NY, USA.). Variance and sphericity assumptions were checked with the Levene and Mauchly tests. Weekly changes in internal load were presented as percentages of change (%) in comparison to the previous week. Linear mixed modelling can be applied to repeated measures data from unbalanced designs, which was the case in our study since players differed in terms of the number of training sessions and matches they participated in. In this study, weekly internal load, and player group (starters vs non-starters) were treated as categorical fixed effects. The Bonferroni test

TABLE 2. Mean ± standard deviation and statistical comparisons for each dependent variable for starter compared to non-starter players.

	Starter players (n = 11)	Non-starter players (n = 8)	95% confidence interval			
	Mean ± SD	Mean ± SD	p value	Lower	Upper	Cohen's d
Total Weekly Load Breath (AU)	1898 ± 385	1062 ± 431	**0.01**	640	1030	2.04
Weekly Training Load Breath (AU)	1382 ± 435	1383 ± 430	0.99	-207.	205	0.00
Weekly Match Load Breath (AU)	699 ± 165	45 ± 40	**0.01**	586	722	5.31
Chronic Weekly Load Breath (AU)	1875 ± 119	1034 ± 234	**0.01**	746	935	4.52
Acute:Chronic Workload Ratio Breath	1.02 ± 0.23	1.05 ± 0.53	0.34	-0.23	0.18	-0.07
Monotony Breath (AU)	3.55 ± 1.10	2.06 ± 0.63	**0.01**	1.06	1.92	1.66
Strain Breath (AU)	6891 ± 3215	2332 ± 1484	**0.01**	3363	5752	1.82
Total Weekly Load Leg (AU)	1816 ± 377	1329 ± 413	**0.01**	298	675	1.23
Weekly Training Load Leg (AU)	1310 ± 433	1317 ± 421	0.95	-210	196	-0.02
Weekly Match Load Leg (AU)	721 ± 171	117 ± 53	**0.01**	532	675	4.65
Chronic Weekly Load Leg (AU)	1798 ± 106	1309 ± 222	**0.01**	400	578	2.81
Acute:Chronic Workload Ratio Leg	1.02 ± 0.24	1.04 ± 0.42	0.86	-0.19	0.16	-0.04
Monotony Leg (AU)	3.49 ± 1.09	2.99 ± 0.98	**0.05**	0.01	0.99	0.48
Strain Leg (AU)	4642 ± 2343	4097 ± 2127	0.31	-522	1612	0.24
Total Weekly Load Cognitive (AU)	1407 ± 306	962 ± 314	**0.01**	297	593	1.44
Weekly Training Load Cognitive (AU)	985 ± 315	950 ± 322	0.65	-117	186	0.11
Weekly Match Load Cognitive (AU)	601 ± 142	103 ± 51	**0.01**	437	557	4.58
Chronic Weekly Load Cognitive (AU)	1388 ± 119	923 ± 188	**0.01**	385	545	2.95
Acute:Chronic Workload Ratio Cognitive	1.02 ± 0.25	1.03 ± 0.41	0.90	-0.18	0.16	-0.03
Monotony Cognitive (AU)	2.23 ± 0.47	1.86 ± 0.35	**0.01**	0.18	0.58	0.91
Strain Cognitive (AU)	3189 ± 1084	1829 ± 791	**0.01**	907	1812	1.43

was used as a post hoc test to assess where differences occurred, with Cohen's *d* being used to calculate effect sizes. The magnitude of differences in all dependent variables between starters and non-starters was assessed using effect size (ES) statistics and was interpreted as < 0.2 = *trivial*, 0.2–0.6 = *small*, > 0.6–1.2 = *moderate*, > 1.2–2.0 = *large*, > 2.0 = *very large* [25]. Significance was set at $p < 0.05$.

RESULTS

The comparison of all dependent variables between starters vs non-starters is presented in Table 2. In general, the internal loads were higher for starters than non-starters for the three differential sRPE. Total weekly load ($p = 0.001$; $d = 1.23$ to 1.44; % difference = 26.82 to 44.05%), weekly match load ($p = 0.001$; $d = 4.58$ to 5.31; % difference = 82.86 to 93.56%), monotony load ($p = 0.001$; $d = 0.48$ to 1.66; % difference = 14.33 to 44.85%) and strain ($p = 0.001$; $d = 0.24$ to 1.82; % difference = 11.74 to 66.16%) for breath, leg and cognitive showed differences between starters and non-starters.

The $sRPE_{breath}$ showed an average weekly variation (as AU) of 29.75 ± 27.0% for starters and 38.96 ± 33.7% for non-starters across the in-season (Figure 2, right Y axis). The $ACWR_{breath}$ ranged between 0.63 to 1.34 for starters and 0.58 to 2.11 for non-starters. The monotony ranged between 2.04 to 7.18 and 1.50 to 6.27 for starters and non-starters, respectively. The breath training strain was significantly higher for starters in comparison with non-starters ($p = 0.01$; $d = 1.82$; % difference = 66.16%).

A similar trend was observed for $sRPE_{leg}$, with an average weekly variation across the season (as AU) of 29.72 ± 28.8% for starters and 40.74 ± 38.3% for non-starters (Figure 2, right Y axis). The range of $ACWR_{leg}$ was 0.62 to 1.27 for starters and 0.59 to 2.24 for non-starters. The monotony range was 2.02 to 6.28 and 1.65 to 6.08 for starters and non-starters, respectively. Leg training strain showed no differences between starters and non-starters ($p = 0.31$; $d = 0.24$; %difference = 11.74%).

For $sRPE_{cog}$ there was less variability than breath and leg weekly load for non-starters, showing 36.42 ± 32.8% and similar values for starters with 30.11 ± 27.6% (Figure 2, right Y axis). The range of $ACWR_{cog}$ was 0.72 to 1.41 for starters and 0.70 to 1.64 for non-starters and monotony was to 1.50 to 3.47 and 1.20 to 2.79, respectively. The cognitive training strain was significantly higher for starters in comparison with non-starters ($p = 0.01$; $d = 1.43$; % difference = 42.65%).

DISCUSSION

The aim of this study was to quantify the internal load in elite female football players from a first division team across the in-season, and to compare between starters and non-starters. The main finding was that starters experienced higher internal loads, including RPE_{breath}, RPE_{leg} and $RPE_{cognitive}$ for total weekly load, match load, monotony and strain.

In our study, non-starters presented higher $sRPE_{breath}$, $sRPE_{leg}$ and $sRPE_{cognitive}$ on MD+1, than starters (Figure 1). Despite lower TL on MD+1 observed for starters than non-starters, there was no difference for total weekly TL, as non-starters showed lower TL in the rest of the weekly training sessions (MD-4, MD-3 and MD-2) and ML (Figure 2). These results are in agreement with Stevens et al., (2017) who reported lower TL in non-starters compared to starters, especially on MD-4, contributing to a considerably lower total weekly load for non-starters compared to starters [15]. The possible reason explaining why the non-starters experienced less TL across the different training sessions of the microcycle (except on MD+1) may be that starting players present higher RPE for the same session due to an incomplete recovery after the match [26]. However, the fact that the team line-up is indicated to starters and non-starters usually on MD-3 may reduce the motivation among non-starters, and thus their TL [27].

Despite the importance of monitoring player workload in order to optimize the training process [28–30], our study is the first longitudinal one (i.e., 35 weeks long) to quantify internal loads in highly training (first division) female football players across the in-season. Previous studies in highly trained female soccer players described the workload during a microcycle [31, 32] without comparison between starters and non-starters. The microcycle involved 7–8 days of preparation camp for an international tournament, with 4–5 training sessions, two friendly matches, and a total load of 1716 ± 603 AU [32], similar as in our study. Despite the decreases (-30.5% MD-5 vs MD-1) in workload during a typical microcycle [31], our novel results indicate meaningful differences in the internal loads between starters and non-starters. These findings may be of key importance to better assess the internal load in highly trained female soccer player, to maximize fitness and reduce injury risk.

In the current investigation, starters experienced greater (32.0 to 41.0%) internal loads compared to non-starters, with total weekly load of $sRPE_{breath}$, $sRPE_{leg}$, and $sRPE_{cognitive}$ of 1,798 ± 385 AU, 1,816 ± 377 AU and 1,407 ± 306 AU among starters, and 1,062 ± 431 AU, 1,329 ± 413 AU and 962 ± 314 AU for non-starters (Table 2). Aside from the absolute values of internal load, the monitoring of weekly variations and spikes in internal loads may also be considered as relevant markers to monitor players' performance, and avoid injury [18]. Indeed, a weekly change in workload > 15% could lead to a 21–49% increase in injury risk in team sports athletes [18]. Our results showed high weekly variations in internal loads ($sRPE_{breath}$, $sRPE_{leg}$, and $sRPE_{cognitive}$) for both starters and non-starters, although larger weekly variations were noted for non-starters. Conversely, training monotony in Portuguese female players was similar between starters and non-starters (4.3 ± 0.7 vs 4.8 ± 0.8), suggesting non-significant variations in workload during the microcycle [31]. The spikes (i.e., total weekly load) for starters were observed in weeks 10, 20, 21, 24, 25, and 30, in line with those weeks that included two matches, or those weeks without a competition. For non-starters spikes for total weekly load were greater compared to

starters, and occurred in weeks without competitions (weeks 10, 17, 20, 26, 27, 31) and weeks with a double match (weeks 12, 14, 22, 28). The coaching staff should consider these workload spikes to better programme higher compensatory workload increments overall for non-starters during training sessions to avoid a decrease in performance and/or increase injury risk. However, the main problem of compensatory training sessions is performing one day after a competition, causing the fatigue to occur later for non-starters; due to this, in the double match weeks it could be difficult to compensate the total weekly workload for non-starters. Despite the potential relevance of our findings in elite female football players, it should be highlighted that no data exist regarding the effect of spikes in total weekly TL on non-contact injuries in elite female football players, calling for future research in this area.

Previous studies suggested that high training monotony and workload strain levels could be associated with increases in injury risk [20, 33]. In our study, monotony and strain values were greater for starters compared to non-starters for breath, leg and cognitive scales. Higher monotony values may suggest low standard deviations of the mean with small variations within a week. Higher strain could suggest greater acute loads performed with a small within-week variation. Originally, monotony and strain workload indices were used to monitor overtraining syndrome [22]. However, several studies have associated high monotony and strain levels with increases and decreases in injury risk [33, 34]. Brink et al. (2010) analysed the workload, injuries and illness in male football players, detecting higher injury risk and illnesses when monotony was elevated. However, in another prospective longitudinal cohort study with 130 professional football players, it was noted that high monotony levels were associated with decreased injury incidence [34]. Although workload indices may help to understand the load dynamics within and between weeks, they could also be used to compare the magnitude of stimulus between players with different playing times. In our study, the leg monotony index showed greater spikes than breath and cognitive monotony indices. The starters experienced higher leg monotony levels in weeks 22, 25 and 32, while non-starters had higher levels in weeks 8 and 11. This shows how load dynamics varies greatly by playing time, the match load being one of the most important factors to optimize player performance [35]. These data suggest that it is necessary to individualize monitoring workload in female football players and propose suitable strategies to compensate the match load. Therefore, female football coaches are challenged in dosing an adequate training stimulus for their players while considering their playing time during matches.

During the 35 weeks analysed in our study, the ACWR range was higher for non-starters than starters for $ACWR_{breath}$ (0.58–2.11 and 0.63–1.34, respectively), $ACWR_{leg}$ (0.59–2.24 and 0.62–1.27, respectively) and $ACWR_{cog}$ (0.70–1.63 and 0.72–1.41, respectively) ratios. While the optimal ACWR has been suggested to be between 0–85 and 1.25 to reduce injury risk in male elite football players [17], no data are available for female players, thus limiting the interpretation of our results. Indeed, female football players suffer 2 to 8 times more injuries than male players [36]. Therefore, future studies should investigate the ACWR in female football players to identify the optimal values to reduce non-contact injuries and achieve successful performance in matches, if they exist.

It is necessary to highlight the importance os using differential RPE such as RPE_{breath}, $sRPE_{leg}$, and $sRPE_{cognitive}$ to measure internal load in elite female football players [37]. Knowing the differential RPE response can help practitioners to prescribe appropriate methods to support the specific (i.e., central or peripheral fatigue) recovery process. In our investigation, RPE_{breath} scores were substantially higher than RPE_{leg} and $RPE_{cognitive}$ for each training session and match for starters and non-starters (Figure 1). These differences may reflect the different physiological stimuli of cardiovascular fitness and resistance training. Monitoring internal load during training and matches can aid athlete management, training prescription and decision making—ultimately facilitating player development and prescription of appropriate methods to support the recovery process.

Our data offer novel information about internal workload in highly trained female football players. However, there are some potential limitations to this study that should be acknowledged. Firstly, the current results come from a single elite female football club during the in-season period. Therefore, generalization of the current findings to teams from different competition levels (e.g., amateur), sports (e.g., basketball), or season period (e.g. preseason) should be conducted with caution. Nonetheless, the current results might be considered valid for football teams using similar weekly schedules during the in-season. Another potential limitation relates to the lack of quantification of other loads that players received in training sessions outside those conducted in the football field, such as strength and conditioning sessions in the gym. This may have caused a slight bias towards underestimation of load in strength training sessions in the gym overall, for non-starters. Future research could identify whether these reductions in total weekly training load may be due to differences in training drills, the availability of starting players or the lack of inclusion of off-field sessions. Additionally, our study did not consider playing positions and contextual factors such as match localization (i.e., home or away), final score, etc., which might potentially affect football players' workload. Moreover, the lack of external load quantification prevents us from identifying its relationship with the internal load response.

CONCLUSIONS

We concluded that starters experienced higher internal load, through RPE_{breath}, RPE_{leg} and RPE_{cog}, for total weekly load, match load, monotony and strain. Therefore, it is recommended that coaches adjust the weekly training loads for highly trained female football players, considering whether they played as starters or non-starters in the last match.

Practitioners involved in elite female football should consider implementing workload monitoring strategies to analyse the weekly

load for all the players, starters and non-starters. The sRPE as a monitoring tool allows one to describe the weekly load to optimize load distribution, considering that all players should receive adequate stimuli to maintain and improve performance and to avoid injuries. Special attention should be given to non-starter players, to guarantee a balanced weekly load distribution during the in-season period. Indeed, non-starter players tended to experience a greater load on MD+1, as a compensatory mechanism for their reduced participation on MD. However, a disproportional reduction is observed toward the rest of the weekly training sessions.

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Conflict of interest declaration

The authors declared no conflict of interest.

REFERENCES

1. Watson A, Brickson S, Brooks A, et al. Subjective well-being and training load predict in-season injury and illness risk in female youth soccer players. Br J Sports Med. 2017; 51:194–199. doi: 10.1136/bjsports-2016-096584
2. Datson N, Hulton A, Andersson H, et al. Applied physiology of female soccer: an update. Sports Med. 2014; 44:1225–1240. doi: 10.1007/s40279-014-0199-1
3. Krustrup P, Mohr M, Ellingsgaard H, et al. Physical demands during an elite female soccer game: Importance of training status. Med Sci Sports Exerc. 2005; 37:1242–1248. doi: 10.1249/01.mss.0000170062.73981.94
4. Mohr M, Krustrup P, Andersson H, et al. Match activities of elite women soccer players at different performance levels. J Strength Cond Res. 2008; 22:341–349. doi: 10.1519/JSC.0b013e318165fef6
5. Datson N, Drust B, Weston M, et al. Match Physical Performance of Elite Female Soccer Players during International Competition. J Strength Cond Res. 2017; 31:2379–2387. doi: 10.1519/JSC.0000000000001575
6. Clemente FM, Silva R, Castillo D, et al. Weekly Load Variations of Distance-Based Variables in Professional Soccer Players: A Full-Season Study. Int J Environ Res Public Health. 2020; 17:3300. doi: 10.3390/ijerph17093300
7. Hulin BT, Gabbett TJ, Lawson DW, et al. The acute: Chronic workload ratio predicts injury: High chronic workload may decrease injury risk in elite rugby league players. Br J Sports Med. 2016; 50:231–236. doi: 10.1136/bjsports-2015-094817
8. Scott TJ, Black CR, Quinn J, et al. Validity and reliability of the session-RPE method for quantifying training in Australian football: a comparison of the CR10 and CR100 scales. J Strength Cond Res. 2013; 27:270–276. doi: 10.1519/JSC.0B013E3182541D2E
9. Los Arcos A, Méndez-Villanueva A, Yanci J, et al. Respiratory and Muscular Perceived Exertion During Official Games in Professional Soccer Players. Int J Sports Physiol Perform. 2016; 11:301–304. doi: 10.1123/IJSPP.2015-0270
10. Barrett S, McLaren S, Spears I, et al. The Influence of Playing Position and Contextual Factors on Soccer Players' Match Differential Ratings of Perceived Exertion: A Preliminary Investigation. Sports (Basel). 2018; 6. doi: 10.3390/SPORTS6010013
11. Paulauskas H, Kreivyte R, Scanlan AT, et al. Monitoring workload in elite female basketball players during the in-season phase: Weekly fluctuations and effect of playing time. Int J Sports Physiol Perform. 2019; 14. doi: 10.1123/ijspp.2018-0741
12. Malone S, Roe M, Doran DA, et al. Protection against spikes in workload with aerobic fitness and playing experience: The role of the acute: Chronic workload ratio on injury risk in elite gaelic football. Int J Sports Physiol Perform. 2017; 12. doi: 10.1123/ijspp.2016-0090
13. Hulin BT, Gabbett TJ, Caputi P, et al. Low chronic workload and the acute: Chronic workload ratio are more predictive of injury than between-match recovery time: A two-season prospective cohort study in elite rugby league players. Br J Sports Med. 2016; 50. doi: 10.1136/bjsports-2015-095364
14. Martín-García A, Gómez Díaz A, Bradley PS, et al. Quantification of a professional football team's external load using a microcycle structure. J Strength Cond Res. 2018; 32. doi: 10.1519/jsc.0000000000002816
15. Stevens TGA, de Ruiter CJ, Twisk JWR, et al. Quantification of in-season training load relative to match load in professional Dutch Eredivisie football players. Sci Med Footb. 2017; 1. doi: 10.1080/24733938.2017.1282163
16. Anderson L, Orme P, di Michele R, et al. Quantification of seasonal-long physical load in soccer players with different starting status from the English premier league: Implications for maintaining squad physical fitness. Int J Sports Physiol Perform. 2016; 11. doi: 10.1123/ijspp.2015-0672
17. Malone S, Owen A, Newton M, et al. The acute: chonic workload ratio in relation to injury risk in professional soccer. J Sci Med Sport. 2017; 20. doi: 10.1016/j.jsams.2016.10.014
18. Gabbett TJ. The training-injury prevention paradox: Should athletes be training smarter and harder? Br J Sports Med. 2016; 50. doi: 10.1136/bjsports-2015-095788
19. Wang C, Vargas JT, Stokes T, et al. Analyzing Activity and Injury: Lessons Learned from the Acute: Chronic Workload Ratio. Sports Med. 2020; 50. doi: 10.1007/s40279-020-01280-1
20. Foster C. Monitoring training in athletes with reference to overtraining syndrome. Med Sci Sports Exerc. 1998; 30. doi: 10.1097/00005768-199807000-00023
21. Alexiou H, Coutts AJ. A comparison of methods used for quantifying internal training load in women soccer players. Int J Sports Physiol Perform. 2008; 3. doi: 10.1123/ijspp.3.3.320
22. Foster C, Florhaug JA, Franklin J, et al. A New Approach to Monitoring Exercise Training. J Strength Cond Res. 2001; 15(1):109–15.
23. Roos L, Taube W, Tuch C, et al. Factors that influence the rating of perceived exertion after endurance training. Int J Sports Physiol Perform. 2018; 13. doi: 10.1123/ijspp.2017-0707
24. Impellizzeri FM, Rampinini E, Coutts AJ, et al. Use of RPE-based training load in soccer. Med Sci Sports Exerc. 2004; 36. doi: 10.1249/01.MSS.0000128199.23901.2F
25. Hopkins WG, Marshall SW, Batterham AM, et al. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41:3–12. doi: 10.1249/MSS.0b013e31818cb278
26. Andersson H, Raastad T, Nilsson J, et al. Neuromuscular fatigue and recovery in elite female soccer: Effects of active recovery. Med Sci Sports Exerc. 2008; 40. doi: 10.1249/mss.0b013e31815b8497

27. Hills SP, Radcliffe JN, Barwood MJ, et al. Practitioner perceptions regarding the practices of soccer substitutes. PLoS One. 2020; 15. doi: 10.1371/journal.pone.0228790
28. Jaspers A, Brink MS, Probst SGM, et al. Relationships Between Training Load Indicators and Training Outcomes in Professional Soccer. Sports Med. 2017; 47. doi: 10.1007/s40279-016-0591-0
29. Los Arcos A, Mendez-Villanueva A, Martínez-Santos R. In-season training periodization of professional soccer players. Biol Sport. 2017; 34:149–155 doi: 10.5114/biolsport.2017.64588
30. Halson SL. Monitoring Training Load to Understand Fatigue in Athletes. Sports Med. 2014; 44. doi: 10.1007/s40279-014-0253-z
31. Fernandes R, Ibrahim Ceylan H, Manuel Clemente F, et al. In-Season Microcycle Quantification of Professional Women Soccer Players-External, Internal and Wellness Measures. Healthcare (Basel). 2022; 10. doi: 10.3390/HEALTHCARE10040695
32. Trewin J. Match-running performance of elite female soccer players: The factors affecting performance and training applications. University of Victoria.; 2017
33. Brink MS, Visscher C, Arends S, et al. Monitoring stress and recovery: New insights for the prevention of injuries and illnesses in elite youth soccer players. Br J Sports Med. 2010; 44. doi: 10.1136/bjsm.2009.069476
34. Delecroix B, McCall A, Dawson B, et al. Workload and non-contact injury incidence in elite football players competing in European leagues. Eur J Sport Sci. 2018; 18. doi: 10.1080/17461391.2018.1477994
35. Sporis G, Jovanovic M, Omrcen D, et al. Can the official soccer game be considered the most important contribution to player's physical fitness level? J Sports Med Phys Fitness. 2011; 51(3):374–80.
36. Joseph AM, Collins CL, Henke NM, et al. A multisport epidemiologic comparison of anterior cruciate ligament injuries in high school athletics. J Athl Train. 2013; 48(6):810–7. doi: 10.4085/1062-6050-48.6.03
37. Wright MD, Songane F, Emmonds S, et al. Differential ratings of perceived match and training exertion in girls' soccer. Int J Sports Physiol Perform. 2020; 15:1315–1323. doi: 10.1123/IJSPP.2019-0595.

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Fractures in professional footballers: 7-years data from 106 team seasons in the Middle East

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ABSTRACT: Epidemiological studies on fractures in European professional football (soccer) are in abundance. However, such data are lacking in Middle Eastern professional footballers and information on fracture treatment is scarce. The aim of this study is to describe the epidemiology of fractures across seven seasons in Qatar Stars League (QSL) footballers. A prospective study of fractures in professional male footballers over 7 consecutive seasons (2013 to 2020), involving 3255 players and 106 team' seasons. Time loss and injuries and illnesses were recorded using standardised digital tools in accordance with international consensus procedures. Fractures were recorded according to onset mechanism, location, diagnoses, treatment and return to play. A total of 108 players sustained fractures during 638,247 hours of player exposure (88.9% training and 11.1% matches), representing 2.7% of all time-loss injuries. The incidence was 0.17 fractures per 1000 h of exposure (match and training incidence of 0.9 and 0.07 fractures / 1000 h, respectively), equivalent to an average of one fracture per team per season. Fractures mostly occurred in the feet (28.2%), hands (21.1%), shoulders (11.3%) and head (i.e., face) (9.9%). Mean (median) absence was 71 (47 days), with 4.6% refractures. Only 34.3% of the fractures required surgery and nearly all players (98.1%) returned to play at the professional level. Almost all professional football players with fractures return to play at the same competitive level after an average of 10 weeks of absence (mean absence was 71 ± 81 (median: 47, Inter Quartile Range [14–93]) days). One in ten continue to play with symptoms and one in twenty may refracture. Long-term effects of fractures are still unknown.

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Multiple surgery
Non-union
Stress fracture

INTRODUCTION

Fractures are not so common in football, with an incidence of just 1 to 2 per season per professional male football team [1]. However, fractures have been shown to be responsible for up to 17% of severe injuries (i.e., time loss > 28 days) [2, 3]. In the UEFA Champions League (UCL), each fracture resulted in a median absence of 32 days (range: 1–278 days), although stress fractures were found to need twice the time to heal (median: 65 days, range: 6–168 days) of sudden onset (traumatic) fractures ((30 days (range: 1–278 days)) [1]. In the same study, fractures occurred mostly due to contact, especially during match play and were located predominantly in the lower limb. In the professional footballers from the Qatar Stars League (QSL), the incidence of fractures in the 2008–2009 season was similar to the UCL findings [4]. However, this study was limited to one season. Neither of the latter studies provided information on treatment [1, 4]. When faced with fractures, clinicians will need to be able to reference clinical service outcomes and return to play estimates. This would allow a reasonable approximation of return to play and enable accurate information for coaching and management staff. It would also bring an awareness of these, more serious injuries, which could potentially be career threatening.

Most previous epidemiological studies on fractures in professional footballers have been done in European clubs and national leagues in temperate environments [1, 5, 6]. Different environmental conditions, variations in training load and/or a different playing style from the European leagues may affect the incidence and prevalence of fractures [7–10]. Therefore, a prospective systematic data collection over multiple seasons would provide accurate information on the morbidity and outcome of fractures in professional footballers in the Middle Eastern region. The aim of the present study was thus to report data on fractures in male professional football players from the QSL over multiple seasons, describing subsequent treatment and return to play timing information.

MATERIALS AND METHODS

Study Design

This prospective epidemiological study included fractures in professional male QSL players aged 18 years and above, from up to 17 teams from 2013–2014 through the 2019–2020 seasons. The inclusion criteria were fracture(s) sustained during training or matches in players, playing and/or training with the first-team squad.

Data Collection

The medical staff (team physician or physiotherapist) of each participating team recorded injury and illness data using an electronic database (the Aspetar Injury and Illness Surveillance Program, using existing surveillance protocols [11, 12]. All injuries, including fractures, were classified using The Orchard Sports Injury Classification System (OSICS, 2017–2020) or previous 2013 to 2016 injuries were recorded with the Sports Medicine Diagnosis Coding System (SMDCS) [12]. These were thereafter independently recoded based on OSICS by two sports physicians. In the rare cases of conflicting outcomes, a consensus meeting was organized to result in the best diagnosis based on the available information and detailed discussion. Details on onset of injury (gradual or sudden, contact or non-contact), location, diagnoses (fracture type), treatment (surgery or conservative), and timing of return to play (RTP) were aligned with the IOC consensus (STROBIS-SIIS) [11].

Injuries diagnosed as fracture(s) were verified by radiological imaging (e.g., X-ray, CT scan, MRI, and/or ultrasound scan) and reported by consultant radiologists. Team physician, physiotherapist and orthopaedic surgeon notes were checked to verify the type and nature of conservative treatment or surgery, date of surgery, medical discharge (return to training with the team) and return to play. Eventual residual symptoms upon discharge, post-surgical complications and/or refractures were also recorded. All efforts were made to retrieve complete data. Data which could not be found or identified were classified as missing. The study is based on a large football epidemiological prospective study approved by the Anti-Doping Laboratory Qatar Ethics Institutional review board (IRB E2017000252).

Definitions

A fracture was defined as a complete or incomplete discontinuity of bone caused by a direct or indirect force [13]. Injury burden is the product of injury incidence and mean severity, and it is expressed in days lost per 1000 h of player' exposure [11]. Time loss was calculated from the date of the fracture to the date of return to full participation and availability for match selection [11]. Severity was defined according to the duration of time loss from football according to Fuller et al. [14]. Index injury is the first fracture occurring to one bone recorded during the study. Refractures are defined as a fracture to the same bone and location within one year of the index injury [11].

Statistical Analysis

Descriptive data are presented as the means, with standard deviation. Median and interquartile range (IQR) are used for fracture severity. The number of time-loss fractures per 1000 player hours of exposure are used for fracture incidence. Independent sample t-test or equivalence nonparametric test were used to compare time loss between binary categorical variables and mechanism of fracture variables. Chi-square test of independence was used to compare the severity percentage according to the mechanism of fracture variables. The level of significance was set at $p < 0.05$. Statistical analyses was performed SPSS V22.0.

RESULTS

Population

For the demographic data of the participants, see Table 1. In total, 3,255 male footballers from up to 17 teams per season (mean ± SD: 15.1 ± 1.6; 106 team seasons) were included from seven consecutive seasons (2013–2014 to 2019–2020) (Table 2). A total of 638,247 h of exposure was recorded. This was equivalent to 6,021 ± 1,235 h per team per season and 196 ± 40 h of exposure per player per season. The training-to-match ratio was 8.0.

TABLE 1. Demographic Data of Footballers (mean ± SD).

Demographic Data	Mean ± SD
Age	26.4 ± 4.7
Weight (kg)	70.5 ± 23.9
Height (cm)	168.9 ± 29.1
Total Players	3255
Total Team Seasons	106
Number of players per season	465 ± 46.8
Number of teams per season	15.1 ± 1.6

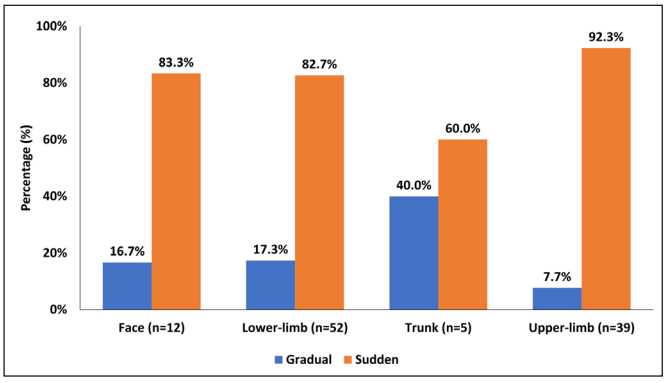


FIG. 1. Percentage of sudden and gradual onset fractures according to main body part (N = 108).

TABLE 2. Incidence and burden of fractures by season from 2013 to 2020. Incidence unit: injury/1000-h of exposure. Burden unit: days of absence/1000-h.

Seasons	Time loss	Time loss injuries	Football Exposure	Incidence rate	95% Confidence Interval		Burden	95% Confidence Interval	
	(Days)	(N)	(Hours)		Lower Bound	Upper Bound		Lower Bound	Upper Bound
2013–2014	1406	17	106160.1	0.2	0.1	0.3	13.2	12.6	14.0
2014–2015	1208	21	99549.3	0.2	0.1	0.3	12.1	11.5	12.8
2015–2016	1552	16	61838.0	0.3	0.1	0.4	25.1	23.9	26.4
2016–2017	980	10	86303.8	0.1	0.1	0.2	11.4	10.7	12.1
2017–2018	866	15	103635.8	0.1	0.1	0.2	8.4	7.8	8.9
2018–2019	967	16	96741.1	0.2	0.1	0.3	10.0	9.4	10.6
2019–2020	659	13	84019.3	0.2	0.1	0.3	7.8	7.3	8.5

Fracture Incidence and Prevalence

Out of the 3,986 recorded injuries, 108 players (2.7%) sustained a fracture(s). Twelve players (11%) sustained more than one fracture in the same incident ((10 players (9%) had two fractures (e.g., tibia and fibula), and two players (2%) had three fractures (e.g., 2nd, 3rd, and 4th metacarpal fracture)). Incidence and burden of fracture by season from 2013 to 2020 is shown in Table 2.

Fracture patterns

The fracture patterns according to location is shown in Figures 1 and Figure 2. Sudden onset fractures were more likely to result from a contact ((n = 83, 90.2%; ($p < 0.001$) than non-contact (n = 9, 9.8%)).. However, there were more non-contact injuries during training (30%) compared to match play (6.3%) ($p = 0.001$).

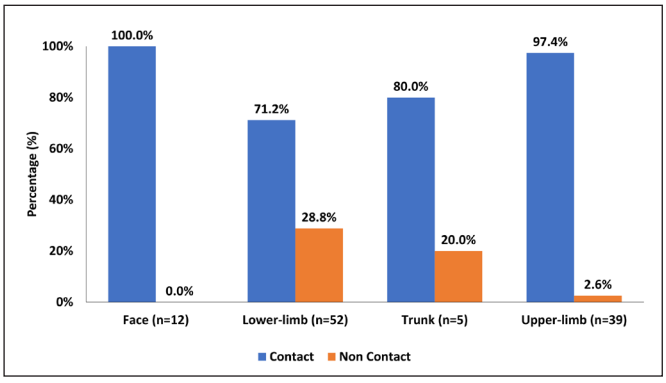


FIG. 2. Percentage of contact and non-contact related fractures according to main body part (N = 108).

Fractures in Match and training

Match play yielded 12.8 times more fractures than training (incidence: 0.9 vs 0.07 fractures/1000 h). Trunk fractures (n = 4, 80%), and head, neck and face fractures (n = 9, 75%) were more likely to occur during matches than training compared to upper limb fractures (n = 16, 43%) and lower limb fractures (n = 20, 40%). Most of the upper limb fractures recorded from training occurred in goalkeepers (n = 8; 50%).

Fracture location

The proportion of fractures according to the body location is shown in Table 4. Goalkeepers were 3 times more likely to have upper limb fractures (n = 12) than lower limb fractures (n = 4). Meanwhile, outfield players were almost twice as likely to have lower limb fractures (n = 48) compared to upper limb fractures (n = 27). The proportion of fractures was 59.2% in the dominant lower limb and 38.5% in the dominant upper limb compared to the contralateral side, but there was no statistical significance in comparison with the non-dominant limb ($p = 0.068$).

Time Loss

Time loss was 71 (± 81; 47 days), with 63% (n = 68) resulting in severe absence (≥ 28 days). Time loss and severity of fracture according to fracture type, onset of injury, mechanism, and player position are shown in Table 3. There was no significant difference in time loss in relation to the onset of fracture, origin, mechanism, or fracture type.

The large majority, 98.1% (106 players) successfully returned to play at the previous level (QSL). Two players retired (1.9%), one unrelated to his fracture.

TABLE 3. Time loss (mean ± SD, median and Inter Quartile Range) and severity of fracture (%) according to fracture type, onset of injury, mechanism, and player position.

	Total	Mean ± SD	Median (Percentile 25–75)	Minor (≤ 7 days)	Major (8–28 days)	Severe (> 28 days)
	N (%)	Days	Days	N (%)	N (%)	N (%)
Origin						
Match	66 (61.1%)	77.0 ± 85.1	47 (14–124)	10 (15.2%)	14 (21.2%)	42 (63.6%)
Training	42 (38.9%)	60.9 ± 75.0	47 (16–78)	8 (19.0%)	8 (19.0%)	26 (61.9%)
Type						
Non-Stress Fracture	97 (89.8%)	70.2 ± 84.6	46 (14–93)	17 (17.5%)	22 (22.7%)	58 (59.8%)
Stress fracture	11 (10.2%)	75.6 ± 44.5	68 (47–86)	1 (9.1%)	0 (0%)	10 (90.9%)
Mechanism						
Contact	91 (84.3%)	66.2 ± 79.3	45 (14–92)	16 (17.6%)	21 (23.1%)	54 (59.3%)
Non-Contact	17 (15.7%)	94.9 ± 90.1	78 (47–93)	2 (11.8%)	1 (5.9%)	14 (82.4%)
Onset of injury						
Gradual	16 (14.8%)	44.1 ± 31.5	44.5 (10.5–74.5)	3 (18.8%)	2 (12.5%)	11 (68.8%)
Sudden	92 (85.2%) *	75.4 ± 86.4	47 (14.5–104)	15 (16.3%)	20 (21.7%)	57 (62.0%)
Player position						
Outfield player	92 (85.2%) *	75.5 ± 84.7	47.5 (15.5–93.5)	12 (13.0%)	19 (20.7%)	61 (66.3%) *
Goalkeeper	16 (14.8%)	43.2 ± 51.7	17.5 (4–59.5)	6 (37.5%)	3 (18.8%)	7 (43.8%)

*Significantly different between groups (onset of injury and player position) $P < .05$

TABLE 4. Time loss (mean, SD and Median) according to treatment and fracture location.

	No Surgery N = 71 (65.7%)			Surgery N = 37 (34.3%)		
	Total	Mean ± SD	Median (Percentile 25–75)	Total	Mean ± SD	Median (Percentile 25–75)
	N (%)	Days	Days	N (%)	Days	Days
Main body part						
Head-face-Neck	7 (9.9%)	12 ± 8	14	5 (13.5%)	29 ± 25	20
*Lower limb**	32 (45.1%)	56 ± 37	51	20 (54.1%)	185 ± 106	156
Trunk	5 (7.0%)	42 ± 33	32	0	—	—
Upper limb	27 (38.0%)	29 ± 36	14	12 (32.4%)	78 ± 73	57
Location						
Ankle	3 (4.2%)	21 ± 19	16	2 (5.4%)	128 ± 45	128
Chest/Ribs/Upper Back	3 (4.2%)	19 ± 13	19	0	—	—
*Foot**	20 (28.2%)	57 ± 43	52	6 (16.2%)	113 ± 36	105
Forearm	1 (1.4%)	59	59	1 (2.7%)	42	42
*Hand**	15 (21.1%)	14 ± 18	6	6 (16.2%)	60 ± 58	42
Head	7 (9.9%)	12 ± 8	14	5 (13.5%)	29 ± 25	20
Knee	4 (5.6%)	62 ± 23	57	1 (2.7%)	219	219
*Lower Leg**	5 (7.0%)	62 ± 22	51	10 (27.0%)	251 ± 107	248
Pelvis/Low Back	2 (2.8%)	75 ± 16	75	0	—	—
Shoulder	8 (11.3%)	55 ± 52	46	4 (10.8%)	49 ± 34	59
Thigh	1 (1.4%)	53	53	0	—	—
Wrist	2 (2.8%)	28 ± 25	28	2 (5.4%)	188 ± 99	188

* Significantly higher days loss in surgery compared to no surgery, $P < 0.05$

Refractures

Refractures was 4.6% (n = 5) with the majority occurring in the lower limb (80%). Of those with refractures, four players had one recurrence and one player had two recurrences (malleolar – supra-syndesmotic). Refractures was in 7.7% of the lower-limb, 2.6% of the upper-limb and none for head-face and neck, or trunk. Most players (60%) who re-fractured had been treated surgically (n = 3, i.e., distal fibula, 5th metatarsal, malleolar (suprasyndesmotic), while 40% had been conservatively managed. (n = 2, i.e., tibial diaphysis, proximal humerus). The mean time to refractures was 231 days (range from 132 to 355 days).

Treatment

The treatment provided and time loss according to fracture location are shown in Table 4. Hardware placement was used for 81% (n = 30) and closed reduction under anesthesia in 19% (n = 7). Thirteen players (43%) needed more than one surgery, for hardware removal. Lower-limb fractures were more often treated with multiple surgeries (two or more) (47.4%) than upper-limb fractures (16.7%). None of the older players (> 28 years) who sustained fractures during training needed surgery. Only one goalkeeper needed surgery for an upper limb fracture (n = 1, 9.1%).

There was no significant difference in the number of surgeries done for gradual onset (stress) fractures (45.5%) compared to sudden onset (traumatic) fractures (32%) (p = 0.20). All stress fractures requiring surgery were located at the 5th metatarsal bone with four (80%) requiring only one surgery and the remaining one (20%) requiring two surgeries.

Complications were seen only in surgically treated fractures (22%, n = 8). These comprised: non-union (n = 2), stress fracture (n = 2), delayed union (n = 1), osteoarthritis (n = 1), deformity (n = 1) and infection (n = 1). The lower limb was the main location for complications (75%) followed by the upper limb and face, with 12.5% each. Only 9.3% (n = 10) had residual symptoms at return to play, i.e., pain (7, 6.5%), swelling, instability and restricted movement (1 each).

DISCUSSION

This study showed that fractures in QSL male professional footballers occurred mostly by sudden onset and contact mechanism; furthermore, fractures were located mostly in the lower limbs and occurred during match play rather than training. Lower limb fractures were also more likely to require surgery; naturally, these needed extended time loss, unlike upper limb fractures.

Fractures representing 2.7% of total time-loss injuries sustained by players was in the range from 2.6% to 4% of previous studies from European professional leagues [3, 15, 16].

Fracture incidence (0.17 fractures per 1000 h of exposure) was similar to the 0.19/1000-h found in German Bundesliga but lower than the 0.27/1000-h from the UCL study [1, 6]. We showed that there was an average incidence of 1.0 fracture per team per season in the QSL. The proportion of stress fractures (10.2%) did not substantially differ from earlier studies, between 4.5% to 11.3% [1].

Slightly higher than the 75% from the UCL study, 85% of the fractures occurred with sudden onset, due to contact, and during match play [1]. The incidence of sudden onset (previously reported as traumatic fracture) and stress fractures (also described as overuse) was similar to the UCL and Swedish Super league findings [1, 5]. Unlike previous studies, the higher proportion of injuries in the dominant limb as seen for soft tissues (predominantly muscle and ligament injuries) was not observed for fractures in our study [15].

In this study, lower limb fractures (48%) were the most common, in accordance with most European professional league study findings (35.3% to 50%) [1, 3, 6]. It has been suggested that the use of shin guards prevented some leg fractures, based on a previous laboratory study, and obviously the use of these is mandatory in the QSL as in other leagues [17]. However, there is no mandate on the type or size of shin guards rendering efficiency potentially inconsistent from the size perspective. Leg fractures have been shown to cause absences of 251 ± 107 days (around 36 weeks (about 8 and a half months), comparable to the time loss after ACL surgery [18]. In practical terms, this amounts to the loss of almost a full season in the major international leagues (usually a player season including pre-season is around 48 weeks (about 11 months), and therefore, any means of eventually preventing such events would have a significant impact on football players careers.

Upper limb fractures (36%) in our study were in the upper range compared with the literature, with the Swedish Premier League (28.6%) and the German Bundesliga (24.9%) situated in a middle-range while the UCL (14%) presented a lower figure [1, 3, 6]. In the goalkeepers of our study, upper limb fractures occurred more commonly during training possibly due to higher frequency of dives, jumps, high speed change of direction compared to matches, as suggested in a review [19]. Interestingly, AlAttar et al. recently suggested that FIFA 11+S upper limb exercises were beneficial to amateur footballers in reducing upper limb injuries of moderate severity [20]. Goalkeeper training increases their ability to land safely and anticipate player or ground contact [19]. Hence, these factors may be part of the reason why the more serious upper limb fractures, i.e., those requiring surgery, were less common.

Head, face, and neck fractures (all facial in our study) (11%) were less common than in European leagues ranging from 16.8% to 30.3% [1, 3, 6], possibly due to fewer headers and different playing styles in players in the QSL, although this has not been objectively assessed to date. As suggested in previous studies, stricter game rules, referee implementation and avoidance strategies in tackling, heading and ball control, in addition to a potential lower engagement in duels (especially aerial ones) may also have contributed to fewer facial fractures in our study [21, 22]. Time loss due to these fractures was similar to findings in European leagues. Indeed, the players of our study were allowed early return to play after facial fractures thanks to thermoplastic face masks

as consistently observed in major international leagues during the last decade [1, 6].

In an earlier study of recreational footballers, only 20% of fractures needed surgery but in our study with professional footballers, the proportion was greater (34.3%) [23]. Previous studies have suggested that athletes who are surgically treated with post-traumatic metacarpal, clavicle, tibial and fibular, or fifth metatarsal fractures have fewer complications, and a quicker return to play, but in our study, this was seen only with fifth metatarsal fractures [24–26]. We showed that time loss due to post-traumatic tibia and fibular fractures was similar to the European leagues and American Football findings [27, 28].

Refractures was slightly less common in the QSL (4.6%) compared with the UCL (7.7%) [1]. This was mainly due to a much lower refractures in the upper limb (2.6% vs 14.3%), trunk (0% vs 10%) in the QSL than in UCL [1]. We speculate that the longer absence to treat these fractures may have contributed to the observed much lower refractures in QSL as the longer time allows for improved fracture consolidation [29]. However, the lower limb refractures (7.7%) in QSL was similar to the UCL [1].

Return to play

Despite a high percentage of players (63%) sustaining fractures causing severe absence (longer than 28 days), only two (1.9%) out of 108 players retired. Therefore, as with earlier studies, almost all professional players (98.1%) returned to play at the previous level, i.e., same level of the competition [23]. One player left the league after a prolonged absence of 403 days, 3 surgeries, and non-union, whereas the other left to play football abroad. Of the 9 players who had post-surgical complications, 8 (88.9%) returned to play whereas the remaining player retired upon discharge from treatment. The residual symptoms seen upon return to play in 10 players (9.3% of 108) did not affect their ability to train and play competitive matches. The high motivation, level of responsibility and financial needs in professional footballers and/or the competency of the team medical staff (including subspeciality musculoskeletal radiologists, orthopaedic surgeons, sports medicine physicians, physiotherapists and biomechanists) supporting them may have contributed to their ability to continue playing despite having symptoms [30].

Strengths and limitations

The study was done with systematic recording and verification of injury data of professional male footballers and importantly, included data on fracture treatment. However, female, and amateur players were not included and obviously deserve specific dedicated studies. There were some missing data about training and match exposure, mechanism of injury and time of injury (minutes in the match or training session). It was difficult to ascertain the nature of contact or the inciting event and identify any referee sanction without video analysis [21]. We also could not utilise the global positioning system technology (GPS) data to quantify training and match load, although a previous author suggested that playing intensity and injury may be correlated [31]. Such data could have been especially useful to determine the potential effect of external load in the contribution of lower limb stress fractures risk during match or training [32, 33].

The choice of treatment depends on multiple factors which may affect time loss e.g., (i) shared decision making between the player, physician, surgeon and/or coach, (ii) risk taking behaviour, (iii) period of season with the importance of upcoming matches potentially influencing the decision (iv) site and classification of fracture and/or (v) player position and importance in terms of being ranked by the coach as first, second or even third in his specific field position [34–38]. The rehabilitation programme differed with fracture location, type of fracture, length of immobilisation and whether the fracture was treated conservatively or surgically. In previous studies, focal extracorporeal shockwave therapy has shown a promising response on non-union and delayed union fractures. However, their effect on return to play has not been studied in athletes [39]. The 12-month follow-up of refractures adopted in our study prevented the possibility of missing some refractures, as previous studies have shown that refracture may occur up to 10 months from the first fracture [28, 40]. But with the one-year post-fracture limit, we might have missed other long-delay refractures, even though actual consensus is setting the limit to one year. Our data did not include a 5-year follow-up for each fractured player (whenever possible, in terms of player' age and availability) which could have been made to study player retention and long-term effects of the fracture on the player's career as suggested in Lavoie-Gagne et al's study [28].

CONCLUSIONS

Almost all professional football players who sustained fractures returned to play at the previous competitive level after an average of 10 weeks, although leg fractures resulted in up to 27 weeks of absence. One case in twenty suffered a refracture requiring further treatment, whilst one-tenth of the injured players continued to play despite having mild symptoms. The long-term effects of football fractures are still unknown and warrants investigation.

Contributors

The research idea was conceptualised by first author A.S.H.N; formal analysis was performed by A.F., and M.T., investigation was done by A.S.H.N., A.F., O.M., K.C. and R.B.; S.C., Z.E., M.T., J.A. and K.A. provided the resources and assisted in data acquisition; The first draft was written by A.S.H.N. and I.B.; All authors reviewed and editing the final manuscript. All authors have read and agreed to the publication of the submitted manuscript.

Competing interests

The authors declare no conflict of interest.

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Data sharing

The datasets used and/or analysed during the current study are available from the corresponding author on request.

Ethical approval

This study was approved by Qatar Anti-Doping Lab Ethics Committee (Doha, Qatar; approval no: E2017000252). All methods were carried out in accordance with the Declaration of Helsinki. All participants were part of routinely clinical visits and data collected were anonymized and stored in confidential and protected computer.

Patient and Public Involvement

Patients or the public WERE NOT involved in the design, or conduct, or reporting, or dissemination plans of our research.

REFERENCES

1. Larsson D, Ekstrand J, Karlsson MK. Fracture epidemiology in male elite football players from 2001 to 2013: 'How long will this fracture keep me out?'. Br J Sports Med. 2016; 50(12):759–63. doi: 10.1136/bjsports-2015-095838.
2. Chomiak J, Junge A, Peterson L, et al. Severe injuries in football players. Influencing factors. Am J Sports Med. 2000; 28(5 Suppl):S58–68. doi: 10.1177/28.suppl_5.s-58
3. Hagglund M, Walden M, Ekstrand J. Injuries among male and female elite football players. Scand J Med Sci Sports. 2009; 19(6):819–27. doi: 10.1111/j.1600-0838.2008.00861.x.
4. Eirale C, Farooq A, Smiley FA, et al. Epidemiology of football injuries in Asia: a prospective study in Qatar. J Sci Med Sport. 2013; 16(2):113–7. doi: 10.1016/j.jsams.2012.07.001
5. Ekstrand J, Torstveit MK. Stress fractures in elite male football players. Scand J Med Sci Sports. 2012; 22(3):341–6. doi: 10.1111/j.1600-0838.2010.01171.x
6. Schiffner E, Latz D, Grassmann JP, et al. Fractures in German elite male soccer players. J Sports Med Phys Fitness. 2019; 59(1):110–15. doi: 10.23736/S0022-4707.17.07901-4
7. Gollan S, Bellenger C, Norton K. Contextual Factors Impact Styles of Play in the English Premier League. J Sports Sci Med. 2020; 19(1):78–83.
8. Nassis GP, Brito J, Dvorak J, et al. The association of environmental heat stress with performance: analysis of the 2014 FIFA World Cup Brazil. Br J Sports Med. 2015; 49(9):609–13. doi: 10.1136/bjsports-2014-094449
9. Tabben M, Eirale C, Singh G, et al. Injury and illness epidemiology in professional Asian football: lower general incidence and burden but higher ACL and hamstring injury burden compared with Europe. Br J Sports Med. 2022; 56(1):18–23. doi: 10.1136/bjsports-2020-102945
10. Rekik R, Bahr R, Cruz F, et al. Mechanisms of ACL injuries in men's football: A systematic video analysis over six seasons in the Qatari professional league. Biol Sport. 2023;40(2):575–86. doi: 10.5114/biolsport.2023.118024
11. Bahr R, Clarsen B, Derman W, et al. International Olympic Committee consensus statement: methods for recording and reporting of epidemiological data on injury and illness in sport 2020 (including STROBE Extension for Sport Injury and Illness Surveillance (STROBE-SIIS)). Br J Sports Med. 2020; 54(7):372–89. doi: 10.1136/bjsports-2019-101969
12. Orchard JW, Meeuwisse W, Derman W, et al. Sport Medicine Diagnostic Coding System (SMDCS) and the Orchard Sports Injury and Illness Classification System (OSIICS): revised 2020 consensus versions. Br J Sports Med. 2020; 54(7):397–401. doi: 10.1136/bjsports-2019-101921
13. Adler CP. [Pathologic bone fractures: definition and classification]. Langenbecks Arch Chir Suppl II Verh Dtsch Ges Chir. 1989:479–86.
14. Fuller CW, Ekstrand J, Junge A, et al. Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. Clin J Sport Med. 2006; 16(2):97–106. doi: 10.1097/00042752-200603000-00003
15. Hawkins RD, Fuller CW. A prospective epidemiological study of injuries in four English professional football clubs. Br J Sports Med. 1999; 33(3):196–203. doi: 10.1136/bjsm.33.3.196
16. Noya Salces J, Gomez-Carmona PM, Gracia-Marco L, et al. Epidemiology of injuries in First Division Spanish football. J Sports Sci. 2014; 32(13):1263–70. doi: 10.1080/02640414.2014.884720
17. Francisco AC, Nightingale RW, Guilak F, et al. Comparison of soccer shin guards in preventing tibia fracture. Am J Sports Med. 2000; 28(2):227–33. doi: 10.1177/03635465000280021401
18. Forsythe B, Lavoie-Gagne OZ, Forlenza EM, et al. Return-to-Play Times and Player Performance After ACL Reconstruction in Elite UEFA Professional Soccer Players: A Matched-Cohort Analysis From 1999 to 2019. Orthop J Sports Med. 2021; 9(5):23259671211008892. doi: 10.1177/23259671211008892
19. White A, Hills SP, Hobbs M, et al. The physical demands of professional soccer goalkeepers throughout a week-long competitive microcycle and transiently throughout match-play. J Sports Sci. 2020; 38(8):848–54. doi: 10.1080/02640414.2020.1736244
20. Al Attar WSA, Faude O, Bizzini M, et al. The FIFA 11+ Shoulder Injury Prevention Program Was Effective in Reducing Upper Extremity Injuries Among Soccer Goalkeepers: A Randomized Controlled Trial. Am J Sports Med. 2021; 49(9):2293–300. doi: 10.1177/03635465211021828
21. Andersen TE, Tenga A, Engebretsen L, et al. Video analysis of injuries and incidents in Norwegian professional football. Br J Sports Med. 2004; 38(5):626–31. doi: 10.1136/bjsm.2003.007955
22. Beaudouin F, Aus der Funten K, Tross T, et al. Head injuries in professional male football (soccer) over 13 years: 29% lower incidence rates after a rule change (red card). Br J Sports Med. 2019; 53(15):948–52. doi: 10.1136/bjsports-2016-097217
23. Robertson GA, Wood AM, Bakker-Dyos J, et al. The epidemiology, morbidity, and outcome of soccer-related fractures in a standard population. Am J Sports Med. 2012; 40(8):1851–7. doi: 10.1177/0363546512448318
24. Etier BE, Scillia AJ, Tessier DD, et al. Return to play following metacarpal fractures in football players. Hand (N Y). 2015; 10(4):762–6. doi: 10.1007/s11552-015-9769-4
25. Hebert-Davies J, Agel J. Return to elite-level sport after clavicle fractures. BMJ Open Sport Exerc Med. 2018; 4(1):e000371. doi: 10.1136/bmjsem-2018-000371
26. Robertson GA, Wood AM. Return to sport following clavicle fractures: a systematic review. Br Med Bull. 2016; 119(1):111–28. doi: 10.1093/bmb/ldw029
27. Knapik DM, Mack CD, Lee R, et al. Epidemiology of Tibial Fractures in Professional American Football Athletes From 2013 to 2019. Orthop J Sports Med. 2021; 9(11):23259671211040878. doi: 10.1177/23259671211040878
28. Lavoie-Gagne O, Gong MF, Patel S, et al. Traumatic Leg Fractures in UEFA Football Athletes: A Matched-Cohort Analysis of Return to Play, Reinjury, Player Retention,

and Performance Outcomes. Orthop J Sports Med. 2021; 9(9):23259671211024218. doi: 10.1177/23259671211024218
29. Axelrad TW, Einhorn TA. Use of clinical assessment tools in the evaluation of fracture healing. Injury. 2011; 42(3):301–5. doi: 10.1016/j.injury.2010.11.043
30. Squyer ER, Dikos GD, Kaehr DM, et al. Early prediction of tibial and femoral fracture healing: Are we reliable? Injury. 2016; 47(12):2805–08. doi: 10.1016/j.injury.2016.10.036
31. Gregson W, Di Salvo V, Varley MC, et al. Harmful association of sprinting with muscle injury occurrence in professional soccer match-play: A two-season, league wide exploratory investigation from the Qatar Stars League. J Sci Med Sport. 2020; 23(2):134–38. doi: 10.1016/j.jsams.2019.08.289
32. Bradley PS, Carling C, Archer D, et al. The effect of playing formation on high-intensity running and technical profiles in English FA Premier League soccer matches. J Sports Sci. 2011; 29(8):821–30. doi: 10.1080/02640414.2011.561868
33. Di Salvo V, Gregson W, Atkinson G, et al. Analysis of high intensity activity in Premier League soccer. Int J Sports Med. 2009; 30(3):205–12. doi: 10.1055/s-0028-1105950
34. Hutchinson RH, Barrie JL. The effects of shared decision making in the conservative management of stable ankle fractures. Injury. 2015; 46(6):1116–8. doi: 10.1016/j.injury.2015.01.013
35. Junge A, Dvorak J, Chomiak J, et al. Medical history and physical findings in football players of different ages and skill levels. Am J Sports Med. 2000; 28(5 Suppl):S16–21.
36. Niederer D, Engeroff T, Wilke J, et al. Return to play, performance, and career duration after anterior cruciate ligament rupture: A case-control study in the five biggest football nations in Europe. Scand J Med Sci Sports. 2018; 28(10):2226–33. doi: 10.1111/sms.13245
37. Swiontkowski MF, Agel J, McAndrew MP, et al. Outcome validation of the AO/OTA fracture classification system. J Orthop Trauma. 2000; 14(8):534–41. doi: 10.1097/00005131-200011000-00003
38. Van Tiggelen D, Wickes S, Stevens V, et al. Effective prevention of sports injuries: a model integrating efficacy, efficiency, compliance and risk-taking behaviour. Br J Sports Med. 2008; 42(8):648–52. doi: 10.1136/bjsm.2008.046441
39. Elster EA, Stojadinovic A, Forsberg J, et al. Extracorporeal shock wave therapy for nonunion of the tibia. J Orthop Trauma. 2010; 24(3):133–41. doi: 10.1097/BOT.0b013e3181b26470
40. Granata JD, Berlet GC, Philbin TM, et al. Failed Surgical Management of Acute Proximal Fifth Metatarsal (Jones) Fractures: A Retrospective Case Series and Literature Review. Foot Ankle Spec. 2015; 8(6):454–9. doi: 10.1177/1938640015592836

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Does the Paleo diet affect an athlete's health and sport performance?

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ABSTRACT: The aim of the study was to assess the impact of an eight-week Paleo diet on the health status (body composition, haematology and biochemistry of blood and urine) and the level of physical capacity (aerobic and anaerobic) of professional handball players. Fifteen athletes were assigned to two groups: 9 in the experimental group (PD) and 6 in the control group (CD). Significant decreases in body mass (BM), body mass index (BMI), and fat mass (FM) as well as an increase in the fat-free mass (FFM) (%) in both groups were observed. There were no significant differences between groups in particular series during the experiment in all haematological and biochemical indicators of blood and urine. Only HDL-C was significantly higher in the last series in the PD compared to the CD (1.63 mmol/l vs. 1.23 mmol/l). In the Wingate test, there were only single intragroup changes, consisting of a significant decrease in the Wt, MAP and Pmean in the experimental group. There were no significant differences between the groups in individual series or intragroup differences during the experiment, determined by the VO_2max, VEmax, $VE \cdot VCO_2^{-1}$, RER, and the time of the test with a gradually increasing load on a treadmill, except for a significant decrease of maximum tidal volume (TVmax) in the PD. No adverse effect of the Paleo diet on the health status was found. The use of the Paleo diet slightly adversely affects anaerobic capacity and does not affect the level of aerobic capacity.

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INTRODUCTION

Paleolithic nutrition is based on the principles of evolutionary biology with a focus on the low carbohydrate options available to hunter-gatherers. The Paleo diet consists mainly of grass-fed and pasture-raised meats, vegetables, fruits, fungi, roots and nuts, excludes grains, legumes and dairy products, and limits refined sugars, starches, processed foods and oils. The Paleo diet is defined by the avoidance of particular food sources rather than a specific macronutrient distribution [1].

There are many scientific articles that evaluate effects of the Paleo diet (PD) on health status in people with diseases, such as ischemic heart disease [2], blood lipid disorder [3], overweight or obesity [4–5], diabetes [2, 4, 6], and metabolic syndrome [7], and even in healthy, inactive adults [8, 9]. Most, albeit not all, studies suggest that a PD has positive effects on body composition [2–5, 7, 9], insulin sensitivity and/or fasting blood glucose [2, 3, 7, 8], blood lipids [3, 4, 7–9], and blood pressure [4, 7, 8]. Only a few studies have examined the effects of a PD with exercise on cardiorespiratory fitness in healthy or unhealthy adults [5, 6, 9].

On average, the authors estimate the following ratio of macronutrients: 35% energy from fats, 35% from carbohydrates, and 30% from protein (although no specific amount is the goal) [7]. Currently, researchers evaluating the nutritional value of the Paleo diet classify it as a moderate-carbohydrate diet [10]. There are many studies determining the impact of a diet with very low amounts of carbohydrates (e.g., ketogenic diet; KD) on athletic performance, while there are only several research trials using a moderate carbohydrate diet in a group of athletes [11]. So far, no scientific studies have been carried out to evaluate the use of the Paleo diet among athletes, despite this diet being currently a very fashionable nutrition strategy willingly used by athletes. It should be noted that the relatively small (but sufficient) amount of carbohydrates in the Paleo diet is increasingly used by athletes with the aim of using fat during exercise and saving carbohydrate reserves. That is why we became interested in this subject and decided to start research assessing the use of the Paleo diet in the context of sports. Considering the athletes' willingnes to the use of the Paleo diet, we wanted to assess the impact of an eight-week Paleo diet on the health status (body composition, haematology and biochemistry of blood and urine) and the level of physical capacity (aerobic and anaerobic) of professional handball players.

MATERIALS AND METHODS

Characteristics of participants

At the beginning, 22 professional handball players training competitively were invited to take part in the experiment involving the

application of an eight-week nutritional intervention. Twenty-two athletes who competed in a local, 2nd league team in Kraków were recruited. The inclusion criteria in the study group were: age 18–25 years, at least 5 years of participation in competitive sports, undertaking regular physical activity at least 5 times a week for more than one hour per training session, and participation in national and/or international competitions. Five participants dropped out of the experiment in the first research series as they failed to maintain the nutritional regime, regardless of the diet they were to use, despite the high taste preference for the diet or a rational and expressed willingness to take up the diet indicated in the questionnaire. Two athletes ultimately failed to meet the inclusion criterion for undertaking physical activity for all subjects. Finally, 15 athletes completed the full-time study. Based on the analysis of taste preferences and after expressing their willingness to undertake a rational or Paleo diet, the competitors were assigned to two groups differing in the type of diet: 9 in the experimental group and 6 in the control group. At baseline, the two groups did not differ in terms of age [experimental group: 22.00 (21.00; 24.00), control group: 24.5 (23.25; 26.50)] or in anthropometric parameters [body height: 1.86 (1.81; 1.95) cm and 1.85 (1.81; 1.89) cm, respectively, and body mass: 91.36 (87.5; 99.50) kg and 88.4 (84.7; 100.65) kg, respectively].

Dietary intervention

To determine the individual total energy demand (ED), before starting the experiment, the players performed 10-day monitoring of total energy expenditure (on 8 training days and 2 non-training days) using a heart rate monitor (Polar M400/RS400) [12]. Median energy expenditure (EE) in the experimental group was: 4288 (4127; 5000) kcal on training days and 3400 (2900; 3412) kcal on non-training days, and accordingly in the control group: 4096 (3853; 4775) kcal and 3040 (2860; 3646) kcal. There were no statistically significant differences in EE. The ED in both groups was determined considering a sustainable energy balance.

Based on the determined energy demand and the individual needs for nutrients, body mass and food preferences, two nutritional strategies have been developed: the rational diet (control diet; CD), in accordance with the current nutritional recommendations for active people [12, 13], and the Paleo diet (PD) based on the qualitative recommendations of the nutritional model [1]. The PD included grass-fed and pasture-raised meats, vegetables, fruits, fungi, roots and nuts, excluded grains, dairy products and legumes, and limited refined sugars and highly processed foods [1]. The all-day food rations were prepared using the "Aliant. Dietetic Calculator" 4.10.14 (Cambridge Diagnostics, Poland) considering individual assumptions developed by the researcher, considering the isocaloric model of the diet. A different energy supply was used on training/match days (training sessions were held from Monday to Friday, and matches were held on Saturdays) and on a day off training, intended for regeneration. For a rational diet, the following energy share of macronutrients was adopted: 15% protein (no more than 20%, depending on body mass; BM), 25% fat (no more than 30%, depending on BM) and approximately 55% carbohydrates (no more than 60%, depending on BM) [13, 14], and for the Paleo diet, accordingly, 30% protein (not less than 20%, depending on BM), 40% fat (not less than 35%, depending on BM) and 30% of carbohydrates (no more than 35%, depending on BM) [8]. A total of 840 daily food rations were created: 504 for the subjects in the experimental group and 336 in the control group, 56 for each subject, which were then prepared by the catering company. The diets were used by competitors for 56 days (eight weeks). During the experiment, the athletes did not take any supplements influencing the resting and exercise metabolism.

Experimental design

The research was conducted in accordance with the Declaration of Helsinki and the research methodology was approved by the Bioethical Committee of the Regional Medical Chamber in Kraków (38/KBL/OIL/2017). The participants were informed in detail about the purpose and course of the study and about the possibility to withdraw from participation in the project at any stage without providing a reason. All the subjects read the written information about the research course, especially the nutritional strategy. The participants provided their written consent for voluntary participation in the trial.

Five measurement points (series) were distinguished: 1 – before the start of nutritional intervention or on the first day of the experiment; 2 – after two weeks of nutritional intervention; 3 – after four weeks of nutritional intervention; 4 – after six weeks of nutritional intervention; 5 – after eight weeks of nutritional intervention (Figure 1). Before starting the experiment and after the 2nd, 4th, 6th and 8th week, the body composition was measured using dual energy X-ray absorptiometry (DXA) using the Lunar iDXA instrument. Fat mass (FM) [% and kg], fat free mass (FFM) [% and kg], lean body mass (body mass without adipose tissue and bone minerals: (LBM) [% and kg], bone mineral content (BMC) [g] and bone mineral density (BMD) [g/cm^2] were analysed. The content of muscle mass (MM) [% and kg] was calculated using the Kim formula [15].

In order to assess the health effects of the Paleo diet, on the first day of the study, on an empty stomach, and on the first day of the week after weeks 2, 4, 6 and 8, a qualified nurse took blood samples from the veins in the elbow pit to determine haematological and biochemical blood indicators, i.e. peripheral blood counts (haematocrit, haemoglobin concentration, erythrocyte count, platelets, white blood cell count – leukocytes, leukocyte differentiation: lymphocytes, monocytes, basophils, eosinophils, neutrophils), glucose, insulin, total cholesterol, high-density lipoprotein (HDL) cholesterol, low-density lipoprotein (LDL) cholesterol, triglycerides (TG), creatinine (Cr), urea (U), uric acid (UA), sodium (Na) and potassium (K), calcium (Ca), magnesium (Mg), liver enzymes: ALT (alanine aminotransferase), AST (aspartic aminotransferase), alkaline phosphatase and GGTP (gamma glutamyltransferase), cystatin C, total bilirubin, free fatty acids (FFA) and beta-hydroxybutyrate (b-HB) (Figure 1). On the

1st day of the tests and after the 2nd, 4th, 6th and 8th weeks, the competitors also left samples of early morning urine to assess their health and acidification levels. Total urine tests were performed, i.e., specific gravity, pH, leukocytes, nitrites, protein, glucose, ketones, urobilinogen, bilirubin, blood (erythrocytes/haemoglobin), colour, transparency as well as sodium, potassium, and creatinine levels.

After the blood was drawn, the participants consumed a standardized meal. For each participant of the experiment, a carbohydrate-protein supplement was prepared for consumption (a gainer made of hydrolysed beef protein without milk proteins). Moreover, each of the subjects consumed ad libitum highly mineralized mineral water. Then, the subjects started the exercise test to assess anaerobic capacity. Afterwards, they performed their first anaerobic test – Wingate's 20-second test for upper limbs. The load was 4.5% of the body mass for the upper limbs (the Monark 834e, Sweden) and 7.5% of the body mass for the lower limbs (the Monark 894e cycle ergometer, Sweden). The software used (MCE 4.2, JBA Staniak, Poland) allowed the following indicators to be registered: total work performed (Wt [kJ], Wt [$J \cdot kg^{-1}$]), mean anaerobic power (Pmean [W], Pmean [$W \cdot kg^{-1}$], maximum anaerobic power (MAP [W], MAP [$W \cdot kg^{-1}$]) and the time of reaching (t_r [s]) and maintaining (t_m [s]) maximum power. After the first anaerobic test, the players consumed a snack in form of a large apple (approx. 150 kcal) and hydrated themselves with highly mineralized water ad libitum. The competitors rested passively between the tests, and after 45 min the subjects began the Wingate test for lower limbs. On the second day, 1.5 hours before starting the aerobic test the subjects ate a meal planned in the food ration (catering) or its liquid substitute (gainer) and then they performed a laboratory exercise test with a gradually increasing load on a treadmill. To determine the maximum oxygen uptake (VO_2max), using the direct method and the maximum heart rate (HRmax), a laboratory test "until failure" was carried out with a gradually increasing load on a treadmill (h/p/Cosmos Saturn treadmill, Germany). The heart rate (HR) was monitored every 30 seconds during the entire exercise test using the Polar S-410 cardiac monitor (Polar-Electro, Finland). The exercise test was preceded by a 2-minute recording of the initial values of cardiovascular and respiratory indicators on the treadmill (in a standing position). The test started with a 6-minute run at the speed [v] of 7 km/h, the same for all test subjects. Then, running speed was increased by 1.2 $km \cdot h^{-1}$ every 2 min. The trial was performed until the athlete reported volitional exhaustion and refused to continue the test. Selected indicators of the respiratory and circulatory systems were analysed, including: maximum oxygen uptake (VO_2max [l/min and ml/min/kg]), maximum minute ventilation (VEmax [l/min]), maximum tidal volume (TVmax), respiratory exchange ratio (RER), respiratory equivalent carbon dioxide ($VE \cdot VCO_2^{-1}$), heart rate (HR [bpm]). The level of indicators was recorded by the Cortex Metalyzer 3B ergospirometer (Germany) and using the MetaSoft Studio computer program (Germany) (Figure 2).

Statistical analysis

The MS Excel 2010 spreadsheet and the PQStat statistical package, version 1.8.0.338, were used for the statistical analysis of the collected results and their interpretation. The basic characteristics of the examined variables were calculated, i.e.: median (Me), upper quartile (Q1), lower quartile (Q3), delta, arithmetic mean ($\overline{x}$), standard deviation (SD) and the minimum (min) and maximum (max). The distribution of data was different from normal, so the results of the analysed scales between the groups PD and CD were compared with the non-parametric Mann-Whitney U test in series 1, 2, 3, 4, 5 for components of body composition and haematological parameters in fasting blood and urine biochemistry or in 1, 3, 5 for indicators of aerobic and anaerobic capacity. Intra-group changes in particular series were compared with Friedman's test and post-hoc Dunn's test with Bonferroni's correction. The test probability at the level of $p < 0.05$ was assumed as significant and at the level of $p < 0.01$ was assumed as highly significant.

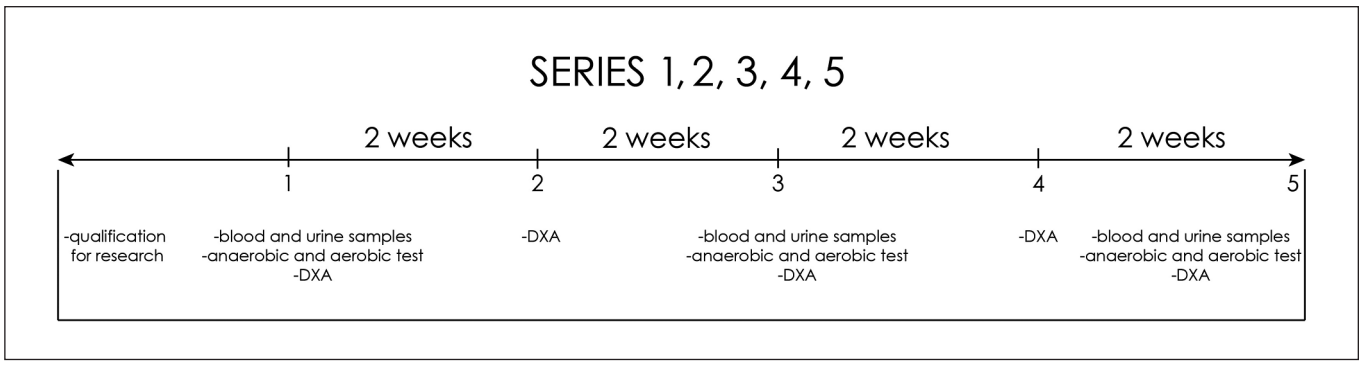


FIG. 1. Five measurement series.

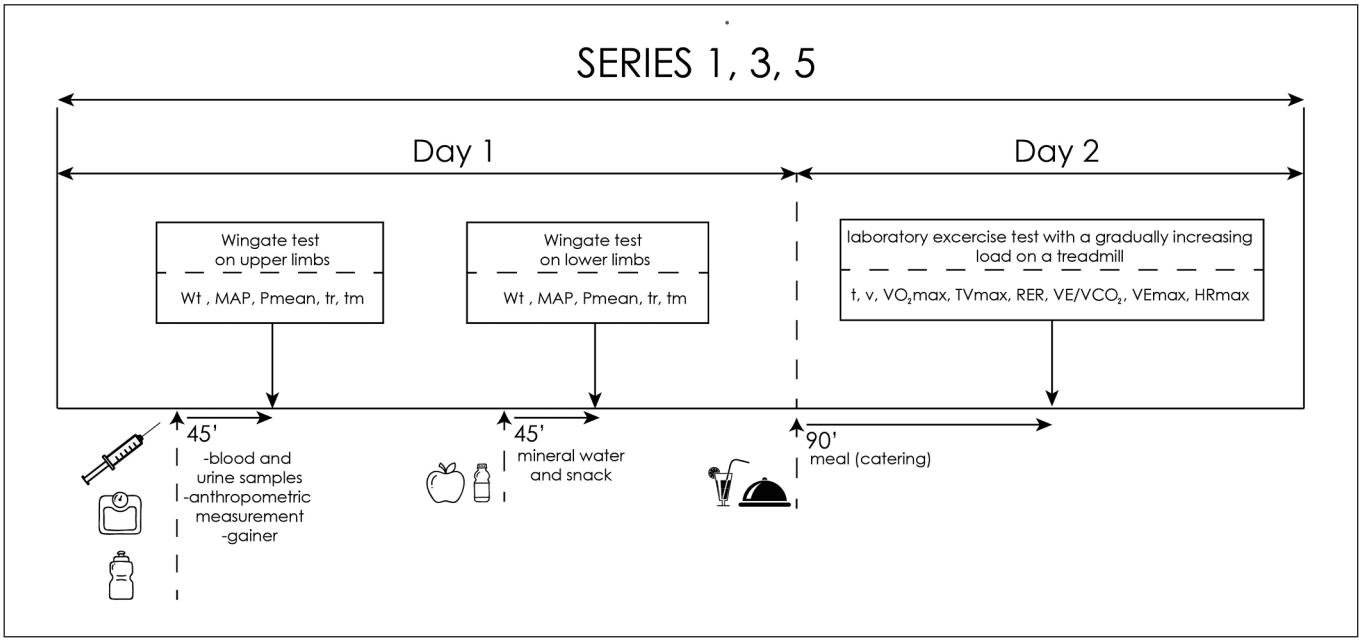


FIG. 2. Scheme of anaerobic and aerobic test days.
Abbreviations: Wt – total work performed; Pmean – mean anaerobic power; MAP – maximum anaerobic power; t_r – time of reaching maximum power; t_m – time of maintaining maximum powe; t-time; v- speed; VO_2max- maximum oxygen uptake; TVmax- maximum tidal volume; RER- respiratory exchange ratio; $VE{\cdot}VCO_2^{-1}$ - respiratory equivalent carbon dioxide; V_E max- maximum minute ventilation; HRmax- maximum heart rate

RESULTS

Analysis of changes in body mass and body composition (muscle mass, adipose fat mass, bone density, content of minerals and hydration level) during the experiment.

There were no significant differences between groups in particular series during the experiment, in all anthropometric parameters and body structure components. During the experiment, significant decreases in BM, BMI, and FM as well as an increase in the FFM (%, but not in kg) in both groups in the last series were observed (Table 1). At the end of the experiment, body mass significantly decreased ($p < 0.01$) in both groups compared to the initial value: in PD by 2.91 kg, and in the CD by 2.95 kg, with the largest decrease (4.45 kg) recorded after 6 weeks in the experimental group. In both groups at the end, significant decreases in BMI ($p < 0.01$) (-0.93 kg/m^2 in PD and -0.5 kg/m^2 in CD) were also observed. In the PD, between the beginning and the end of the experiment, there was a reduction in fat mass of 5% ($p < 0.001$), and in the CD of 1% ($p = 0.01$). Similar observations were made for the analysis of the fat mass in kg. In the PD, FFM increases by 3.6% ($p < 0.001$) were observed at the end of the experiment compared to the baseline value, and in the CD by 1.89% ($p = 0.02$). Analysis of changes in FFM in kg showed a slight non-statistically significant decrease, in both groups during the experiment (Table 1).

Analysis of changes in selected haematological and biochemical indicators of blood and urine during the experiment

There were no significant differences between groups in particular series during the experiment in all haematological and biochemical indicators of blood and urine (Table 1). Only HDL-C was significantly higher ($p = 0.039$) in the last series in the PD compared to the CD (1.63 mmol/l vs. 1.23 mmol/l). All the values were within the reference range during the experiment. Intergroup differences were related to lower amounts of monocytes and leukocytes in the middle of the experiment in the group of athletes on a PD, with the differences levelling off at the end of the experiment, and they were similar or the same as at the beginning of the experiment. No significant intergroup differences in lipid profile, carbohydrates and fat metabolism, kidney and liver parameters, or electrolytes were observed between series 1–5 except for sodium and calcium in the PD, which increased significantly ($p < 0.05$) at the end of the experiment (Table 1). All urinary indicators stayed at reference values during the interventions. Urinary ketones were absent or traced in both groups, and the differences were not significant, either between groups or within groups during the experiment.

Analysis of the level of anaerobic and aerobic performance of handball players during the experiment

There were no significant differences between groups in particular series during the interventions in all the values of anaerobic capacity (Table 2). In the Wingate test on upper limbs, there were only

TABLE 1. Anthropometric parameters, body structure components, haematological and biochemical blood values. Data are reported as median, quartiles and point of change (absolute changes).

	PD (n = 9)						CD (n = 6)					
	1 Me (Q1; Q3)	1–2	1–3	1–4	1–5	F	1 Me (Q1; Q3)	1–2	1–3	1–4	1–5	F
Anthropometric parameters												
BM [kg]	91.36 (87.50;99.50)	-1.76	-0.19*	-4.45**	*-2.91***	**	88.40 (84.70;100.65)	-0.8	-0.85	-2.3	*-2.95***	**
BMI [kg/m^2]	26.07 (25.75; 27.01)	-0.82	-0.85*	-0.64**	*-0.93***	**	25.99 (25.90; 27.90)	-0.28	-0.31	-0.49	*-0.5***	**
FM [%]	22.60 (19.00; 23.30)	-1.6	-3.0**	-3.20**	*-5.0***	**	19.15 (18.45; 24.28)	-1.5	-2.1	-2.25**	*-1.0**	**
FM [kg]	18.90 (16.15; 21.55)	-1.67	-2.03	-2.73**	*-3.45***	**	16.17 (13.89; 23.41)	-1.41	-1.9	-2.3**	*-2.11***	**
FFM [%]	78.39 (73.95; 81.85)	+1.18	+2.61*	+3.03**	*+3.6***	**	81.68 (76.77; 82.38)	+1.48	+2.08	+2.17**	*+1.89**	**
FFM [kg]	72. 93 (67.49; 75.74)	-0.04	-1.77	-1.79	-1.16	NS	72.47 (70.84; 77.33)	+0.69	+0.86	+0.74	+0.72	NS
MM [%]	42.03 (39.00; 42.87)	-0.69	-1.06*	-0.44*	+0.6	*	43.17 (42.00; 43.57)	-2.14	-1.67	-0.65	-1.05	NS
MM [kg]	38.20 (35.11; 41.13)	-1.71	-1.73*	-1.43*	-0.75	*	38.18 (36.72; 42.41)	-1.04	-1.5	-1.18	-1.0	*
BMC [g]	3877.00 (3548; 4207)	-54	-48	-60	-52	*	3972 (3741; 4229)	+27	+1	+11	-2	NS
BMD [g/cm^2]	1.42 (1.39; 1.58)	-0.02	-0.03	+0.02	+0.01	**	1.55 (1.44; 1.63)	-0.07	-0.07	-0.08	-0.05	NS
Blood counts												
HGB [g/dl]	15.50 (14.80; 16.00)	-0.5	-0.4	0	-0.4	NS	15.50 (14.88; 15.68)	-0.2	+0.1	+01	0	NS
HCT [%]	45.80 (43.2; 47.60)	-1.3	-1.0	-0.7	-1.0	NS	45.60 (43.73; 46.35)	-1.0	+0.1	-0.55	-0.95	NS
Erythrocytes [mln/μl]	5.44 (5.20; 5.53)	-0.13	-0.11	-0.15	-0.29	NS	5.22 (5.07; 5.39)	+0.02	+0.05	+0.14	-0.16	NS
MCHC [g/dl]	34.30 (33.50; 34.30)	0	-0.40	+0.2	+0.1	NS	34.00 (33.93; 34.15)	-0.05	+0.25	+0.20	+0.60	NS
MCH [p/g]	29.16 (28.60; 29.80)	+0.14	+0.14	+0.14	-0.06	NS	29.35 (28.68; 30.40)	+0.40	+0.45	+0.25	+0.30	NS
MCV [fl]	84.34 (84.10; 87.50)	+0.16	-0.24	+0.16	+0.16	NS	86.95 (83.50; 89.95)	+0.01	+0.25	-0.75	-1.40	*
RDW-CW [%]	12.60 (12.20; 12.90)	-0.1	-0.1	-0.2**	-0.2	*	12.70 (12.25; 13.15)	+0.05	+0.2	-0.1	-0.3	NS
Leukocytes [tys/μl]	6.79 (6.44; 7.78)	-1.5	-1.46#	-1.09	-0.58	**	8.14 (6.03; 8.67)	-1.34	-1.51#	-1.83	-1.78	NS
Monocytes [tys/μl]	0.60 (0.50; 0.60)	-0.10	-0.10#	-0.10#	0	**	0.65 (0.53; 0.93)	0	+0.05#	-0.05#	-0.05	NS
Lymphocytes [tys/μl]	2.80 (2.40; 3.43)	-0.4	-0.5**	-0.1	-0.5	**	2.70 (2.25; 3.15)	-0.5	-0.3	-0.45	-0.6	NS
Neutrophils [tys/μl]	3.60 (3.20; 4.00)	-0.9	-1.1**	-0.8	-0.8	**	3.95 (3.08; 4.30)	-0.35	-0.5	-0.9	-1.25	NS
Basophils [tys/μl]	0.03 (0.03; 0.05)	0	+0.02	-0.01	-0.01	NS	0.065 (0.04; 0.08)	0	-0.005	-0.005	-0.005	NS
Eosinophils [tys/μl]	0.11 (0.15; 0.33)	+0.03	+0.08	+0.07	+0.07	NS	0.17 (0.13; 0.29)	-0.03	-0.05	-0.01	+0.05	NS
Platelets [tys/μl]	264 (249.00; 277.10)	-2	-18	-30	0	*	259.5 (252.5; 321.25)	+24	+1	+6.5	+5.5	NS
PDW [fl]	13.50 (12.58; 15.50)	+1.3	+0.9	+1.5	+0.2	*	14.55 (13.40; 15.33)	+0.85	+1.6	+1.05	+1.4	NS
P-LCR [%]	36.00 (32.19; 41.70)	+1.7	+3.0	+4.0	-0.30	*	37.60 (34.53; 40.75)	+4.95	+4.35	+3.6	+2.70	*
MPV [fl]	11.20 (10.78; 12.10)	+0.4	+0.4	+0.6	+0.1	*	11.45 (11.10; 11.80)	+0.55	+0.55*	+0.50	+0.35	*
PCT [%]	0.3 (0.3; 0.3)	0	0	0	0	NS	0.3 (0.3; 0.375)	0	0	0	0	NS

TABLE 1. Continue

	PD (n = 9)						CD (n = 6)					
	1 Me (Q1; Q3)	1–2	1–3	1–4	1–5	F	1 Me (Q1; Q3)	1–2	1–3	1–4	1–5	F
Lipid profile												
TC [mmol/l]	3.84 (3.77; 4.31)	+0.03	+0.53	+0.33	+0.27	NS	4.65 (4.22; 4.77)	-0.41*	-0.10	-0.27	-0.19	*
HDL-C [mmol/l]	1.39 (1.31; 1.91)	+0.15	0	+0.03	+0.24#	NS	1.29 (1.08; 1.64)	-0.10	-0.11	-0.09	-0.06#	NS
LDL-C [mmol/l]	2.18 (2.05; 2.52)	-0.25	+0.27	-0.06	+0.05	NS	2.14 (1.81; 2.54)	-0.07	+0.30	+0.28	+0.36	NS
TG [mmol/dl]	1.02 (0.78; 1.38)	-0.31*	-0.29	-0.37	-0.11	*	1.36 (1.16; 1.96)	-0.48	+0.5	-0.11	-0.35	NS
Carbohydrates and fat metabolism												
Glucose [mmol/l]	5.29 (4.86; 5.44)	-0.6*	-0.45	-0.69**	-0.13	**	5.10 (5.04; 5.19)	-0.29	-0.31	-0.15	-0.09	NS
Insulin [μIU/ml]	7.20 (6.69; 8.20)	-1.3	-1.5	-1.65	-0.24	NS	6.63 (5.70; 7.51)	-0.48	+0.86	+0.87	-0.58	NS
FFA [mmol/l]	0.56 (0.24; 0.68)	-0.07	-0.24	-0.18	-0.27	NS	0.24 (0.14; 0.39)	+0.32	+0.21	+0.04	+0.05	NS
b-HB [mmol/l]	0.05 (0.03; 0.06)	+0.14	+0.05	+0.09	+0.03	NS	0.04 (0.03; 0.04)	+0.12	+0.10	-0.02	+0.03	NS
Electrolytes												
Sodium [mmol/l]	142.00 (141.00;95.00)	-1	0	-2	*+13**	*	141.5 (139.50;142)	-2.5	-0.5	-1	0	NS
Calcium [mmol/l]	2.36 (2.29; 2.45)	+0.09	+0.13**	+0.11*	*+0.14**	**	2.42 (2.39; 2.47)	+0.06	+0.10	+0.02	-0.01	NS
Magnesium [mmol/l]	0.83 (0.81; 0.84)	+0.06	+0.03	+0.05	+0.02	NS	0.83 (0.81; 0.85)	+0.11*	+0.06	+0.03	0	**
Potassium [mmol/l]	4.51 (4.34; 4.79)	0	-0.01	+0.11	-0.14	NS	4.58 (4.36; 4.92)	-0.03	+0.02	+0.09	+0.14	NS
Kidney parameters												
Creatinine [μmol/l]	93.00 (81.00; 95.00)	+13	+12	+10*	+1	*	94.00 (93.25; 94.00)	+6.5	+7	+1.5	*+9.5**	**
eGFR [ml/min/1.73m^2]	88.13 (83.79; 91.00)	-12.32	-11.71	-9.94	-1.09	*	85.93 (84.09; 86.19)	-6.9	-8.36	-3.53	-9.63	*
Urea [mmol/l]	5.00 (4.60; 8.49)	+2.2	+1.6	+1.9	+1.9	NS	5.70 (5.53; 6.10)	-0.35	+0.4	+0.55	+1.7	NS
Uric acid [μmol/l]	320 (310.00; 368.00)	+51	+18	+42	+19	NS	303(274.25; 314.50)	+71*	+44	+36	+34	NS
Cystatin C [mg/dl]	0.86 (0.76; 0.86)	-0.08	-0.08	-0.02	+0.07	*	0.79 (0.70; 0.89)	+0.04	+0.07	+0.03	+0.10	**
Urine pH	6.5 (5; 7)	-1.5	-1.5	-1.5	-1.5	NS	5.5 (5; 6.75)	0	-0.5	+0.25	-0.5	NS
Liver parameters												
ALT [U/l]	21.00 (18.00; 32.00)	+5	+4.7	+1	+1	NS	25.50 (19.25; 34.75)	-1.6	-3.7	-4.2	-4.9	NS
AST [U/l]	23.00 (19.00; 28.00)	+1	+1	-2.2	-1.2	NS	26.50 (25.25; 27.75)	+1.52	-1.82	-4.12	-3.07	NS
Alkaline Phosphatase [U/l]	88.00 (63.00; 106.00)	-9	-12	-8	+3	*	77.50 (67.50; 90.50)	+4.5	+4	-1.5	0	NS
GGTP [mmol/l]	17.00 (11.00; 20.00)	-2	-4	-4*	-4	*	16.00 (11.75; 20.25)	-2	-3	-3	-2.5	NS
Total bilirubin [μmol/l]	7.70 (6.10; 8.50)	+1.5	+2.2	+2.8	0	NS	7.40 (5.78; 12.25)	+2.75	+3.2	+1.55	+1.55	NS

Abbreviations: PD – Paleo diet; CD – control diet; Me – median; Q1 – upper quartile; Q3 – lower quartile; 1–2; 1–3; 1–4; 1–5 – differences between particular series; F – Friedman's Test; BM – body mass; BMI – body mass index; FM – fat mass; FFM – fat free mass; MM – muscle mass; BMC – body mineral content; BMD – body mass density; HGB – haemoglobin; HCT – hematocrit; MCHC – mean corpuscular hemoglobin concentration; MCH – mean corpuscular haemoglobin; MCV – mean corpuscular volume; RDW-CV – red blood cell distribution with coefficient of variation; PDW – platelet distribution width; P-LCR – platelet-large cell ratio; MPV – mean platelet volume; PCT – procalcitonin; TC – total cholesterol; HDL-C – high-density lipoprotein cholesterol; LDL-C – low-density lipoprotein cholesterol; TG – triglycerides; FFA – free fatty acids; b-HB – beta-hydroxybutyrate; e-GFR – estimated glomerular filtration rate; ALT – alanine aminotransferase; AST – aspartate aminotransferase; GGTP – gamma-glutamyl transferase; italics – changes between 1–5 series; * – test probability at the level of $p < 0.05$ intragroup; ** – $p < 0.01$; # – test probability at the level of $p < 0.05$ intergroup; ## – $p < 0.01$ in U-Mann test.

TABLE 2. Anaerobic and aerobic capacity. Data are reported as median, quartiles and point of change (absolute changes).

	PD (n = 9)				CD (n = 6)			
	1 Me (Q1; Q3)	**1–3**	**1–5**	**F**	**1 Me (Q1; Q3)**	**1–3**	**1–5**	**F**
Wingate test on upper limbs								
Wt [kJ]	10.31 (10.13; 11.20)	+0.26	*-0.42**	*	10.27 (9.61; 11.00)	+0.27	-0.21	NS
Wt [$J \cdot kg^{-1}$]	112.00 (107.00;117.00)	-4	+4	NS	110.00 (104.50; 117.75)	+5	+7.5	NS
MAP [W]	597.93 (586.00; 660)	+7.07	*-33.93***	*	597.50 (560.00; 664.25)	+11.5	-15.5	NS
MAP [$W \cdot kg^{-1}$]	6.45 (5.96; 6.99)	-0.17	+0.06	NS	6.41 (6.23; 6.75)	+0.43	+0.44	NS
Pmean [W]	515.71 (506.00; 560.00)	+12.29	*-20.71**	**	513.00 (480; 550)	+14	-10.5	NS
Pmean [$W \cdot kg^{-1}$]	5.60 (5.30; 5.90)	-0.20	+0.20	NS	5.50 (5.23; 5.85)	+0.25	+0.35	NS
t_r [s]	5.14 (5.10; 5.23)	+0.18	+0.4	NS	4.71 (4.30; 5.40)	+0.03	+0.32	NS
t_{mz} [s]	3.70 (3.16; 3.75)	+0.32	-0.07	NS	2.52 (2.34; 2.62)	+0.87	+0.96	NS
Wingate test on lower limbs								
Wt [kJ]	17.65 (17.27; 19.71)	-1.02	*-1.8***	**	17.40 (16.45; 17.83)	-0.05	-2.53	NS
Wt [$J \cdot kg^{-1}$]	191.21 (181.00; 196.00)	+2.79	*-12.21***	**	186.00 (182.25; 191.25)	+5.36	-5.36	NS
MAP [W]	1063.00 (1028.00; 1164.15)	-5	*-117***	**	1092.50 (954.75; 1141)	-29	*-87.5**	*
MAP [$W \cdot kg^{-1}$]	11.47 (10.62; 11.65)	0	-0.56	*	11.50 (10.58; 12.68)	-0.18	-0.55	NS
Pmean [W]	882.00 (864.00; 985;00)	-50	*-90***	**	870.00 (822.51; 892.00)	-2.5	-38.5	NS
Pmean [$W \cdot kg^{-1}$]	9.55 (9.10; 9.80)	+0.15	-0.65	*	9.30 (9.08; 9.60)	+0.27	-0.11	NS
t_r [s]	4.08 (3.86; 4.23)	+0.02	+0.25	NS	3.63 (3.25; 4.44)	-0.09	-0.10	NS
t_m [s]	3.03 (2.65; 3.73)	-0.13	-0.28	NS	2.52 (2.34; 2.62)	+0.22	+0.3	NS
Aerobic capacity test								
VO_2max [l/min]	4.40 (3.85; 4.64)	-0.10	-0.11	NS	4.26 (4.09; 4.43)	-0.18	-0.05	NS
VO_2max [ml/kg/min]	46.00 (42.33; 49.00)	+1	0	NS	48.00 (43.25; 49.00)	+0.93	+0.68	NS
VEmax [l/min]	147.60 (143.60; 166.70)	+5.5	-0.7	NS	153.55 (146.28; 162.78)	+3.1	-0.65	NS
TVmax [l]	2.85 (2.65; 3.38)	0	*-0.08**	*	2.69 (2.61; 2.90)	+0.11	+0.09	NS
RER	1.10 (1.08; 1.13)	0	+0.02	NS	1.14 (1.12; 1.17)	+0.03	+0.01	NS
$VE \cdot VCO_2^{-1}$	29.80 (28.60; 32.80)	-0.70	-0.80	NS	29.70 (29.23; 30.70)	+0.45	-0.79	NS
HRmax [bpm]	187 (184; 195)	0	*-3***	**	187 (176; 197)	-1	*-4**	*
t [min]	16.50 (15.00:18.50)	+0.5	0	NS	17.75 (15.88;18.88)	+1.25	+0.5	NS
v [km/h]	14.86 (14.10; 15.50)	+0.54	+0.54	*	16.05 (14.53; 16.60)	+0.7	+0.6	NS

Abbreviations: PD – Paleo diet; CD – control diet; Me – median; Q1 – upper quartile; Q3 – lower quartile; 1–3; 1–5 – differences between particular series; Wt– total work performed; MAP – maximum anaerobic power; Pmean – mean anaerobic power; t_r– time of reaching maximum power; t_m – time of maintaining maximum power; VO_2max – maximum oxygen uptake; VE_{max} – maximum minute ventilation; TVmax – maximum tidal volume; RER – respiratory exchange ratio; $VE \cdot VCO_2^{-1}$ – respiratory equivalent carbon dioxide; HRmax – maximum heart rate; t-time; v – speed; F – Friedman's Test; italics – changes between 1–5 series; * – test probability at the level of $p < 0.05$ intragroup; ** – $p < 0.01$.

single intragroup changes, consisting of a significant decrease in the Wt (kJ), MAP (W) and Pmean (W) in the experimental group. A significant decrease ($p = 0.014$) in the total amount of work performed between the beginning and the end of the intervention (10.31 kJ vs. 9.89 kJ) was observed. Also, in MAP and Pmean significantly lower values were found between the initial and final series: 597.93 W vs. 564.00 W and 515.71 W vs. 495.00 W, respectively (Table 2). In the Wingate test on lower limbs in the PD, post-hoc analysis showed a significant decrease ($p = 0.001$) between the beginning and the end of the intervention in the Wt (17.65 kJ vs. 15.85 kJ). Similarly, the total work performed per kilogram of BM differed significantly ($p = 0.004$) in the PD. During the experiment significantly lower MAP values between the baseline and end series in the PD ($p = 0.003$) (1063.00 W vs. 946.00 W) and in the CD ($p = 0.028$) (1092.00 W vs. 1005.00 W) were observed. A significant decrease ($p = 0.018$) in MAP per kg BM was observed between the mid point and the end of the experiment (11.47 $W \cdot kg^{-1}$ vs. 10.91 $W \cdot kg^{-1}$) only in the PD. During the intervention, significant differences ($p = 0.008$) in Pmean with a downward trend ($p = 0.002$) were observed only in the PD. These changes consisted in significantly lower ($p = 0.007$) mean anaerobic power, especially between the beginning and end of the experiment (882.00 W vs. 792.00 W) (Table 2). There were no significant differences between the groups in individual series or intragroup differences during the experiment, determined by the VO_2max (minute and relative to BM), VEmax, $VE \cdot VCO_2^{-1}$, RER, and the time of the test with a gradually increasing load on a treadmill, except for a significant decrease ($p = 0.018$) of TVmax, between the beginning and the end of the intervention ($p = 0.014$) (2.85 l vs. 2.73 l). HRmax significantly decreased between the initial and final series in the PD ($p = 0.001$) (187 bpm vs. 184 bpm) and CD ($p = 0.014$) (187 bpm vs. 183 bpm) group (Table 2). Tables with the results showing arithmetic means and standard deviation are included in the paper's appendix.

DISCUSSION

There is no research assessing the impact of the Paleo diet on body composition in a group of professional athletes. In our research the eight-week application of the Paleo and control diet had a positive effect on body composition through a decrease in BM, BMI, FM (% and kg) and an increase in FFM% (but not in kg). The beneficial impact of PD on body structure (BM, waist circumference, weight/height ratio and % of FM) applies to various groups: healthy people with a sedentary lifestyle [9], inactive people with planned physical activity (aerobic and resistance training) [4–6] or patients with: ischemic heart disease [2], lipid profile disorders [3], overweight and obesity [4, 5], diabetes [5, 6], or metabolic syndrome [7]. The applied Paleo diets were characterized by consumption ad libitum, while with the normoenergetic nature of PD, the changes showed mainly no body mass reduction effect [8] but were often related to the improvement of some metabolic indicators [7, 8]. There are only a few studies in which the normoenergetic model of the Paleo diet was used [7, 8]. It is not unequivocally determined whether applying the energy deficit or the distribution of macronutrients is the cause of the changes in body weight. In the study by Michalczyk et al. [11], FM of basketball players did not depend on the amount of fat, but the amount and quality of carbohydrates consumed in the Carbo-L (a 7-day carbohydrate loading protocol) or low-carbohydrate diet and the increase in FM occurred only as a result of loading with carbohydrates. Conversely, a meta-analysis of 94 studies on low-carbohydrate diets found that weight loss following a low-carbohydrate diet was associated with a reduction in energy consumption and dietary duration, but not with a reduction in dietary carbohydrates [16]. Similarly, we observed a significant reduction in BM and FM in both the experimental and control groups, although in the first weeks the reduction effect was more visible in the PD group. Moreover, maintaining FFM during fat reduction was observed in athletes and inactive people using a lower carbohydrate (LCD) and ketogenic diet (VLCD-KD) [17–18]. In contrast, McSwiney et al. [18] found that after a short-term ketogenic diet in endurance-trained males there was a decrease in both FM and FFM. It seems that the PD (as well as the KD and LCD), when it provides an adequate supply of calories and is accompanied by properly selected training, should result in the maintenance of FFM, especially in a short time of use.

An important factor in the discussion on the necessity of following alternative diets is their impact on health. Scientists dealing with alternative strategies mention a number of possible positive consequences of adopting various nutritional strategies, e.g., the ketogenic diet, training with high or low availability of carbohydrates [19, 20]. It is recommended to implement dietary strategies to increase antioxidant potential of the diet (e.g. fresh fruits, vegetables, sprouts as well as seeds) [21]. In addition, reduction in consumption of refined foods, including carbohydrates, may be critical in preventing or treating metabolic-related cognitive deficits [22]. We found that the eight-week use of the PD does not cause significant, unfavourable changes in health. We observed no effect on lipid profile, except for higher HDL cholesterol concentration after eight weeks of using the Paleo diet. This trend is in line with analyses of the use of the Paleo diet in inactive people. In a meta-analysis Ghaedi et al. [23] found that PD reduces the concentration of total cholesterol (TC), LDL cholesterol and triglycerides (TG) and increases the concentration of HDL cholesterol. Similar results were obtained by Manheimer et al. [24], observing favourable changes in HDL concentration. According to Noakes et al. [25], changes in the blood lipid profile depend on the dietary fat content. A positive effect on the lipid profile in the group of athletes on the LCD and KD was also observed and according to the authors it may have been caused by the predominance of polyunsaturated fatty acids [11, 26]. Moreover, the Paleo diet provided significantly more pro-inflammatory saturated fatty acids (SFAs) and cholesterol. Unfavourable changes in lipid profile that result from applying the high fat diets are more pronounced after diets high in SFAs. Higher consumption of SFA and cholesterol could cause hypercholesterolaemia in 20 ultra-endurance athletes [27] and low-carbohydrate diets

promote atherosclerotic changes in athletes [28]. The Paleo diet is not a risk that stimulates the development of cardiovascular diseases resulting from disturbances in the lipid profile [23]. Therefore, it can be concluded that with a high supply of polyunsaturated fatty acids (PUFAs) even a high content of SFAs and cholesterol in the diet did not have a negative effect on the lipid profile. In our research, no changes in all assessed indicators of metabolism of carbohydrates and fat were found, which remained within the reference values throughout the entire experiment in the PD and CD, as also occurred in the group of basketball players on an LCD [11]. A meta-analysis by Jamka et al. [29] showed that the Paleo diet may improve glucose tolerance, reduce insulin secretion, and increase insulin sensitivity in people with impaired glucose metabolism, as well as other healthy diets (the Mediterranean diet, diabetes diet, and a diet recommended by the Dutch Health Council). Other studies with limited carbohydrate intake showed a decrease in blood insulin concentration at rest or during exercise [30, 31] or no effect [26, 32–34]. Scientific studies show that lipolysis and fat oxidation increased as insulin levels decreased [25]. Elevated ketone levels are necessary to induce decreased insulin production and thus increase fat utilization [35]. Perhaps that is why in our research no decrease in blood insulin was observed. In numerous studies using the KD, the level of ketosis considered desirable was also not observed [36]. In turn, the studies by Zając et al. [26] showed that the KD in cyclists caused a fourfold increase in the concentration of b-HB before exercise and a twofold increase in resting FFA concentration in plasma. Our analysis did not show that use of the PD increased the oxidation of fatty acids, and the level of ketones in the urine was minimal or undetectable in the course of the experiment.

There was no effect of the 8-week PD on blood counts, electrolytes and kidney and liver function indicators, which remained within the reference intervals throughout the intervention. In the research by Urbain et al. [30], no effect of the 6-week ketogenic diet on the level of total bilirubin, AST, or creatine was found, but a significant decrease in alkaline phosphatase, and increases in ALT, concentration of urea and uric acid were observed at the end of the experiment in the group of 42 healthy adults. Uric acid concentration may serve as one biomarker of keto-adaptation in the kidneys [37]. Researchers have found that serum uric acid remains above baseline levels even after 12 weeks on the KD [38]. In our research, no changes in uric acid concentration in the PD were found. On the other hand, long-term use of an acidic diet in combination with exercise leads to an initial impairment of renal function [39]. In the analysis of the effect of the 6-week ketogenic diet on healthy adults, no changes in creatinine levels were found.

Numerous studies have been conducted investigating the potential ergogenic effects of low-carbohydrate diets. The LCD accelerate the feeling of fatigue and reduce concentration by reducing the effectiveness of training [28]. On the other hand, many studies have shown that LCD (most often with higher protein content, above 30%) through weight loss, and in some cases resulting in an increase in FFM, especially in weight-category sports, may contribute to the improvement of exercise capacity [17, 18, 34, 40]. Especially in short-term resistance efforts, it is recommended to eat more carbohydrates, which is based on evidence supporting the importance of glycogen as both an energy "fuel" and a regulator of skeletal muscle adaptive responses during exercise [41]. On the other hand, there is insufficient evidence that carbohydrates are required for mammalian target of rapamycin complex-1 (mTORC-1) signalling during muscle protein synthesis [42], especially when dietary protein intake is adequate [43]. Thus, adaptive changes resulting from the use of LCD may, on the one hand, improve the aerobic capacity, but on the other hand may reduce the possibility of using exogenous carbohydrates, which in turn may contribute to the lack of improvement in efficiency, and may even worsen the exercise capacity, during more intense physical efforts [19, 44]. An undoubted advantage of the Paleo diet is the sufficient carbohydrate content (in the context of glycogen availability), but the disadvantage may be the lack of ketosis occurring in the KD – enabling the use of fatty acids in energy processes. However, as previously demonstrated in some sports, for instance team sports, it is not necessary to consume high carbohydrates in the daily diet due to the lower training volume and the shorter duration of the competition [11]. In this case, the Paleo diet may be the correct choice. It has been reported that supervised exercise in combination with the Paleo diet (PDEX) influenced the maintenance of LBM in men and increased cardiovascular capacity in patients with diabetes [4]. Higher VO_2max values have also been observed in healthy, inactive, non-overweight people after PD. However, these changes would be the result of training rather than diet [9]. In the research of Popp et al. [45], which compared the PD in combination with physical activity to a "MyPlate" diet that included both aerobic training and resistance training, a greater improvement in exercise capacity was observed with a rational diet ("MyPlate"). Kang et al. [36] identified a few independent studies in which no effect of a KD on VO_2max was demonstrated [32–34, 46, 47], while in two research papers, the authors reported a decrease in VO_2max in l/min [30, 48], and an increase in VO_2max [26]. A significant increase in VO_2max was observed in a group of cyclists using KD compared to a mixed diet [26]. The authors explain the improvement in VO_2max (ml/kg/min) accompanying the use of the KD as a consequence of a decrease in BM and FM [26]. Our research did not show an effect of the use of the PD on the maximum oxygen uptake or other indicators of aerobic capacity, either in absolute or relative values, despite the BM reduction. So, it was found in our research that the normoenergetic PD model can be successfully used by athletes without adversely affecting aerobic capacity. Analysing the indicators of anaerobic capacity, we observed a decrease in total amount of work performed in the PD, the maximum and mean power in absolute values in both the Wingate test and in relative Wt [$J \cdot kg^{-1}$] only in the Wingate test on lower limbs. However, the time to achieve and maintain MAP in the PD did not decrease significantly. Kang et al. [36] reported seven studies assessing the effect of the KD on anaerobic capacity. In a few,

there was no effect on muscle strength and power [17, 49, 50]. In studies by Rhyu and Cho [40] in both diet groups, KD and NKD (non-ketogenic diet), with a distribution of macronutrients similar to the PD, the diet resulted in a decrease in MAP and Pmean of taekwondo athletes. Research suggests that low-carbohydrate, high-fat or ketogenic diets may be useful in weight loss, most often without compromising strength or power [36]. It cannot be clearly stated that the Paleo diet adversely affects anaerobic capacity in athletes. A longer follow-up and larger sample size are recommended in future clinical trials of the Paleo diet used on athletes.

LIMITATIONS

The factor limiting the research was the size of the research group. The high cost of catering to meet individual energy needs, representing a high level of sports and the specific products of the Paleo diet (meat, fish, seafood, eggs, nuts, fruit, and vegetables) made it impossible to include more athletes in the experiment (22 people were planned and 15 athletes completed the study). Preparing meals with the assumption of maintaining balanced energy especially with high energy demand and the specific composition of the Paleo diet eliminated the possibility of methodological errors. The presented results of the pilot studies are the nucleus of the planned research process on a larger scale.

CONCLUSIONS

1. Eight-week intervention of the Paleo diet resulted in a decrease in body mass, body mass index and the amount of fat mass, which should be considered a beneficial effect of the diet in the context of the body structure of handball players.
2. There was no adverse effect of the Paleo diet on the health status of research participants, assessed with the following indicators: peripheral blood count, lipid profile, carbohydrate and fat metabolism, concentration of selected electrolytes, kidney and liver function and urine assessment. The use of the Paleo diet significantly increased the concentration of HDL cholesterol in the group following the Paleo diet compared to the rational diet, even with a significantly higher content of SFA and cholesterol in the Paleo diet (3 and 2 times higher than the norm, respectively).
3. Eight-week use of the Paleo diet slightly adversely affects anaerobic capacity, reducing some of the assessment indicators, i.e., total work performed, mean and maximum anaerobic power, and does not affect the level of aerobic capacity of handball players.
4. The Paleo diet can be used by representatives of disciplines that do not require high availability of carbohydrates (e.g., team sports) and players planning to obtain optimal body composition in a short period of time.

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Conflict of interest statement

The authors declare no conflict of interest.

REFERENCES

1. Konner M, Eaton SB. Paleolithic nutrition: Twenty-five years later. Nutr. Clin. Pract. 2010; 25:594–602.
2. Lindeberg S, Jonsson T, Granfeldt Y, Borgstrand E, Soffman J, Sjostrom K, Ahren BA. Palaeolithic diet improves glucose tolerance more than a Mediterranean-like diet in individuals with ischemic heart disease. Diabetologia 2007; 50:1795–1807.
3. Pastore RL, Brooks JT, Carbone JW. Paleolithic nutrition improves plasma lipid concentrations of hypercholesterolemic adults to a greater extent than traditional heart-healthy dietary recommendations. Nutr. Res. 2015; 35:474–479.
4. Otten J, Stomby A, Waling M, Isaksson A, Tellström A, Lundin-Olsson L, Brage S, Ryberg, M, Svensson M, Olsson T. Benefits of a Paleolithic diet with and without supervised exercise on fat mass, insulin sensitivity, and glycemic control: A randomized controlled trial in individuals with type 2 diabetes. Diabetes Metab. Res. Rev. 2017; 33:e2828.
5. Otten J, Stomby A, Waling M, Isaksson A, Söderström I, Ryberg M, Svensson M, Hauksson J, Olsson T. A heterogeneous response of liver and skeletal muscle fatt the combination of a Paleolithic diet and exercise in obese individuals with type 2 diabetes: A randomized controlled trial. Diabetes 2018; 61:1548–1559.
6. Stomby A, Otten J, Ryberg M, Nyberg L, Olsson T, Boraxbekk CJ. A Paleolithic Diet with and without Combined Aerobic and Resistance Exercise Increases Functional Brain Responses and Hippocampal Volume in Subjects with Type 2 Diabetes. Front. Aging Neurosci. 2017; 9:391.
7. Boers I, Muskiet FA, Berkelaar E, Schut E, Penders R, Hoenderdos K, Wichers HJ, Jong MC. Favourable effects of consuming a Palaeolithic-type diet on characteristics of the metabolic syndrome: Arandomized controlled pilot-study. Lipids Health Dis. 2014; 13:160.
8. Frassetto LA, Schloetter M, Mietus-Snyder M, Morris RC, Sebastian A. Metabolic and physiologic improvements from consuming a Paleolithic, hunter-gatherer type diet. Eur. J. Clin. Nutr. 2009; 63:947–955.
9. Smith MM, Trexler ET, Sommer AJ, Starkoff BE, Devor ST. Unrestricted Paleolithic diet is associated with unfavorable changes to blood lipids in healthy subjects. Int. J. Exerc. Sci. 2014; 7:128–139.
10. Frączek B, Pięta A, Burda A, Mazur-Kurach, P, Tyrała F. Paleolithic Diet—Effect on the Health Status and Performance of Athletes? Nutrients 2021; 13:1019.
11. Michalczyk M, Zajac A, Mikolajec K, Zydek G, Langfort J. No Modification in Blood Lipoprotein Concentration but Changes in Body Composition After 4 Weeks of Low Carbohydrate Diet (LCD) Followed by 7 Days of Carbohydrate Loading in Basketball Players. J. Hum. Kinet. 2018; 65:125–137.
12. Frączek B, Grzelak A, Klimek A. Analysis of Daily Energy Expenditure of Elite Athletes in Relation to Their Sport, the Measurement Method and Energy

Requirement Norms. Journal of Human Kinetics. 2019; 70:81–92.
13. Dietary Reference Values for nutrients. Summary report. European Food Safety Authority (EFSA). 2017:15121,92.
14. Kerksick ChM, Wilborn CD, Roberts MD, Smith-Ryan A, Kleiner SM, Jäger R, Collins R, Cooke M, Davis JN, Galvan E, Greenwood M, Lowery LM, Wildman R, Antonio J, Kreider RB. ISSN exercise & sports nutrition review update: research & recommendations. J Int Soc Sports Nutr. 2018; 15(1):38.
15. Kim J, Wang Z, Heymsfield S, Baumgartner R, Gallagher D. Total-body skeletal muscle mass: estimation by a new dual-energy X-ray absorptiometry method. American Journal of Clinical Nutrition. 2002; 76:378–83.
16. Bravata DM, Sanders L, Huang J, Krumholz HM, Olkin I, Gardner CD.: Efficacy and safety of low-carbohydrate diets: a systematic review. JAMA, 2003; 289(14):1837–50.
17. Paoli A, Grimaldi K, D'Agostino D, Cenci L, Moro T, Bianco A, Palma A. Ketogenic diet does not affect strength performance in elite artistic gymnasts. J. Int. Soc. Sports Nutr. 2012; 9(1):34.
18. McSwiney FT, Ben Fusco B, McCabe L et al. Changes in body composition and substrate utilization after a short-term ketogenic diet in endurance-trained males. Biol Sport. 2021; 38(1):145–152.
19. Jeukendrup AE. Periodized nutrition for athletes. Sports Med. 2017; 47:51–63.
20. Dearlove DJ, Harrison OK, Hodson L, Jefferson A, Clarke K., Cox PJ. The Effect of Blood Ketone Concentration and Exercise Intensity on Exogenous Ketone Oxidation Rates in Athletes. Med. Sci. Sports Exerc. 2021; 53(3):505–516.
21. Frączek B, Gacek M, Pięta A, Tyrała F, Mazur-Kurach P, Karpęcka E. Dietary mistakes of Polish athletes in relation to the frequency of consuming foods recommended in the Swiss food pyramid for active people. Rocz Panstw Zakl Hig. 2020; 71(1):97–104.
22. Karpęcka E, Frączek B. Macronutrients and water – do they matter in the context of cognitive performance in athletes? Balt J Health Phys Activ. 2020; 12(3):114–135.
23. Ghaedi E, Mohammadi M, Mohammadi H, Ramezani-Jolfaie N, Malekzadeh J, Hosseinzadeh M, Salehi-Abargouei A. Effects of a paleolithic Diet on Cardiovascular Disease Risk Factors: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. Adv. Nutr., 2019; 10(4):634–646
24. Manheimer EW, van Zuuren EJ, Fedorowicz Z, Pijl H. Paleolithic nutrition for metabolic syndrome: Systematic review and meta-analysis. Am. J. Clin. Nutr., 2015; 102(4):922–932.
25. Noakes M, Foster PR, Keogh JB, James AP, Mamo JC, Clifton PM. Comparison of isocaloric very low carbohydrate/high saturated fat and high carbohydrate/low saturated fat diets on body composition and cardiovascular risk. Nutr Metab (Lond). 2006; 3(1):7.
26. Zając A, Poprzęcki S, Maszczyk A, Czuba M, Michalczyk M, Zydek G. The effects of a ketogenic diet on exercise metabolism and physical performance in off-road cyclists. Nutrients. 2014; 6(7):2493–2508.
27. Creighton BC, Hyde PN, Maresh CM, Kraemer WJ, Phinney SD, Volek JS. Paradox of hypercholesterolaemia in highly trained, keto-adapted athletes. BMJ Open Sport Exerc. Med. 2018; 4(1):e000429.
28. Moctezuma-Velázquez C, García-Juárez I, Soto-Solís R, Hernández-Cortés J, Aldo Torre. Nutritional assessment and treatment of patients with liver cirrhosis. Nutrition. 2013; 29(11–12):1279–85.
29. Jamka M, Kulczynski B, Juruć A, Gramza-Michałowska A, Stokes CS, Walkowiak J. The Effect of the paleolithic Diet vs. Healthy Diets on Glucose and Insulin Homeostasis: A systematic review and meta-analysis of randomized controlled trials. J. Clin. Med. 2020; 9:296.
30. Urbain P, Strom L, Morawski L, Wehrle A, Deibert P, Bertz H. Impact of a 6-week non-energy-restricted ketogenic diet on physical fitness, body composition and biochemical parameters in healthy adults. Nutr Metab (Lond). 2017; 14(1):17.
31. Durkalec-Michalski K, Nowaczyk PM, Siedzik K. Effect of a four-week ketogenic diet on exercise metabolism in CrossFit-trained athletes. J Int Soc Sports Nutr. 2019; 16(1):16.
32. Phinney SD, Bistrian BR, Evans WJ, Gervino E, Blackburn GL. The human metabolic response to chronic ketosis without caloric restriction: Preservation of submaximal exercise capability with reduced carbohydrate oxidation. Metabolism. 1983; 32(8):769–776.
33. Helge JW, Richter EA, Kiens B. Interaction of training and diet on metabolism and endurance during exercise in man. J Physiol., 1996; 492(1):293–306.
34. Volek JS, Freidenreich DJ, Saenz C, Kunces LJ, Creighton BC, Bartley JM, Davitt PM, Munoz CX, Anderson JM, Maresh CM, Lee EC, Schuenke MD, Aerni G, Kraemer WJ, Phinney SD. Metabolic characteristics of keto-adapted ultra-endurance runners. Metabolism. 2016; 65(3):100–110.
35. Evans M, McSwiney FT, Brady AJ, Egan B. No Benefit of Ingestion of a Ketone Monoester Supplement on 10-km Running Performance. Med. Sci. Sports Exerc. 2019; 51(12):2506–2515.
36. Kang J, Ratamess NA, Faigenbaum AD, Bush J. Ergogenic Properties of Ketogenic Diets in Normal-Weight Individuals: A Systematic Review, Journal of the American College of Nutrition 2020; 39(3):1–11.
37. Sherrier M, Li H. The impact of keto-adaptation on exercise performance and the role of metabolic-regulating cytokines. Am J Clin Nutr. 2019; 110(3):562–573.
38. Mohorko N, Cernelic-Bizjak M, Poklar-Vatovec T, Grom G, Kenig S, Petelin A, Jenko-Praznikar Z. Weight loss, improved physical performance, cognitive function, eating behavior, and metabolic pro le in a 12-week ketogenic diet in obese adults. Nutr Res., 2019; 62:64–77.
39. Baranauskas M, Jablonskiene V, Abaravičius JA, Samsoniene L, Stukas R. Dietary Acid-Base Balance in High-Performance Athletes; Int. J. Environ. Res. Public Health. 2020; 17(15):5332.
40. Rhyu HS, Cho SY. The effect of weight loss by ketogenic diet on the body composition, performance-related physical fitness factors and cytokines of Taekwondo athletes. J Exerc Rehabil. 2014; 10(5):326–31.
41. Phinney SD. Ketogenic diets and physical performance. Nutrition & Metabolism. 2004; 17(1):1–2.
42. Escobar KA, Van Dusseldorp TA, Kerksick CM. Carbohydrate intake and resistance-based exercise: are current recommendations reflective of actual need? Br J Nutr. 2016; 116(12):2053–65.
43. Phillips SM. A Brief Review of Critical Processes in Exercise-Induced Muscular Hypertrophy. Sports Med. 2014; 44(1)71–77.
44. Close GL, Hamilton L, Philp A, Burke LM, Morton JP. New strategies in sport nutrition to increase exercise performance. Free Radic Biol Med. 2016; 98:144–58.
45. Popp CJ, Bohan Brown MM, Bridges WC, Jesch ED. The Effectiveness of MyPlate and paleolithic-based Diet Recommendations, both with and without Exercise, on Aerobic Fitness, Muscular Strength and Anaerobic Power in Young Women: A randomized Clinical Trial, Int J Exerc Sci. 2018:11(2):921–933.
46. Zinn C, Wood M, Williden M, Chatterton S, Maunder E: Ketogenic diet benefits body composition and well-being but not performance in a pilot case study of New Zealand endurance athletes. J. Int. Soc. Sports Nutr. 2017; 14, 22–31.
47. Kephart WC, Pledge CD, Roberson PA, Mumford PW, Romero MA, Mobley CB, Martin JS, Young KC, Lowery RP, Wilson JM, Huggins KW, Roberts MD.

The three-month effects of a ketogenic diet on body composition, blood parameters, and performance metrics in crossfit trainees: A pilot study. Sports (Basel.). 2018; 6(1):1.
48. Fleming J, Sharman MJ, Avery NG, Love DM, Gomez AL, Scheett TP, Kraemer WJ, Volek JS. Endurance capacity and high-intensity exercise performance responses to a high fat diet. Int J Sport Nutr Exerc Metab. 2003; 13(4):466–478.
49. Greene DA, Varley BJ, Hartwig TB, Chapman P, Rigney M. A low-carbohydrate ketogenic diet reduces body mass without compromising performance in powerlifting and Olympic weight-lifting athletes. J Strength Cond Res. 2018; 32(12):3373–3382.
50. Heatherly AJ, Killen LG, Smith AF, Waldman HS, Seltmann CL, Hollingsworth A. O'Neal EK. Effects of Ad libitum Low-Carbohydrate High-Fat Dieting in Middle-Age Male Runners. Med. Sci. Sports Exerc. 2018; 50(3):570–579.

SUPPLEMENTARY TABLE 1. Anthropometric parameters, body structure components, hematological and biochemical blood values. Data are reported as arithmetic mean, standard deviation and point of change (absolute changes).

	PD (n = 9)						CD (n = 6)					
	1 $\bar{x} \pm$ SD	1–2	1–3	1–4	1–5	F	1 $\bar{x} \pm$ SD	1–2	1–3	1–4	1–5	F
Anthropometric parameters												
BM [kg]	93.52 ± 9.74	-2.46	-3.47*	-4.47**	*-4.65***	**	92.47 ± 13.10	-0.67	-1.05	-1.69	-2.45**	**
BMI [kg/m^2]	26.73 ± 1.79	-0.71	-1.00*	-1.30**	*-1.33***	**	27.16 ± 2.28	-0.22	-0.34	-0.52	-0.75**	**
FM [%]	23.25 ± 5.82	-1.73	-2.64**	-2.97**	*-3.92***	**	21.68 ± 5.45	-1.73	-2.60	-3.31**	*-3.53**	**
FM [kg]	20.70 ± 7.04	-1.71	-2.77	-3.25**	*-4.09***	**	19.83 ± 8.04	-1.58	-2.42	-3.05**	*-3.36***	**
FFM [%]	77.28 ± 5.82	+1.61	+2.63*	+2.76**	*+3.69***	**	79.24 ± 5.26	+1.70	+2.56	+3.20**	*+3.40**	**
FFM [kg]	72.06 ± 7.47	-0.41	-0.45	-0.94	-0.25	NS	72.63 ± 5.78	+0.94	+1.41	+1.37	+0.93	NS
MM [%]	41.10 ± 3.13	-0.88	-0.39*	-0.18*	+0.63	*	42.35 ± 1.70	-0.88	-0.75	+0.16	-0.16	NS
MM [kg]	38.37 ± 4.38	-1.81	-1.73*	-1.90*	-1.33	*	38.96 ± 4.03	-1.13	-0.89	-1.21	+3.39	*
BMC [g]	3877.29 ± 496.30	-14.56	-9.89	-4.48	-13.69	*	3997.00 ± 397.05	+3.33	-2.17	-10.33	-15.83	NS
BMD [g/cm^2]	1.47 ± 0.12	-0.03	-0.04	0	-0.01	**	1.54 ± 0.11	-0.04	-0.05	-0.04	-0.03	NS
Blood counts												
HGB [g/dl]	15.31 ± 1.13	-0.34	-0.22	-0.12	-0.19	NS	15.28 ± 0.69	-0.21	+0.19	+0.17	-0.18	NS
HCT [%]	45.00 ± 3.21	-1.23	-0.89	-0.88	-1.24	NS	42.90 ± 1.89	-0.70	+0.50	+0.15	-1.32	NS
Erythrocytes [mln/μl]	5.25 ± 0.46	-0.14	-0.08	-0.07	-0.08	NS	5.19 ± 0.33	-0.11	-0.02	0	-0.12	NS
MCHC [g/dl]	34.03 ± 0.57	+0.14	+0.20	+0.37	+0.56	NS	34.03 ± 0.44	+0.07	+0.04	+0.27	+0.60	NS
MCH [p/g]	29.24 ± 0.81	+0.08	-0.01	+0.12	-0.05	NS	29.48 ± 0.94	+0.25	+0.45	+0.35	+0.37	NS
MCV [fl]	85.95 ± 2.53	-0.11	-0.45	-0.64	-1.23	NS	86.63 ± 3.44	+0.57	+1.20	+0.42	-0.51	*
RDW-CW [%]	12.67 ± 0.42	-0.17	-0.21	-0.34**	-0.24	*	12.70 ± 0.44	+0.02	+0.02	+0.12	-0.18	NS
Leukocytes [tys/μl]	7.33 ± 1.43	-1.58	-1.96#	-1.20	-1.00	**	7.74 ± 1.81	-0.91	-0.49#	-1.22	-0.88	NS
Monocytes [tys/μl]	0.63 ± 0.16	-0.06	-0.15#	-0.13#	-0.01	**	0.73 ± 0.24	-0.08	-0.03#	-0.10#	-0.03	NS
Lymphocytes [tys/μl]	2.95 ± 0.72	-0.61	-0.67**	-0.38	-0.47	**	2.77 ± 0.63	-0.42	-0.10	-0.10	-0.20	NS
Neutrophils [tys/μl]	3.49 ± 0.86	-0.81	-1.10**	-0.62	-0.48	**	3.92 ± 1.59	-0.30	-0.24	-0.90	-0.60	NS
Basophils [tys/μl]	0.05 ± 0.03	-0.01	0	-0.01	-0.01	NS	0.07 ± 0.03	-0.01	-0.01	-0.01	-0.01	NS
Eosinophils [tys/μl]	0.24 ± 0.11	-0.06	-0.05	-0.01	-0.01	NS	0.23 ± 0.16	-0.06	-0.08	-0.04	+0.01	NS
Platelets [tys/μl]	266.23 ± 31.93	-5.45	-21.00	-27.12	-6.23	*	290.33 ± 62.64	-7.00	-20.83	-6.16	-22.83	NS
PDW [fl]	14.14 ± 2.00	+0.05	+0.63	+0.99	-0.13	*	14.48 ± 1.17	+0.84	+1.25	+1.19	+1.32	NS
P-LCR [%]	35.64 ± 6.82	+1.69	+3.19	+3.72	-0.05	*	37.65 ± 4.09	+3.43	+3.85	+3.23	+2.65	*
MPV [fl]	11.24 ± 0.85	+0.29	+0.4	+0.49	+0.07	*	11.47 ± 0.48	+0.40	+0.50*	+0.44	+0.38	*
PCT [%]	0.30 ± 0	0	0	-0.01	0	NS	0.35 ± 0.08	-0.02	-0.03	-0.06	-0.05	NS
Lipid profile												
TC [mmol/l]	4.20 ± 0.76	-0.20	+0.30	+0.05	-0.07	NS	4.55 ± 0.63	-0.59*	-0.19	-0.23	-0.42	*
HDL-C [mmol/l]	1.49 ± 0.34	+0.20	-0.01	+0.02	+0.25#	NS	1.45 ± 0.48	-0.10	-0.08	-0.17	-0.11#	NS
LDL-C [mmol/l]	2.19 ± 0.61	-0.26	+0.20	+0.13	-0.01	NS	2.32 ± 0.72	-0.28	+0.12	+0.09	+0.01	NS
TG [mmol/dl]	1.17 ± 0.46	-0.34*	-0.34	-0.26	-0.19	*	1.70 ± 0.85	-0.43	-0.47	-0.32	-0.68	NS
Carbohydrates and fat metabolism												
Glucose [mmol/l]	5.20 ± 0.32	-0.59*	-0.31	-0.51**	-0.15	**	5.14 ± 0.18	-0.37	-0.28	-0.21	-0.17	NS
Insulin [μIU/ml]	8.24 ± 3.35	-1.1	-1.55	-0.45	+0.01	NS	7.59 ± 2.85	+0.11	+1.72	+0.16	-1.62	NS
FFA [mmol/l]	0.50 ± 0.22	-0.01	-0.08	+0.07	-0.14	NS	0.34 ± 0.26	+0.25	+0.16	+0.04	0	NS
b-HB [mmol/l]	0.05 ± 0.02	+0.21	+0.12	+0.14	+0.09	NS	0.08 ± 0.11	+0.18	+0.06	+0.01	+0.03	NS

SUPPLEMENTARY TABLE 1. Continue

	PD (n = 9)						CD (n = 6)					
	1 $\bar{\times}$ ± SD	1–2	1–3	1–4	1–5	F	1 $\bar{\times}$ ± SD	1–2	1–3	1–4	1–5	F
Electrolytes												
Sodium [mmol/l]	142.65 ± 2.02	-2.15	-1.35	-0.65	*-0.21**	*	140.80 ± 1.34	-1.47	+0.2	+0.5	+0.70	NS
Calcium [mmol/l]	2.36 ± 0.08	+0.10	+0.15**	+0.12*	*+0.11**	**	2.44 ± 0.07	+0.03	+0.07	0	+0.02	NS
Magnesium [mmol/l]	0.83 ± 0.03	+0.05	+0.05	+0.04	+0.02	NS	0.83 ± 0.04	+0.08*	+0.07	+0.03	-0.01	**
Potassium [mmol/l]	4.60 ± 0.28	-0.09	-0.11	+0.03	-0.07	NS	4.63 ± 0.29	-0.05	-0.01	-0.03	+0.06	NS
Kidney parameters												
Creatinine [μmol/l]	90.26 ± 9.72	+8.07	+9.96	+9.41*	+2.96	*	93.33 ± 1.60	+11.00	+9.67	+4.84	*+10.67**	**
eGFR [ml/min/1.73 m^2]	86.40 ± 5.15	-6.59	-7.52	-6.62	-2.62	*	85.92 ± 2.61	-9.67	-9.03	-4.42	-9.94	*
Urea [mmol/l]	6.15 ± 1.90	+1.08	+0.63	+1.36	+0.38	NS	5.90 ± 1.22	-0.17	-0.20	+0.82	+1.07	NS
Uric acid [μmol/l]	330.90 ± 47.06	+38.7	+34.46	+35.9	+5.21	NS	297.85 ± 49.16	+81.15*	+57.65	+58.95	+39.32	NS
Cystatin C [mg/dl]	0.82 ± 0.10	-0.04	-0.02	0	+0.06	*	0.79 ± 0.10	+0.04	+0.07	+0.04	+0.09	**
Urine pH	6.10 ± 0.92	-0.66	-0.82	-0.6	-0.77	NS	5.83 ± 0.90	-0.08	-0.50	-0.08	-0.41	NS
Liver parameters												
ALT [U/l]	25.37 ± 8.49	-1.53	+2.82	-1.65	-0.53	NS	29.17 ± 12.69	-1.79	+0.35	-4.30	-3.79	NS
AST [U/l]	25.38 ± 8.90	-1.04	-0.42	-3.15	-3.18	NS	25.33 ± 6.07	+2.69	-0.65	-2.95	-1.90	NS
Alkaline Phosphatase [U/l]	84.65 ± 22.06	-8.54	-6.76	-4.43	+0.57	*	80.33 ± 15.65	+0.34	+2.5	-2.16	+1.00	NS
GGTP [mmol/l]	20.27 ± 14.15	-5.05	-7.05	-7.16*	-5.94	*	16.83 ± 6.41	-2.66	-2.16	-2.00	-3.83	NS
Total bilirubin [μmol/l]	7.64 ± 2.13	+2.03	+2.38	+2.39	+0.88	NS	9.81 ± 5.61	+1.09	+0.92	-1.03	-0.76	NS

Abbreviations: PD – Paleo diet; CD – control diet; $\times$ – arithmetic mean; SD – standard deviation; 1–2; 1–3; 1–4; 1–5 – differences between particular series; F – Friedman's Test; BM – body mass; BMI – body mass index; FM – fat mass; FFM – fat free mass; MM – muscle mass; BMC – body mineral content; BMD – body mass density; HGB – haemoglobin; HCT – hematocrit; MCHC – mean corpuscular hemoglobin concentration; MCH – mean corpuscular haemoglobin; MCV – mean corpuscular volume; RDW-CV – red blood cell distribution with coefficient of variation; PDW – platelet distribution width; P-LCR – platelet-large cell ratio; MPV – mean platelet volume; PCT – procalcitonin; TC – total cholesterol; HDL-C – high-density lipoprotein cholesterol; LDL-C – low-density lipoprotein cholesterol; TG – triglycerides; FFA – free fatty acids; b-HB – beta-hydroxybutyrate; e-GFR – estimated glomerular filtration rate; ALT – alanine aminotransferase; AST – aspartate aminotransferase; GGTP – gamma-glutamyl transferase; italics-changes between 1–5 series; * – test probability at the level of $p < 0.05$ intragroup; ** – $p < 0.01$; # – test probability at the level of $p < 0.05$ intergroup; ## – $p < 0.01$ in U-Mann test.

SUPPLEMENTARY TABLE 2. Anaerobic and aerobic capacity. Data are reported as arithmetic mean, standard deviation and point of change (absolute changes).

	PD (n = 9)				CD (n = 6)			
	$1\bar{x} \pm SD$	1–3	1–5	F	$1\bar{x} \pm SD$	1–3	1–5	F
Wingate test on upper limbs								
Wt [kJ]	10.36 ± 1.04	-0.48	*-1.01**	*	10.25 ± 1.02	+0.28	-0.01	NS
Wt [J·kg^{-1}]	111.85 ± 10.55	-2.07	-5.07	NS	111.33 ± 7.87	+5.67	+4.84	NS
MAP [W]	595.77 ± 71.92	-29.90	*-59.10***	*	601.17 ± 67.63	+13.33	-0.017	NS
MAP [W·kg^{-1}]	6.41 ± 0.71	-0.12	-0.30	NS	6.52 ± 0.42	+0.29	+0.26	NS
Pmean [W]	517.97 ± 52.03	-24.41	*-50.19**	**	512.33 ± 51.15	+14.17	0	NS
Pmean [W·kg^{-1}]	5.59 ± 0.56	-0.10	-0.26	NS	5.57 ± 0.40	+0.26	+0.23	NS
t_r [s]	5.26 ± 0.82	+0.20	+0.18	NS	4.86 ± 0.72	-0.13	+0.17	NS
t_m [s]	4.11 ± 1.43	-0.17	-0.36	NS	3.12 ± 0.74	+0.49	+0.60	NS
Wingate test on lower limbs								
Wt [kJ]	17.90 ± 1.99	-1.01	*-2.15***	**	17.31 ± 2.24	-0.04	-0.88	NS
Wt [J·kg^{-1}]	189.91 ± 10.52	-1.69	*-10.47***	**	187.33 ± 12.67	+3.63	-1.95	NS
MAP [W]	1062.35 ± 114.55	-30.68	*-132.91***	**	1077.83 ± 176.07	-37.71	*-38.85**	*
MAP [W·kg^{-1}]	11.25 ± 0.57	_+0.17	-0.65	*	11.61 ± 1.11	-0.12	+0.08	NS
Pmean [W]	895.35 ± 99.56	-50.70	*-83.81***	**	865.33 ± 112.09	-2.00	-40.08	NS
Pmean [W·kg^{-1}]	9.49 ± 0.53	-0.09	-0.28	*	9.37 ± 0.64	+0.19	-0.02	NS
t_r [s]	4.04 ± 0.56	+0.01	+0.65	NS	3.72 ± 0.84	-0.21	+0.03	NS
t_m [s]	3.81 ± 2.21	-1.03	+0.13	NS	2.48 ± 0.52	+0.26	+0.16	NS
Aerobic capacity test								
VO_2max [l/min]	4.31 ± 0.56	-0.01	-0.14	NS	4.22 ± 0.26	-0.01	-0.02	NS
VO_2max [ml/kg/min]	45.70 ± 4.05	+2.3	+1.63	NS	45.83 ± 4.37	+1.48	+1.90	NS
VEmax [l/min]	149.93 ± 15.90	-5.63	-9.06	NS	154.10 ± 8.69	+2.76	-5.31	NS
TVmax [l]	2.99 ± 0.49	-0.04	*-0.13**	*	2.91 ± 0.51	-0.08	-0.04	NS
RER	1.11 ± 0.04	-0.01	-0.01	NS	1.14 ± 0.04	+0.01	-0.01	NS
VE·VCO_2^{-1}	30.12 ± 2.41	-0.76	-0.83	NS	30.37 ± 2.08	+0.47	-0.52	NS
HRmax [bpm]	188.59 ± 7.96	-2.14	*-6.81***	**	186.00 ± 11.56	-0.23	*-5.98**	*
t [min]	16.78 ± 2.02	+0.89	+0.44	NS	17.00 ± 2.39	+0.80	+0.25	NS
v [km/h]	14.70 ± 1.15	+0.43	+0.66	*	15.45 ± 1.37	+0.79	+0.52	NS

Abbreviations: PD – Paleo diet; CD – control diet; × – arithmetic mean; SD – standard deviation; 1–3; 1–5 – differences between particular series; Wt– total work performed; MAP – maximum anaerobic power; Pmean – mean anaerobic power; t_r– the time of reaching maximum power; t_m – time of maintaining maximum power; VO_2max – maximum oxygen uptake; VE max – maximum minute ventilation; TV_{max} – maximum tidal volume; RER – respiratory exchange ratio; VE·VCO_2^{-1} – respiratory equivalent carbon dioxide; HR_{max} – maximum heart rate; t-time; v – speed; F – Friedman's Test; italics – changes between 1–5 series; * – test probability at the level of $p < 0.05$ intragroup; ** – $p < 0.01$.

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Relationships between external loads, sRPE-load, and self-reported soreness across a men's collegiate soccer season

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ABSTRACT: The purpose was to examine relationships between external loads (ELs), perceived exertion, and soreness. Collegiate men soccer players (n = 19) were monitored for 72 sessions (training: n = 53; matches: n = 19). Likert scale assessments (0–6) of lower body soreness were collected prior to each session, and ELs were collected using positional monitoring technology. Session rate of perceived exertion (sRPE-load) was calculated by multiplying perceived exertion values (Borg CR-10 Scale) by respective session duration to determine internal load. Multiple analyses of variance were used to determine differences in ELs across seasons (pre-season, in-season, post-season) and sessions (training, match). Bivariate Pearson correlation coefficients and linear regression analyses were used to evaluate relationships among soreness, ELs, and sRPE-load. Greatest ELs were observed during pre-season and post-season phases ($p < 0.001$). Sessions with high perceived exertion and low soreness were associated with higher ELs ($p < 0.05$). Duration ($t = 16.13$), total distance ($t = 9.17$), sprint distance ($t = 7.54$), player load ($t = 4.22$), top speed ($t = 4.69$), and acceleration ($t = 2.02$) positively predicted sRPE-load ($F = 412.9$, $p < 0.001$, $R^2 = 0.75$). Soreness was weakly and trivially correlated with ELs ($p < 0.05$). The very strong relationship between ELs and sRPE-load highlights the utility of sRPE-load as a practical means to estimate workload; however, more research into the relationship between soreness and workload is warranted.

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INTRODUCTION

Preparation for soccer is often characterized by periodization schemes that target technical, tactical, and physical development throughout the year to meet competition demands and mitigate injury risks [1–3]. This process involves strategic manipulation of training variables (i.e., volume, intensity, frequency, density) at key time points to elicit sport-specific adaptations [1, 4]. However, it can be challenging to quantify sport-specific training demands outside of resistance training and conditioning-related activities. Further, within the current National Collegiate Athletic Association (NCAA) format, constraints exist that may hinder optimal preparation and performance. For example, a two-week pre-season precedes a congested competitive season, in which athletes may compete in > 20 matches over 12–15 weeks [1, 5]. This season-structure underscores the importance of quantifying training in a manner that is practical while sensitive to the potential risks associated with a congested season, such as non-functional overreaching, overtraining syndrome, illness, and injury [1, 6–9].

Technical and tactical components of soccer training are often designed with prescriptions of external load (EL) parameters, which include volume and intensity metrics. The use of wearable technologies, such as global positioning systems (GPS) equipped with inertial sensors, enables coaches to quantify ELs while reducing error and guesswork in a streamlined process [6, 10]. Despite its cost-prohibitive nature, GPS implementation creates opportunities for real-time observation of EL metrics as well as a retrospective analysis of broader trends across different season phases. Previous studies have reported higher ELs during pre-season compared to in-season for various professional [11] and collegiate [12] soccer populations. These observations are likely the result of an increased focus on rebuilding physical capacities, compounded by a short pre-season, leading to an intensified training period prior to the start of the competitive season [12]. Differences between in-season and post-season phases have been investigated in DI soccer players, with reductions observed in post-season ELs compared to in-season [12]. These findings may

reflect either the intentional reduction of EL prescription during post-season training in order to elicit a "peaking" effect or, by contrast, the chronic accumulation of fatigue leading to attenuated post-season physical outputs [12, 13]. However, further investigation is necessary to determine differences between in- and post-season ELs in DIII soccer players.

Despite the benefits of GPS monitoring, EL is likely not the sole driver of physiological adaptation. Rather, internal load (IL) – the physiological stress imposed by the completion of EL – is thought to mediate the adaptive responses from training [6, 14]. Moreover, in team sports like soccer, a given EL can elicit significant variation in IL between players [6]. Thus, IL metrics can be useful in quantifying team and individual responses to training. One cost-effective and valid method of estimating IL is the session Rating of Perceived Exertion (sRPE-load) [15], which is strongly correlated with EL in a variety of athletic populations [6, 16–18] and may serve as an effective proxy for EL. Thus, a relationship between external and internal loads seems to exist, but because of large differences that occur in the physical demands of athletes across levels of play and sports, continued investigation is warranted.

However, EL and sRPE-load measures alone may not represent the totality of physical stress incurred nor do they provide insight into the recovery status of athletes over successive days, weeks, and months of training and competition. Therefore, other IL indices, such as measures of physical wellness, may be used to inform training prescription and track recovery status [19]. Customized self-reported perceived wellness measures have garnered interest as time-efficient, cost-effective, and valid measures of IL to quantify and monitor more holistic trends in the constructs of fatigue, recovery, muscle soreness, and stress [20–22]. While previous investigations have observed correlations between perceived muscle soreness and EL across two-week time periods [21, 23], a longitudinal examination of these associations across a full collegiate soccer season has not been conducted. Thus, the purpose of the current study was to quantify ELs and examine the relationships between sRPE-load, and perceived soreness in training sessions across a collegiate men's soccer season.

MATERIALS AND METHODS

Subjects

National Collegiate Athletic Association (NCAA) Division III men soccer athletes (n = 19) classified as "starters" (i.e., those players that participated in > 50% of a match's duration) participated [12, 24, 25]. Goalkeepers and non-starters were excluded due to the relatively low total distances they traveled. All athletes were under the direction of a Certified Strength and Conditioning Specialist® and were following similar training regimens. All athletes completed a medical history form and were cleared for intercollegiate athletic participation. Risks and benefits were explained to athletes, and an institutionally approved written informed consent form was signed before participation. All procedures involving human subjects were conducted in accordance with the requirements of the Declaration of Helsinki and approved by the college's Institutional Review Board for Human Subjects (IRB # 3182021).

TABLE 1. Structure of the 12-week season

Week	Season Phase	# of Training Sessions	# of Matches	Total # of Sessions
1	Pre-Season	8	1*	9
2	Pre-Season	6	1*	8
	In-Season	0	1	
3	In-Season	4	2	6
4	In-Season	4	2	6
5	In-Season	4	2	6
6	In-Season	4	2	6
7	In-Season	4	1	5
8	In-Season	4	1	5
9	In-Season	4	2	6
10	In-Season	4	2	6
11	Post-Season	3	1	4
12	Post-Season	4	1	5
Total		53	19	72

* Denotes pre-season scrimmage

Study Design

Data were collected over 12 weeks during the 2021 NCAA men's soccer season (training sessions: n = 53; matches: n = 19 [2 scrimmages, 17 competitions]) for a total of 1,368 individual player sessions (Table 1). Lower body soreness was collected each afternoon, prior to training, while athlete RPE was collected approximately 15 minutes after the cessation of each training session. Lower body soreness and RPE measures were collected on training days only; match days were excluded. EL was quantified during all field training sessions and matches using 10 Hz GPS/GNSS technology (Player Tek, Catapult Sports, Melbourne, Australia). The 10 Hz units have been shown to provide a valid and reliable estimate of kinematic data with sufficient inter-unit reliability for comparisons between athletes [26, 27]. These devices use a minimum of 3 satellites, and units were turned on outside 30 minutes before sessions. To promote reliability, players wore the same unit for each match throughout the season. Devices were worn according to manufacturer guidelines in a supportive harness positioned between the scapulae.

Lower Extremity Soreness

Athletes provided subjective ratings of lower body soreness (quadriceps, hamstrings) on Likert scales ranging from 0–6 (0 = complete absence of pain; 1 = light pain felt only when touched/a vague ache; 2 = moderate pain felt only when touched/a slight persistent pain; 3 = light pain when walking up or down stairs; 4 = light pain when walking on a flat surface/painful; 5 = moderate pain, stiffness, or weakness when walking/very painful; and 6 = severe pain that limits my ability to move) [28, 29]. Soreness measures were collected immediately before training sessions only; match days were excluded. To investigate the relationship between soreness and EL, sessions were stratified into high (≥ 3) and low (≤ 2) soreness classifications.

External Load

EL metrics collected for training sessions and matches were: total distance, sprint efforts, sprint distance (> 5.5 m/s), top speed, acceleration efforts (> 3 m/s^2), player load (PL), player load per minute (PL/min), and power plays (power output > 20 watts/kg > 1 sec). PL was yielded from the triaxial accelerometer within the device using a proprietary formula:

$$\sum\sqrt{(instantaneous\ rate\ of\ change\ in\ acceleration\ in\ all\ 3\ orthogonal\ planes)}$$

After each training session and match, data were downloaded using the proprietary software, which automatically detects and removes outlier data [30].

Session Rate of Perceived Exertion

RPE was collected using the modified Borg CR-10 scale [31] for training sessions only. Athletes provided their RPE approximately 15 minutes post-training session to avoid the recency effect and to ensure their perceived intensity would reflect the entire training session. Further, each athlete reported RPE in isolation to avoid influence from teammates. Session RPE (sRPE-load) was calculated by multiplying the given RPE by the duration of the training session in minutes and expressed using arbitrary units (AU). To investigate the relationship between sRPE-load and other measures of load, sessions were stratified by RPE into high (RPE ≥ 6) and low (RPE ≤ 5) difficulty. Specifically, this approach was used to determine if differences in external workloads existed when sessions were categorized into "high" and "low" RPE [6].

Statistical Analysis

SPSS version 25.0 (IBM, Armonk, NY) was used for summary statistics. All values are presented as *means* ± *SDs*. A multiple analysis of variance (MANOVA) was used to determine 1) seasonal differences (pre-season vs in-season vs post-season) in EL measures; 2) differences in weekly ELs between training sessions and matches; and 3) differences in ELs stratified by high and low RPE and lower body soreness. Bonferroni post hoc comparisons were calculated when a significant main effect or interaction was identified. Partial eta^2 (η^2) effect sizes were calculated and interpreted as follows: small: 0.01–0.06; moderate: 0.06–0.14; and large: > 0.14 [32]. Bivariate Pearson and Spearman correlation coefficients determined relationships among sRPE-load, ELs, and quadricep and hamstring soreness. The strength of correlation coefficients was classified as trivial ($|r| < 0.10$), weak ($0.10 \leq |r| < 0.30$), moderate ($0.30 \leq |r| < 0.50$), strong ($0.50 \leq |r| < 0.70$), very strong ($0.70 \leq |r| < 0.90$), and nearly perfect ($|r| \geq 0.90$) [33]. When strong-to-very strong correlations existed, a multiple linear regression was used to assess the predictive ability of EL markers on perceived measures ($p < 0.05$).

RESULTS

Differences in EL and IL across the season are displayed in Table 2. Significant differences across pre-, in-, and post-season were observed in training sessions for sRPE-load, and in all sessions (training sessions and matches) for total distance, acceleration efforts, PL, PL/min, and power plays. Specifically, sRPE-load ($F = 69.06$, $\eta^2 = 0.15$), total distance ($F = 47.49$, $\eta^2 = 0.10$), and PL ($F = 34.16$, $\eta^2 = 0.07$) were highest in pre-season (sRPE-load: 480.7 ± 231 AU, 95% CI [453.3, 508.1]; total distance: 5885 ± 2065 m, 95% CI [5620, 6151]; PL: 269.9 ± 92.3 AU, 95% CI [257.9, 282.3]) compared to in-season (sRPE-load: 292.4 ± 171 AU, 95% CI [276.9, 307.9]; total distance: 4393 ± 1681 m, 95% CI [4242, 4543]; PL: 212.5 ± 78.5 AU, 95% CI [205.6, 219.3]) and post-season (sRPE-load: 326.9 ± 157 AU, 95% CI [290.81, 363.12]; total distance: 5068 ± 1809 m, 95% CI [4718, 5418]; PL: 240.6 ± 77.9 AU, 95% CI [224.6, 256.6]) ($p < 0.001$). Accelerations ($F = 22.57$, $p < 0.001$, $\eta^2 = 0.05$), PL/min ($F = 18.98$, $p < 0.001$, $\eta^2 = 0.04$), and power plays ($F = 24.12$, $p < 0.001$, $\eta^2 = 0.06$) did not differ across pre-season (accelerations: 49.1 ± 25.1, 95% CI [45.7, 52.5]; PL/min: 2.49 ± 0.51 AU, 95% CI [2.4, 2.6]; power plays: 26.4 ± 17.7, 95% CI [24.4, 28.5]) and post-season (accelerations:

TABLE 2. Measures of athlete (n = 19) workload across the competitive season

	Pre-Season (n = 16)	In-Season (n = 47)	Post-Season (n = 9)	p-value	η^2
sRPE-load (AU)*	480.7 ± 231	292.4 ± 171	326.9 ± 157	< 0.001	0.15
Total distance (m)	5885 ± 2065	4393 ± 1681	5068 ± 1809	< 0.001	0.10
Sprint distance (m)	74.4 ± 75.6	65.2 ± 86.2	74.8 ± 68.7	0.31	0.003
Sprint efforts (#)	1.94 ± 2.4	1.55 ± 2.2	1.88 ± 1.9	0.07	0.01
Acceleration efforts (#)	49.1 ± 25.1	36.3 ± 21.7	43.9 ± 24.9	< 0.001	0.05
Top speed (m/s)	7.22 ± 1.2	7.13 ± 1.4	7.48 ± 1.2	0.04	0.01
Player load (AU)	269.9 ± 92.3	212.5 ± 78.5	240.6 ± 77.9	< 0.001	0.07
PL/min (AU/min)	2.49 ± 0.51	2.76 ± 0.50	2.75 ± 0.50	< 0.001	0.04
Power plays (#)	26.4 ± 17.7	18.5 ± 12.4	23.6 ± 12.6	< 0.001	0.06

Values are mean ± SD. sRPE-load: session rate of perceived exertion; PL/min: player load per minute. *Training sessions, only

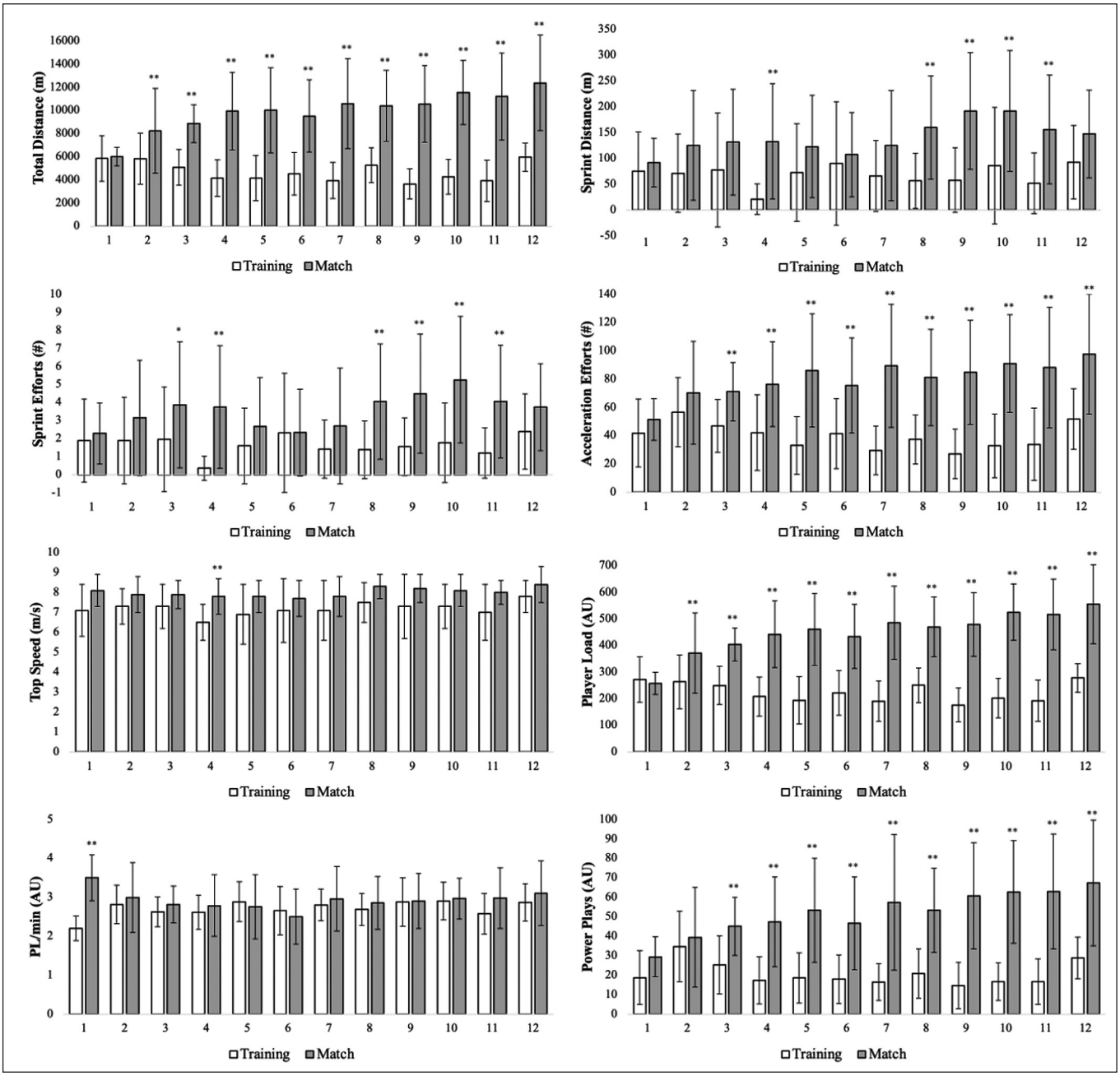


FIG. 1. Weekly external load measures between training sessions and matches. * p < 0.01; ** p < 0.001; x-axis represents week.

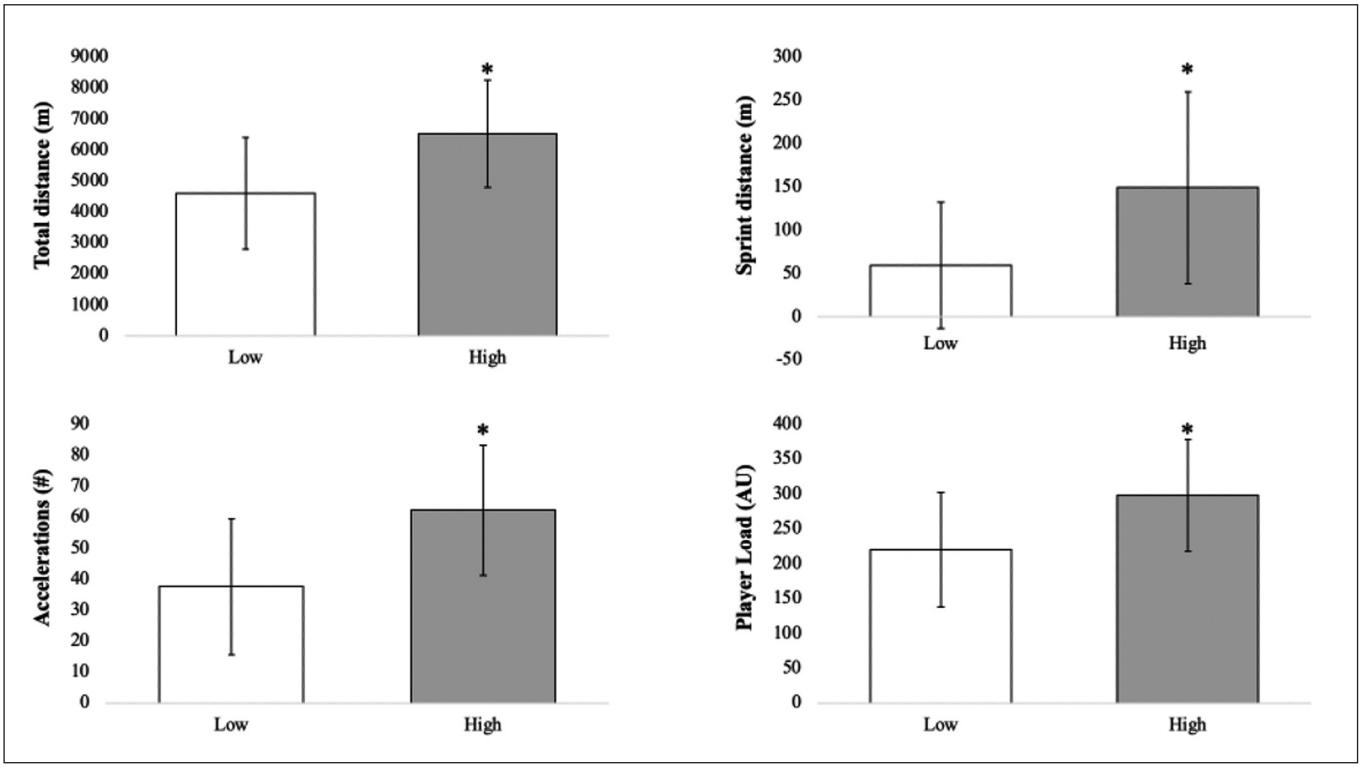


FIG. 2. Training session total distance, player load, acceleration, sprint distance, and high-speed distance stratified by high (≥ 6) or low (≤ 5) perceived session exertion.
* $p < 0.001$.

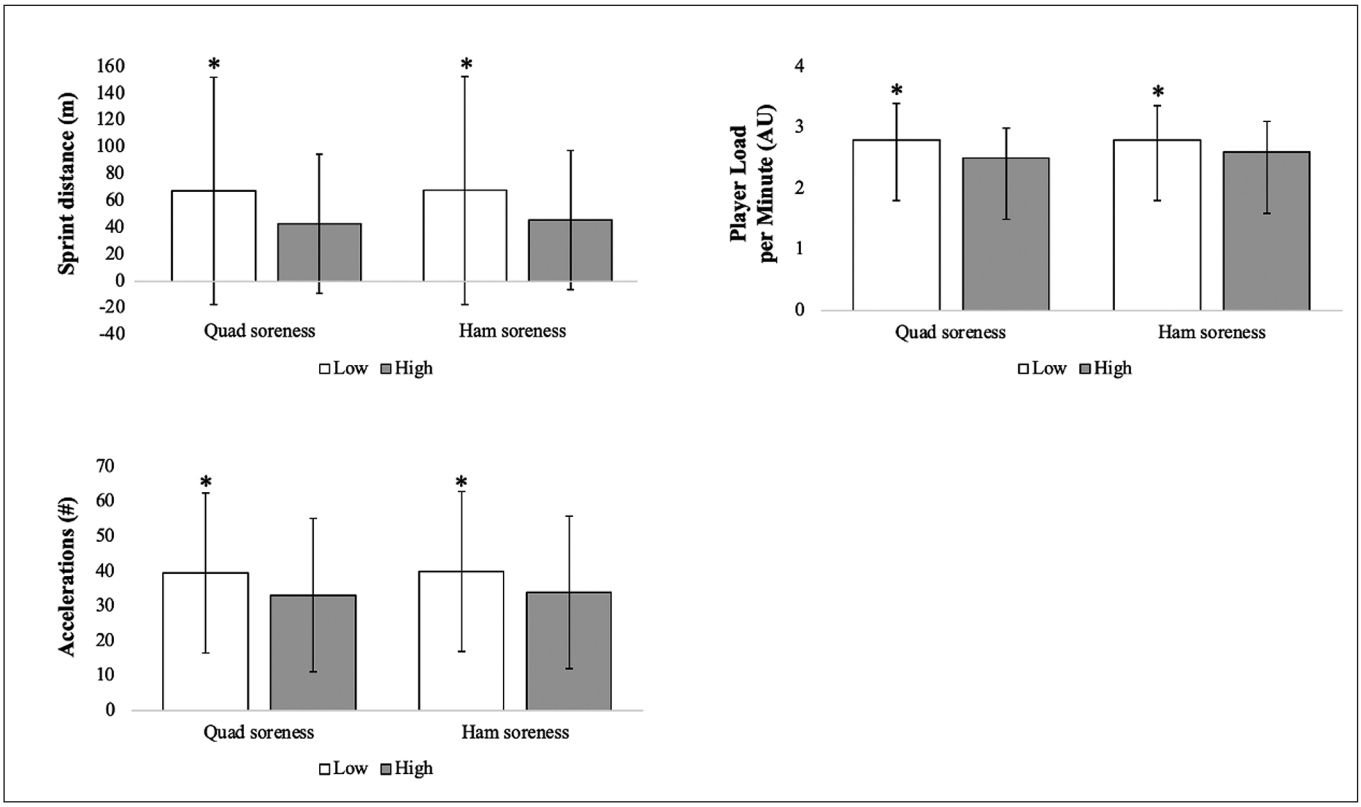


FIG. 3. Training session acceleration, sprint distance, and PL/min stratified by high (≥ 3) or low (≤ 2) perceived quadricep and hamstring sorencess.
* $p < 0.001$.

43.9 ± 24.9, 95% CI [39.5, 48.4]; PL/min: 2.75 ± 0.50 AU, 95% CI [2.7, 2.8]; power plays: 23.6 ± 12.6, 95% CI [20.9, 26.2]), but were higher than their respective in-season (accelerations: 36.3 ± 21.7, 95% CI [34.3, 38.2]; PL/min: 2.76 ± 0.50 AU, 95% CI [2.7, 2.8]; power plays: 18.5 ± 12.4, 95% CI [17.4, 19.7]) values.

Differences between weekly training session and match ELs are presented in Figure 1.

When training sessions were stratified and coded as high or low RPE, significant differences in total distance (high: 6531 ± 1731 m; low: 4608 ± 1809 m, $p < 0.001$), PL (high: 298 ± 80 AU; low: 221 ± 82 AU, $p < 0.001$), accelerations (high: 63 ± 21; low: 38 ± 22, $p < 0.001$), and sprint distance (high: 150 ± 111 m; low: 60 ± 73 m, $p < 0.001$) were observed (Figure 2).

When training sessions were stratified and coded as high or low perceived quadricep and hamstring soreness, significant differences in same-day sprint distance ($p = 0.006$), acceleration ($p = 0.02$), and PL/min ($p = 0.03$) were observed (Figure 3).

Correlations coefficients, p-values, and 95% confidence intervals for all relationships can be found in Tables 3–5. sRPE-load was very strongly correlated with training session duration ($r = 0.89$, 95% CI [0.98, 0.99]), total distance ($r = 0.88$, 95% CI [0.89, 0.96]), accelerations ($r = 0.73$, 95% CI [0.67, 0.77]), top speed ($r = 0.77$, 95% CI [0.62, 0.79]), and PL ($r = 0.88$, 95% CI [0.85, 0.92]); strongly correlated with sprint distance ($r = 0.56$, 95% CI [0.55, 0.77]), and power plays ($r = 0.67$, 95% CI [0.76, 0.89]); and moderately correlated with PL/min ($r = 0.43$, 95% CI [0.29, 0.52]) (Table 3). Duration ($t = 16.13$, $p < 0.001$), total distance ($t = 9.17$, $p < 0.001$), sprint distance ($t = 7.54$, $p < 0.001$), PL ($t = 4.22$, $p = 0.001$), top speed ($t = 4.69$, $p < 0.001$), and acceleration ($t = 2.02$, $p = 0.04$) all significantly predicted post-training sRPE-load ($F = 412.9$, $p < 0.001$, $R^2 = 0.75$).

TABLE 3. Correlations between various external load measures and training session sRPE-load

Variable	r	95% CI	p-value
Duration (min)	0.89	0.98–0.99	< 0.001
Total distance (m)	0.88	0.89–0.96	< 0.001
Sprint distance (m)	0.56	0.55–0.77	< 0.001
Accelerations (#)	0.73	0.67–0.77	< 0.001
Top speed (m/s)	0.77	0.62–0.79	< 0.001
Player load (AU)	0.88	0.85–0.92	< 0.001
PL/min (AU/min)	0.43	0.29–0.52	< 0.001
Power plays (#)	0.67	0.76–0.89	< 0.001

PL/min: player load per minute

TABLE 4. Correlations between pre-training soreness and same-day workload measures

Quadricep Soreness				Hamstring Soreness			
Variable	**r**	**95% CI**	**p-value**	**Variable**	**r**	**95% CI**	**p-value**
sRPE-load	-0.01	-0.08 – 0.07	0.84	**sRPE-load**	-0.07	-0.13 – 0.03	0.07
Duration	0.02	-0.13 – 0.07	0.55	**Duration**	0.01	-0.10 – 0.09	0.72
Total distance	-0.12	-0.25 – -0.07	0.001	**Total distance**	-0.06	-0.17 – 0.01	0.08
Sprint distance	-0.17	-0.24 – -0.09	< 0.001	**Sprint distance**	-0.15	-0.25 – -0.09	< 0.001
Sprint efforts	-0.16	-0.26 – -0.08	< 0.001	**Sprint efforts**	-0.12	-0.25 – -0.07	0.001
Accelerations	-0.16	-0.24 – – 0.09	< 0.001	**Accelerations**	-0.11	-0.20 – -0.05	0.002
Top speed	-0.08	-0.47 – -0.08	0.04	**Top speed**	-0.07	-0.39 – 0.003	0.07
Player load	-0.13	-0.23 – -0.07	< 0.001	**Player load**	-0.08	-0.17 – -0.01	0.04
PL/min	-0.22	-1.21 – -0.57	< 0.001	**PL/min**	-0.14	-0.94 – -0.29	< 0.001
Power plays	-0.18	-0.31 – -0.11	< 0.001	**Power plays**	-0.10	-0.22 – -0.01	0.01

PL/min: player load per minute

TABLE 5. Correlations between workload measures and next-day soreness

Quadricep Soreness				Hamstring Soreness			
Variable	**r**	**95% CI**	**p-value**	**Variable**	**r**	**95% CI**	**p-value**
sRPE-load*	0.27	0.16–0.31	< 0.001	**sRPE-load***	0.17	0.07–0.22	< 0.001
Duration	0.22	0.11–0.26	< 0.001	**Duration**	0.14	0.05–0.19	0.001
Total distance	0.18	0.10–0.25	< 0.001	**Total distance**	0.14	0.05–0.19	0.001
Sprint distance	0.04	0.04–0.12	0.29	**Sprint distance**	0.01	0.09–0.08	0.89
Sprint efforts	0.03	0.02–0.05	0.39	**Sprint efforts**	0.02	0.01– 0.03	0.89
Accelerations	0.09	0.01–0.16	0.04	**Accelerations**	0.08	0.002–0.15	0.06
Top speed	0.27	0.09–0.28	< 0.001	**Top speed**	0.17	0.03–0.21	< 0.001
Player load	0.16	0.09–0.24	< 0.001	**Player load**	0.13	0.04–0.19	0.003
PL/min	0.14	0.08–0.14	< 0.001	**PL/min**	0.13	0.06–0.15	0.003
Power plays	0.11	0.03–0.19	0.09	**Power plays**	0.11	0.01–0.18	0.01

PL/min: player load per minute. *Training sessions, only

Pre-training quadricep soreness was weakly negatively correlated with total distance (r = -0.12, 95% CI [-0.25, -0.07]), sprint distance (r = -0.17, 95% CI [-0.24, -0.08]), power plays (r = -0.18, 95% CI [-0.31, -0.11]), sprint efforts (r = -0.16, 95% CI [-0.26, -0.08]), accelerations (r = -0.16, 95% CI [-0.24, – 0.09]), PL (r = -0.13, 95% CI [-0.23, -0.07]), and PL/min (r = -0.22, 95% CI [-1.21, -0.57]); and trivially correlated with top speed (r = -0.08, 95% CI [-0.47, -0.08]). Pre-training hamstring soreness was weakly negatively correlated with same-day workload measures, including sprint distance (r = -0.15, 95% CI [-0.25, -0.09]), power plays (r = -0.10, 95% CI [-0.22, -0.01]), sprint efforts (r = -0.12, 95% CI [-0.25, -0.07]), accelerations (r = -0.11, 95% CI [-0.20, -0.05]), and PL/min (r = -0.14, 95% CI [-0.94, -0.29]); and trivially correlated with top speed (r = -0.07, 95% CI [-0.39, 0.003])and PL (r = -0.08, 95% CI [-0.17, -0.01]) (Table 4).

sRPE-load (r = 0.27, 95% CI [0.16, 0.31]), session duration (r = 0.22, 95% CI [0.11, 0.26]), total distance (r = 0.18, 95% CI [0.10, 0.25]), power plays (r = 0.11, 95% CI [0.03, 0.19]), top speed (r = 0.27, 95% CI [0.09, 0.28]), PL (r = 0.16, 95% CI [0.09, 0.24]), and PL/min (r = 0.14, 95% CI [0.08, 0.14]) were weakly positively correlated with next-day quadricep soreness; sprint distance (r = 0.04, 95% CI [0.04, 0.12]), sprint efforts (r = 0.03, 95% CI [0.02, 0.05]), and acceleration efforts (r = 0.09, 95% CI [0.01, 0.16]) were trivially correlated. sRPE-load (r = 0.17, 95% CI [0.07, 0.22]), session duration (r = 0.14, 95% CI [0.05, 0.19]), total distance (r = 0.14, 95% CI [0.05, 0.19]), power plays (r = 0.11, 95% CI [0.01, 0.18]), top speed (r = 0.17, 95% CI [0.03, 0.21]), PL (r = 0.13, 95% CI [0.04, 0.19]), and PL/min (r = 0.13, 95% CI [0.06, 0.15]) were weakly correlated with next-day hamstring soreness (Table 5).

DISCUSSION

Investigation of the relationships between ELs, sRPE-load, and perceived soreness throughout an entire NCAA DIII men's collegiate soccer season is unique to the current study. The main findings include: 1) significant differences were observed in workloads across season phases, including notably high pre-season and post-season loads; 2) EL parameters significantly predicted (R^2 = 0.76) post-training sRPE-load; and 3) trivial and weak correlations existed between workloads and same-day and next-day self-perceived soreness measures.

Previous studies have demonstrated significant differences in workloads across season phases in collegiate [12] and professional [11] soccer populations, with pre-season consistently yielding greater total distance, high speed running, and sRPE-load than in-season [12]. Findings from the current study are in agreement, as higher pre-season workloads (training and match) were observed compared to in-season, although a seemingly higher total distance and lower sRPE-load than previously reported in NCAA DI men soccer athletes [12]. High pre-season workloads appear to be a consistent theme across NCAA DI and DIII men's soccer [12, 21, 34], highlighting concerns over health, injury, and player availability. A congested pre-season phase (~2 weeks), characterized by steep workload intensification and accumulation, may be associated with maladaptations that can lead to injury/illness [1, 6, 8]. Thus, pre-season for collegiate soccer presents a heightened challenge characterized by two competing goals: 1) accumulating high physical and physiological workloads following the offseason period, and 2) managing workload accumulation in a manner that elicits positive adaptations, while avoiding maladaptive consequences prior to the start of the competitive season. These competing goals may be even more challenging to manage at the NCAA DIII level as athletic programs cannot mandate

off-season team workouts or practices. Therefore, quantification of workloads is integral to the design of a productive pre-season period. Interestingly, the current study observed similar workloads between pre-season and post-season, which conflicts with prior research, which has found that post-season often reflects an intentional reduction of EL prescription as part of tapering strategies [12, 13]. One possible explanation is teams are often faced with more skilled opponents during the post-season phase, which may cause some teams to sustain greater ELs during post-season training in preparation for these competitions. Further, the time between the conclusion of the in-season phase and the first post-season match may differ between leagues and levels of play, which may preclude teams from implementing optimal tapering strategies. In the current study, athletes trained on three out of the four days between the final in-season and first post-season matches, with only one day off. Post-season tournament structure and match frequency may also influence the EL loads for various teams. Eight days separated the first and second post-season matches in the current study, possibly contributing to the increased workloads observed during this period. Nevertheless, this observation is novel and further investigation is warranted into the variance of ELs across season phases to optimize periodization schemes and match-play outcomes.

Of note, when training sessions were stratified based upon RPE (high: ≥ 6; low: ≤ 5), differences in ELs (total distance, PL, accelerations, and sprint distance) were evident. These findings are in alignment with prior research in NCAA DI women soccer players, signifying RPE is acutely sensitive to the changing magnitude of EL parameters across multiple levels, which supports the well-documented relationship between internal (e.g., RPE) and external (e.g., GPS) workload metrics [6, 14, 16, 21, 24] and further highlights the utility of RPE. Similarly, the current study observed differences in same-day sprint distance, acceleration, and PL/min when pre-training quadricep and hamstring soreness were stratified as high (≥ 3) or low (≤ 2). It appears intensity metrics are attenuated when athletes report high pre-session perceived soreness, pointing to the potential efficacy for coaching staffs to conduct soreness appraisals and implement an individualized approach to load-management strategies.

Training sRPE-load was positively correlated with session duration, total distance, PL, acceleration efforts, and top speed, with duration and total distance being significant predictors of sRPE-load, accounting for 73% of the variance. These results support previous findings that total distance is most strongly associated with IL [16, 35], pointing to the sensitivity of RPE to modulations in volume-load parameters. The strong relationship between total distance and sRPE-load has been reported in NCAA DI and DII men and women soccer players [6, 21, 36], professional men soccer players [17, 37], and youth soccer players [18, 35]. Further, similar relationships between PL and sRPE-load have been observed in professional [19] and semi-professional [17] men soccer players, and NCAA DI women soccer players [6]. Of the aforementioned studies examining correlations within NCAA soccer players, only two [6, 36] demonstrated strong relationships between EL and sRPE throughout an entire season, meriting further investigation with season-long data. The very strong relationship between sRPE-load and volume metrics shows the utility of sRPE-load as a valid and reliable method of workload measurement. However, as sRPE-load is dependent upon total session duration, the relationship between volume-based parameters (i.e., total distance, PL) and sRPE-load, may be a reflection of session duration.

Previous investigations have demonstrated associations between changes in self-reported wellness measures and workloads during seasonal phases [21, 23] and entire soccer seasons [20, 22]. The current study uniquely examined these associations across a full NCAA DIII collegiate season (12 weeks) and discovered pre-training quadricep soreness was weakly correlated with same-day total distance, sprint distance, power plays, sprint efforts, accelerations, PL, and PL/min; and trivially correlated with top speed. Similarly, pre-training hamstring soreness was weakly correlated with sprint distance, power plays, sprint efforts, accelerations, and PL/min; and trivially correlated with top speed, and PL. Current results do not reflect the magnitude of correlation demonstrated in previous investigations that have reported a moderate to large negative correlation between same-day muscle soreness and sRPE-load [22], PL [23], total distance [23], and sprint distance [23] in professional men soccer players. However, data from Clemente (2018) were collected from small-sided games during the final two weeks of the season, which mirrors neither the season-long data collection period nor the diverse tactical structures and physiological demands of sessions as represented in the current study. Further, preseason morning soreness was found to negatively predict same-day total distance, PL, HSR, and sRPE-load in NCAA DI men soccer players [21]. However, the aforementioned studies employed a 7-point Likert scale assessing total body soreness, whereas the current study assessed specific muscle group (quadricep and hamstring) soreness, which may be partly responsible for the disparate outcomes. In addition, athletes in the current study submitted their soreness scales during the early afternoon period just prior to training, as opposed to a morning measurement. This distinction could explain the weak relationships observed between muscle soreness and sRPE-load, as afternoon scores may have been influenced by preceding physiotherapeutic treatment sessions and general movement/activity throughout the day. Thus, equivocal results appear to exist between perceived muscle soreness and same-day workload parameters across competition levels and durations of data collection periods, meriting further research into these relationships using a standardized approach to assessing soreness.

The current study investigated the relationship between EL, IL, and next-day soreness. In particular, sRPE-load, session duration, total distance, power plays, top speed, PL, and PL/min were weakly correlated with next-day quadricep soreness, while accelerations were trivially correlated with next-day quadricep soreness. Further,

sRPE-load, session duration, total distance, power plays, top speed, PL, and PL/min were weakly correlated with next-day hamstring soreness. Taken together, these findings appear to support minimal associations between several workload metrics and next-day soreness. Previously, EL measures have been found to predict next-day perceptions of soreness and fatigue, respectively, including total distance, PL, HSR, and sRPE-load [21], while, IL measures (i.e., RPE) have been shown to demonstrate trivial to small correlations with next-day muscle status (i.e., muscle soreness) [38]. However, while wellness/soreness questionnaires – both standardized and customized versions – have been found to be valid measures of IL across a variety of populations [39, 40], challenges emerge when comparing results from different constructs and questionnaires across studies. Unlike the computation of IL via sRPE-load (i.e., RPE × session duration), which was designed for consistent implementation across studies [14, 15], the computation of IL via customized wellness questionnaires can yield variability. Specifically, the required movements, degree of contact and style of play of sports may influence the subsequent degrees of soreness experienced by athletes, which may influence the utility of certain wellness, or specifically soreness (i.e., whole-body versus muscle-specific) questionnaires. Alone, wellness constructs may be insufficient tools to quantify IL, but can play an important role in capturing the multifactorial nature of sport-induced physiological stress.

Although the first study to investigate the relationships between EL, sRPE-load, and perceived soreness throughout an entire NCAA DIII collegiate men's soccer season, the current study is not without limitations. For example, only training sRPE-load and soreness measures were collected, thus, match-day data were not included in the analysis. Further, because quadriceps and hamstrings where the only muscles assessed for soreness, the lower extremity soreness metric used in the current study may not have captured the totality of perceived muscular soreness experienced by the athletes. Also, the use of different monitoring technologies, (i.e., video analysis, LPS, etc.) poses challenges to drawing comparisons across the literature, as each system may provide propriety metrics to classify match demands or exhibit varying degrees of accuracy, which may limit the generalizability to other programs.

CONCLUSIONS

We found differences in workload measures between season phases in conjunction with differences in EL parameters when training session RPE and soreness were stratified into high and low categories. While significantly greater pre-season loads were observed compared to in-season, which supports previous results, the increased post-season loads relative to in-season is a novel finding. In accordance with previous investigations, the current study reported a very strong relationship between EL and sRPE-load, highlighting the utility of sRPE-load as a practical and affordable means of workload quantification, either alongside or in place of positional monitoring technology. Lastly, weak associations between workloads and soreness were observed. Due to conflicting results with prior research and the inherent difficulty in comparing results of wellness questionnaires across different studies and durations of data collection periods, more research is warranted into the relationship between soreness and workload and the efficacy of administering self-reported scales as primary quantifiers of IL. Nevertheless, soreness appraisals may provide coaches and practitioners with increased awareness of the cumulative physical "cost" of sport demands.

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Declaration of Interest

The authors declare no conflict of interest.

REFERENCES

1. Favero TG, White J. Periodization in college soccer. Strength Cond J. 2018; 40(3):33–44.
2. Gamble P. Periodization of training for team sports athletes. Strength Cond J. 2006; 28(5):56–66.
3. Naclerio F, Moody J, Chapman M. Applied periodization: a methodological approach. J. Hum Sport Exerc. 2013; 8(2):350–66.
4. Blumenstein B, Lidor R, Tenenbaum G. Periodization and planning of psychological preparation in elite combat sport programs: the case of judo. Int J Sports Physiol Perf. 2005; 3(1):7–25.
5. NCAA. 2021–2022 NCAA Division III Manual. Available at: http://www.ncaapublications.com. Accessed Jun 2, 2022.
6. Askow AT, Lobato AL, Arndts DJ, Jennings W, Kreutzer A, Erickson JL, Esposito PE, Oliver JM, Foster C, Jagim AR. Session rating of perceived exertion (sRPE) load and training impulse are strongly correlated to GPS-derived measures of external load in NCAA division I women's soccer athletes. J. Funct. Morphol. Kinesiol. 2021; 6(90).
7. Tummala SV, Chhabra A, Makovicka JL, Patel KA, Hartigan DE. Hip and groin injuries among collegiate male soccer players: the 10-year epidemiology, incidence, and prevention. Orthopedics. 2018; 41(6):831–36.
8. Jones CM, Griffiths PC, Mellalieu SD. Training load and fatigue marker associations with injury and illness: a systematic review of longitudinal studies. Sports Med. 2017; 47(5):943–74.
9. Mandorino M, Figueiredo AJ, Condello G, Tessitore A. The influence of maturity on recovery and perceived exertion, and its relationship with illnesses and non-contact injuries in young soccer players. Biol Sport. 2022; 39(4):839–48.
10. Bertschy M, Howard JT, Oyama S, Cheever K. Reduced injury prevalence in soccer athletes following GPS guided acclimatization. Int J Exerc Sci. 2021; 14(7):1070–77.
11. Jeong T-S, Reilly T, Morton J, Bae S-W, Drust B. Quantification of the physiological loading of one week of "pre-season" and one week of "in-season" training in professional soccer players. J Sports Sci. 2011; 29(11):1161–66.
12. Curtis RM, Huggins RA, Benjamin CL, Sekiguchi Y, Adams WM, Arent SM, Jain R, Miller SJ, Walker AJ, Casa DJ. Contextual factors influencing external and internal training loads in collegiate

men's soccer. J Strength Cond Res. 2020; 34(2):374–81.
13. Marqués-Jiménez D, Calleja-González J, Arratibel I, Delextrat A, Terrados N. Fatigue and recovery in soccer: evidence and challenges. Open Sports Sci J. 2017; 10(1):52–70.
14. Impellizzeri FM, Marcora SM, Coutts AJ. Internal and external training load: 15 years on. Int J Sports Physiol Perform. 2019; 14(2):270–73.
15. Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, Doleshal P, Dodge C. A new approach to monitoring exercise training. J Strength Cond Res. 2001; 15(1):109–15.
16. McLaren SJ, Macpherson TW, Coutts AJ, Hurst C, Spears IR, Weston M. The relationships between internal and external measures of training load and intensity in team sports: a meta-analysis. Sports Med. 2018; 48(3):641–58.
17. Casamichana D, Castellano J, Calleja-Gonzalez J, San Román J, Castagna C. Relationship between indicators of training load in soccer players. J Strength Cond Res. 2013; 27(2):369–74.
18. Marynowicz J, Lango M, Horna D, Kikut K, Andrzejewski M. Predicting ratings of perceived exertion in youth soccer using decision tree models. Biol Sport. 2022; 39(2):245–52.
19. Scott D, Norris D, Lovell R. Dose–response relationship between external load and wellness in elite women's soccer matches: do customized velocity thresholds add value? Int. J Sports Physiol Perform. 2020; 15(9):1245–51.
20. Draper G, Wright M, Chesterton P, Atkinson G. The tracking of internal and external training loads with next-day player-reported fatigue at different times of the season in elite soccer players. Int J Sports Sci Coach. 2021; 16(3):793–803.
21. Fields JB, Lameira DM, Short JL, Merrigan JM, Gallo S, White JB, Jones MT. Relationship between external load and self-reported wellness measures across a men's collegiate soccer preseason. J Strength Cond Res. 2021; 35(5):1182–86.
22. Moalla W, Fessi MS, Farhat F, Nouira S, Wong DP, Dupont G. Relationship between daily training load and psychometric status of professional soccer players. Res Sports Med. 2016; 24(4):387–94.
23. Clemente FM. Associations between wellness and internal and external load variables in two intermittent small-sided soccer games. Physiol Behav. 2018; 197:9–14.
24. McFadden BA, Walker AJ, Bozzini BN, Sanders DJ, Arent SM. Comparison of internal and external training loads in male and female collegiate soccer players during practices vs. games. J Strength Cond Res. 2020; 34(4):969–74.
25. Bozzini BN, McFadden BA, Walker AJ, Arent SM. Varying demands and quality of play between in-conference and out-of-conference games in division I collegiate women's soccer. J Strength Cond Res. 2020; 34(12):3364–68.
26. Cummins C, Orr R, O'Connor H, West C. Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. Sports Med. 2013; 43(10):1025–42.
27. Beato M, Bartolini D, Ghia G, Zamparo P. Accuracy of a 10 Hz GPS uit in measuring shuttle velocity performed at different speeds and distances (5–20 M). J Hum Kinet. 2016; 54:15–22.
28. Kristensen NS, Hertel E, Skadhauge CH, Kronborg SH, Petersen KK, McPhee ME. Psychophysical predictors of experimental muscle pain intensity following fatiguing calf exercise. PLoS ONE. 2021; 16(7).
29. Vickers AJ. Time course of muscle soreness following different types of exercise. BMC Musculoskelet Disord. 2001; 2(5).
30. Shergill AS, Twist C, Highton J. Importance of GNSS data quality assessment with novel control criteria in professional soccer match-play. Int J Perform. 2021; 21(5):820–30.
31. Chen MJ, Fan X, Moe ST. Criterion-related validity of the Borg ratings of perceived exertion scale in healthy individuals: a meta-analysis. J Sports Sci. 2002; 20(11):873–99.
32. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front Psychol. 2013; 4(863).
33. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1):3–13.
34. Fields JB, Merigan JM, Gallo S, White JB, Jones MT. External and internal load measures during preseason training in men collegiate soccer athletes. J Strength Cond Res. 2021; 35(9):2572–78.
35. Marynowicz J, Kikut K, Lango M, Horna D, Andrzejewski M. Relationship between the session-RPE and external measures of training load in youth soccer training. J Strength Cond Res. 2020; 34(10):2800–04.
36. A. Pustina A, Sato K, Liu C, A. Kavanaugh A, L. Sams M, Liu J, D. Uptmore K, H. Stone M. Establishing a duration standard for the calculation of session rating of perceived exertion in NCAA division I men's soccer. J Trainology. 2017; 6(1):26–30.
37. Scott BR, Lockie RG, Knight TJ, Clark AC, Janse de Jonge XAK. A comparison of methods to quantify the in-season training load of professional soccer players. Int J Sports Physiol Perform. 2013; 8(2):195–202.
38. Lechner S, Ammar A, Boukhris O, Trabelsi K, M Glenn J, Schwarz J, Hammouda O, Zmijewski P, Chtourou H, Driss T, Hoekelmann A. Monitoring training load in youth soccer players: effects of a six-week preparatory training program and the associations between external and internal loads. Biol Sport. 2023; 40(1):63–75.
39. Borresen J, Lambert MI. The quantification of training load, the training response and the effect on performance. Sports Med. 2009; 39(9):779–95.
40. Buchheit M. Monitoring training status with HR measures: do all roads lead to Rome? Front Physiol. 2014; 5(73).

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Eccentric overload differences between loads and training variables on flywheel training

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ABSTRACT: There is considerable debate about the existence of a real eccentric overload in flywheel exercises. This study aimed to analyse the differences in concentric: eccentric mechanical output ratios between different loads and variables in the flywheel squat exercise. Twenty physically active men (22.9 ± 2.2 years, height: 1.8 ± 0.1 m, weight: 79.6 ± 8.2 kg) performed a loading test using five moments of inertia. Angular speed was measured using a rotary encoder, while the vertical force was measured using force plates. For each variable (angular speed, angular acceleration, power, vertical force, and torque), mean and peak values were calculated for concentric and eccentric phases to allow comparisons across the loads. We tested the possible differences in Load × Phase (concentric and eccentric) and Load × Variable. The level of significance was established as $p < 0.05$. A significant Load × Phase interaction was found in mean angular speed, peak vertical force, peak angular acceleration, peak power and peak torque. Higher eccentric overload values were observed with speed-derived variables (angular speed, angular acceleration and power). In conclusion, speed-derived peak variables and lower loads are more likely to show an eccentric overload and can be used to monitor responses to flywheel training.

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INTRODUCTION

Athletes must move in all directions and with frequent changes of direction to meet the performance needs of their sport [1]. These movements are carried out at different speeds and may require high-intensity accelerations and decelerations, which can impact physical loading and fitness [2]. There are different training equipment to improve acceleration or deceleration abilities; for instance, traditional resistance training can improve acceleration ability (i.e., the initial part of a sprinting action) [3]. In contrast, flywheel resistance training devices have mostly been used in training programs to improve performance during the eccentric phase of the movement [4]. With these devices, the athlete first pulls a rope or a strap at the desired (i.e., maximal) intensity, thus spinning a flywheel disk during the concentric phase. Then the rope or strap recoils around the rotary shaft during the eccentric phase, where the athlete is instructed to decelerate the kinetic energy produced during the concentric phase [5].

During flywheel resistance training, practitioners try to achieve a so-called eccentric overload with their athletes, which can be explained as the production of a greater mechanical output during the eccentric phase compared to the concentric one [6, 7]. In a recent meta-analysis, Muñoz-López et al. [8] showed that most of the research that used flywheel resistance training with the purpose to achieve an EO neither measured it nor achieved that. EO can be easily measured using the eccentric:concentric ratio (E:C) [9]. E:C is a parameter used to quantify the application of kinetic variables (e.g., force) during the eccentric phase of a movement in comparison to the concentric phase [6]. Therefore, if the kinetic energy measured is higher during the eccentric phase than the concentric phase, an E:C would be greater than 1 and EO would be achieved [6]. However, a known problem related to EO during flywheel resistance training is its accurate quantification and its reliability [7, 10]. The absence of an EO during flywheel resistance training can be related to the following reasons: 1) the participant is not able to decelerate the kinetic energy towards the end of the eccentric phase, 2) low experience or poor familiarization of the participants with flywheel resistance training [5], 3) the proper selection of the mechanical output used to monitor it [8], or 4) the external load used [11, 12].

An effective selection of the inertial load may be critical to induce EO [13]. Some authors showed significant differences in speed [14–16], power [11, 15, 17], angular acceleration [14, 17], or vertical force [16, 17] between different moments of inertia in flywheel squat exercises. Some authors reported that the lower the moment of inertia, the higher the speed [11, 14, 16]. For the leg

extension exercise, Martinez-Aranda and Fernandez-Gonzalo [12] showed that EO is more likely to be produced with a moment of inertia of 0.0375 kg·m^2. However, they calculated the EO only using peak force, while Muñoz-López et al. [8] showed an influence of the variable selected when the occurrence of EO is assessed. Sabido et al. [11] showed that a lower moment of inertia (i.e., 0.025 kg·m^2) resulted in higher concentric peak power outputs, whereas higher inertial loads (i.e., 0.075 kg·m^2) were more likely to produce higher eccentric peak power outputs. However, other researchers reported that a generalization about the use of moments of inertia for all exercises is not possible because mechanical outputs are very dependent on the exercise selected, the characteristics of the athletes and their previous familiarization with the devices [7]. Therefore, it is impossible to state that lower moments of inertia are more suitable for EO production because several factors can affect kinetic and kinematic parameters in both concentric and eccentric phases [7].

A common approach to understanding the neuromuscular profile for a given exercise is to study the force-velocity profile [18]. Typically, the force-velocity profile is calculated using the force and speed of the concentric phase using several external loads in a progressive loading test. Although it has been widely studied with stack machines and free weights (here categorized as traditional resistance equipment), to our knowledge, only a few studies have analyzed it using flywheel resistance training devices [18, 19], reporting both concentric and eccentric outputs. Flywheel devices are equipped with a rotary encoder instead of a linear encoder (used with traditional resistance equipment), which can help to understand better the mechanical rotation demands of both concentric and eccentric phases. To the best of our knowledge, no study has yet investigated the force-velocity relationships using angular variables (i.e., angular speed or torque), nor have investigated those relationships during the eccentric phase of the exercise.

Considering the increasing interest in implementing flywheel resistance training in strength and conditioning programs, especially due to the opportunities to increase muscle activation [20], acute performance, and chronic adaptations [21], it is important to know how to monitor EO over a range of moments of inertia effectively. Therefore, this study aimed to determine the differences in EO between the moments of inertia and the mechanical outputs used in a flywheel squat, which is one of the preferential exercises implemented in those programs. A secondary objective was to compare the force-velocity profile of the concentric and eccentric phases of this exercise. We hypothesized that, first, the kinetic and kinematic outputs will vary across the loads used, and second, the EO level is variable- and load-dependent.

MATERIALS AND METHODS

Experimental Approach to the Problem

This study used a randomized observational design to measure the mechanical output during the concentric and the eccentric phase of the flywheel squat exercise using different loads. Subjects performed a randomized loading test using five different moments of inertia (e.g., *loads*). Before testing, subjects conducted two familiarization sessions across all the loads used during the test.

Subjects

A total of 25 physically active males participated in this study (age: 22.9 ± 2.2 years, height: 1.8 ± 0.1 m, weight: 79.6 ± 8.2 kg). The main inclusion criteria were having a minimum of two years of experience in the squat exercise and having participated for a minimum of 6 months in weekly resistance training programs involving the lower body muscles. At the beginning of the familiarization sessions, none of the subjects had experience executing flywheel squat exercise. We also instructed the subjects not to change their daily nutritional habits or consume any ergogenic aid at least 48 h before testing execution. The minimum sample size required for the statistical test used (two-way repeated-measures ANOVA), considering 80% statistical power, an alpha error of 0.05, and a moderate f effect size of 0.3, was 16 subjects (Power = 0.84). The study protocol followed the guidelines of the Declaration of Helsinki and was approved by the local ethics committee.

Intervention

Prior to the execution of the tests, the subjects warmed up for 10 minutes. The warm-up consisted of 5 minutes of cycling on an electronic ergometer at a self-selected submaximal pace, followed by mobilization exercises for the ankle, knee, hip, and trunk joints for 5 minutes. Furthermore, the subjects ended the warm-up with five countermovement jumps and six submaximal repetitions of the harness squat exercise with the lowest load used in the tests.

The squat exercise was performed on a cylindrical shaft flywheel resistance device (kBox 3, Exxentric, AB Bromma, Sweden). The loading test consisted of 5 sets (one set for each load in random order), with 5 minutes of rest interspersing the sets. The loads used for each set were 0.025 kg·m^2, 0.050 kg·m^2, 0.075 kg·m^2, 0.100 kg·m^2, 0.125 kg·m^2. The radius width of the cylinder was 0.025 m. Two submaximal repetitions were used to accelerate the flywheel disk initially. From the third repetition (the first for further analyses), subjects had to accelerate the flywheel disk at maximum voluntary effort, pulling until the end of the concentric phase. We instructed the participants to decelerate as hard as possible the spinning flywheel disk at the end during the eccentric phase. Only subjects who committed to completing the five loads were considered (n = 20); therefore, 5 subjects were excluded.

Data were recorded using a rotary encoder (EMS22Q, Bourns, Riverside, CA, USA) connected to the flywheel shaft and a prototype multichannel acquisition system (SmartCoach MultiChannel, SmartCoach Technologies Inc., Pleasanton, CA, USA), with specific computer software (SmartPlot V4.7.0, SmartCoach Technologies Inc., Pleasanton, CA, USA). We calculated the mean and peak values for the speed, acceleration, power and torque variables from the raw speed captured for each concentric and eccentric phase movement.

In addition, we recorded the vertical ground reaction force using two force platforms (SmartCoach Europe AB, Stockholm, Sweden), synchronized and connected to the SmartCoach Multichannel. From the force platforms, we calculated the mean and peak force. The sampling rate was set at 100 Hz for both capture systems. Finally, we calculated the E:C value as the eccentric phase value divided by the concentric phase value. The average from the three fastest repetitions of each set (i.e., with the highest concentric speed) was considered for further analysis. Further information on data acquisition and computation is published elsewhere [17].

Statistics

Data are shown as mean ± standard deviation (SD). Data normality was checked using the Shapiro-Wilk test. The sphericity assumption was tested using Mauchly's sphericity test and corrected using the Greenhouse-Geisser correction in the case of being positive. We used a two-way ANOVA repeated measures test with two within-subjects factors (Load (i.e., moments of inertia) × Phase (i.e., concentric or eccentric)). In addition, we tested the differences between loads in the E:C using a two-way ANOVA repeated measures test with two within-subjects factors (Load × Variable). When a significant interaction was found in both cases, we performed a post hoc analysis using the Bonferroni correction. Alpha level to determine significant differences was 5%, therefore $p = 0.05$. We used the partial eta squared (η^2_p) to measure the effect size of the differences for the interactions such as 0.01–0.059 (small), 0.06–0.139 (medium), and > 0.14 (large). We used the Cohen's *d* to measure the effect size of the post-hoc differences as follows: < 0.20 (trivial), 0.2–0.59 (small), 0.6–1.19 (moderate), 1.2–2.0 (large), and > 2.0 (very large)[22]. Finally, we calculated and plotted the mean ± SD of force, torque, power, and velocity to represent different mechanical relationships for each movement phase. We used the JASP software for Windows (JASP Team, Version 0.16) for all statistical tests.

RESULTS

Concentric and eccentric outputs

The mean and peak values for each variable during the concentric and eccentric phases are shown in Table 1 and Table 2, respectively.

From the mean variables, only the Mean Angular Speed ($p < 0.001$, $\eta^2_p = 0.45$ – *large*) showed a significant Load × Phase interaction. In addition, the eccentric Mean Angular Speed was significantly higher than concentric Mean Angular Speed for 0.050 kg·m^2 ($p < 0.001$, $d = 0.54$ – *moderate*), 0.075 kg·m^2 ($p < 0.05$, $d = 0.48$ – *small*), 0.100 kg·m^2 ($p < 0.001$, $d = 0.72$ – *moderate*), and 0.125 kg·m^2 ($p < 0.001$, $d = 0.60$ – *moderate*).

The Peak Vertical Force ($p < 0.001$, $\eta^2_p = 0.44$ – *large*), the Peak Angular Acceleration ($p < 0.001$, $\eta^2_p = 0.35$ – *large*), the Peak Power ($p < 0.001$, $\eta^2_p = 0.23$ – *large*), and the Peak Torque ($p = 0.009$, $\eta^2_p = 0.16$ – *large*) showed a significant Load × Phase interaction. In addition, the Peak Vertical Force concentric outputs were higher than the eccentric outputs at 0.075 kg·m^2 ($p < 0.001$, $d = 0.70$ – *moderate*), 0.100 kg·m^2 ($p < 0.001$, $d = 1.08$ – *large*), and 0.125 kg·m^2 ($p < 0.001$, $d = 1.23$ – *large*). For the Peak Angular Acceleration, eccentric outputs were higher than concentric outputs for 0.025 kg·m^2 ($p < 0.001$, $d = 1.44$ – *large*), 0.050 kg·m^2 ($p < 0.001$, $d = 1.68$ – *large*), 0.075 kg·m^2 ($p < 0.001$, $d = 0.99$ – *large*), and 0.100 kg·m^2 ($p < 0.05$, $d = 1.02$ – *large*). For the Peak Power, the eccentric outputs were higher than concentric outputs for 0.025 kg·m^2 ($p < 0.001$, $d = 0.76$ – *moderate*).

TABLE 1. Descriptive mean variables and differences for Load, Phase, and Load × Phase. CON = concentric phase. ECC = eccentric phase.

Variable	Load (kg·m^2)										Differences		
	0.025		0.050		0.075		0.100		0.125		Load	Phase	Load × Phase
	CON	ECC	CON	ECC	CON	ECC	CON	ECC	CON	ECC			
Angular speed (rad/s)	99.6 ± 14.4	96.7 ± 10.9	75.5 ± 8.0	80.3 ± 9.3	63.5 ± 7.2	67.6 ± 8.1	54.7 ± 5.8	61.1 ± 8.6	48.5 ± 5.4	53.8 ± 7.0	$p < 0.001$ $\eta^2_p = 0.93$	$p < 0.001$ $\eta^2_p = 0.62$	$p < 0.001$ $\eta^2_p = 0.45$
Angular acceleration (rad/s^2)	189.7 ± 19.0	209.0 ± 44.9	116.9 ± 17.8	129.4 ± 22.1	81.7 ± 14.2	92.9 ± 20.1	61.8 ± 12.9	68.9 ± 19.4	51.8 ± 9.8	57.1 ± 9.8	$p < 0.001$ $\eta^2_p = 0.55$	$p < 0.001$ $\eta^2_p = 0.57$	$p = 0.081$ $\eta^2_p = 0.13$
Power (W)	433.4 ± 86.8	469.3 ± 149.5	416.8 ± 103.7	450.6 ± 117.2	366.5 ± 93.8	407.7 ± 123.1	323.3 ± 93.8	358.1 ± 124.7	299.6 ± 86.5	327.2 ± 118.4	$p < 0.001$ $\eta^2_p = 0.58$	$p < 0.001$ $\eta^2_p = 0.47$	$p = 0.936$ $\eta^2_p = 0.01$
Torque (N·m)	4.7 ± 0.5	5.2 ± 1.1	5.8 ± 0.9	6.5 ± 1.1	6.1 ± 1.1	7.0 ± 1.5	6.2 ± 1.3	6.9 ± 2.0	6.5 ± 1.2	7.1 ± 1.9	$p < 0.001$ $\eta^2_p = 0.55$	$p < 0.001$ $\eta^2_p = 0.57$	$p = 0.695$ $\eta^2_p = 0.03$
Vertical force (N)	1483.5 ± 124.3	1371.6 ± 156.0	1582.6 ± 203.9	1452.8 ± 198.2	1604.7 ± 250.9	1458.7 ± 231.5	1583.5 ± 249.0	1434.2 ± 272.3	1618.6 ± 266.5	1454.2 ± 284.0	$p < 0.001$ $\eta^2_p = 0.19$	$p = 0.012$ $\eta^2_p = 0.93$	$p = 0.287$ $\eta^2_p = 0.06$

TABLE 2. Descriptive peak variables and differences for Load, Phase, and Load × Phase. CON = concentric phase. ECC = eccentric phase.

Variable	Load (kg·m²)										Differences		
	0.025		0.050		0.075		0.100		0.125		Load	Phase	Load X Phase
	CON	ECC	CON	ECC	CON	ECC	CON	ECC	CON	ECC			
Angular speed (rad/s)	161.3 ± 17.6	158.9 ± 18.3	129–0 ± 12.6	127.4 ± 13.7	110.0 ± 10.3	108.4 ± 11.1	96.5 ± 10.6	95.7 ± 11.5	86.7 ± 9.0	85.5 ± 9.2	$p < 0.001$ $\eta^2_p = 0.95$	$p < 0.001$ $\eta^2_p = 0.71$	$p = 0.672$ $\eta^2_p = 0.03$
Angular acceleration (rad/s²)	323.5 ± 51.2	380.2 ± 71.6	182.5 ± 25.4	248.7 ± 51.0	133.7 ± 20.6	172.8 ± 45.4	100.5 ± 14.9	125.3 ± 31.0	84.8 ± 12.6	104.6 ± 25.4	$p < 0.001$ $\eta^2_p = 0.95$	$p < 0.001$ $\eta^2_p = 0.82$	$p < 0.001$ $\eta^2_p = 0.35$
Power (W)	754.6 ± 166.5	921.1 ± 298.1	800.0 ± 184.4	835.0 ± 255.0	735.8 ± 188.9	774.3 ± 231.0	666.6 ± 207.4	696.0 ± 220.7	647.5 ± 194.6	622.2 ± 218.1	$p = 0.027$ $\eta^2_p = 0.46$	$p < 0.001$ $\eta^2_p = 0.23$	$p < 0.001$ $\eta^2_p = 0.23$
Torque (N·m)	8.1 ± 1.3	9.5 ± 1.8	9.1 ± 1.3	12.4 ± 2.6	10.0 ± 1.6	13.0 ± 3.4	10.0 ± 1.5	12.5 ± 3.1	10.6 ± 1.6	13.1 ± 3.0	$p < 0.001$ $\eta^2_p = 0.57$	$p < 0.001$ $\eta^2_p = 0.79$	$p = 0.009$ $\eta^2_p = 0.16$
Vertical force (N)	1671.7 ± 140.5	1613.6 ± 168.3	1797.7 ± 195.5	1691.8 ± 223.1	1911.7 ± 270.8	1735.5 ± 272.6	1958.1 ± 269.6	1688.7 ± 262.1	2039.2 ± 315.2	1731.8 ± 313.1	$p < 0.001$ $\eta^2_p = 0.41$	$p < 0.001$ $\eta^2_p = 0.81$	$p < 0.001$ $\eta^2_p = 0.44$

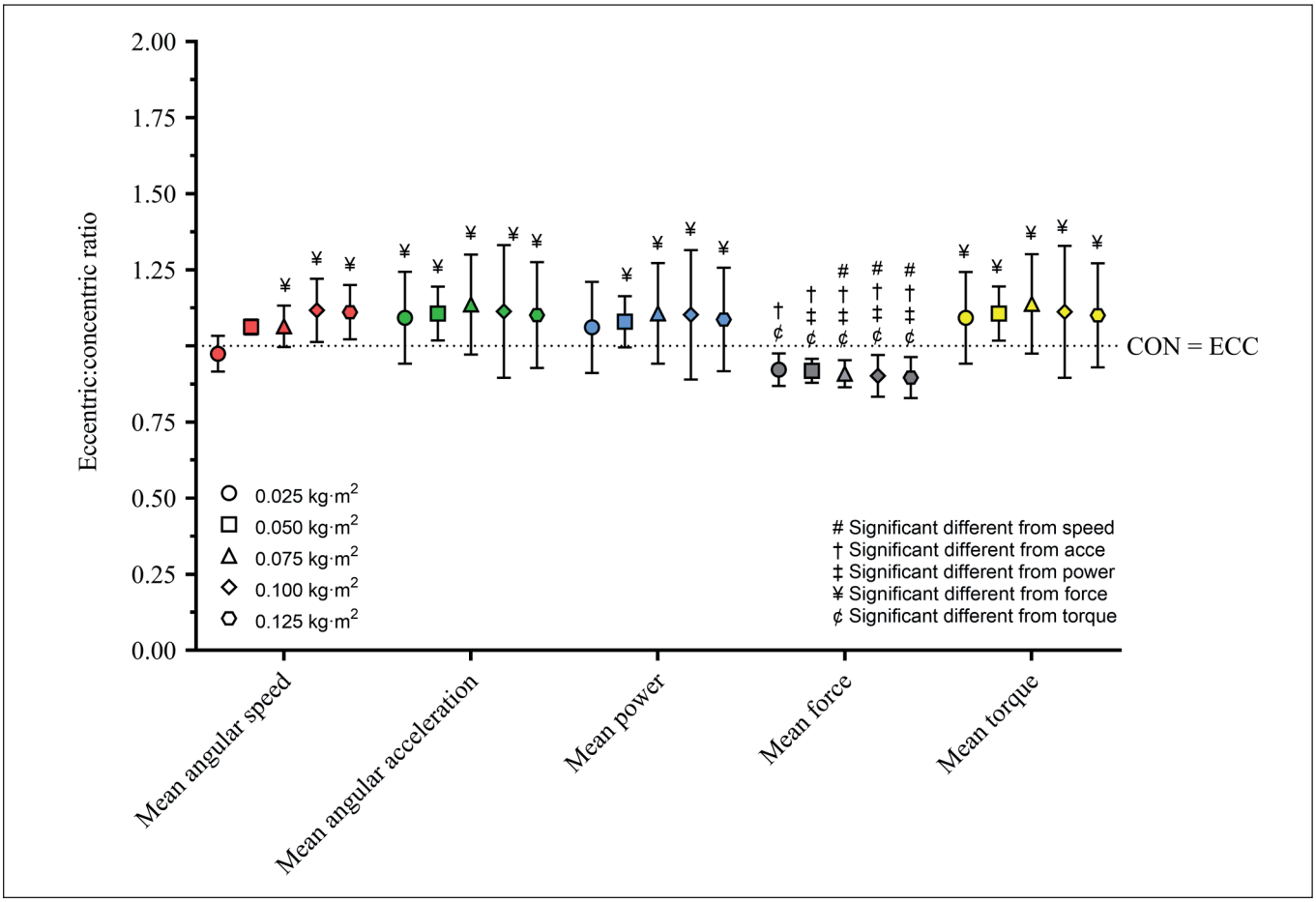


FIG. 1. Eccentric:concentric ratio for each moment of inertia and mechanical variable mean values. The dotted horizontal line represents a ratio equal to 1. Values above this line represents an eccentric overload.

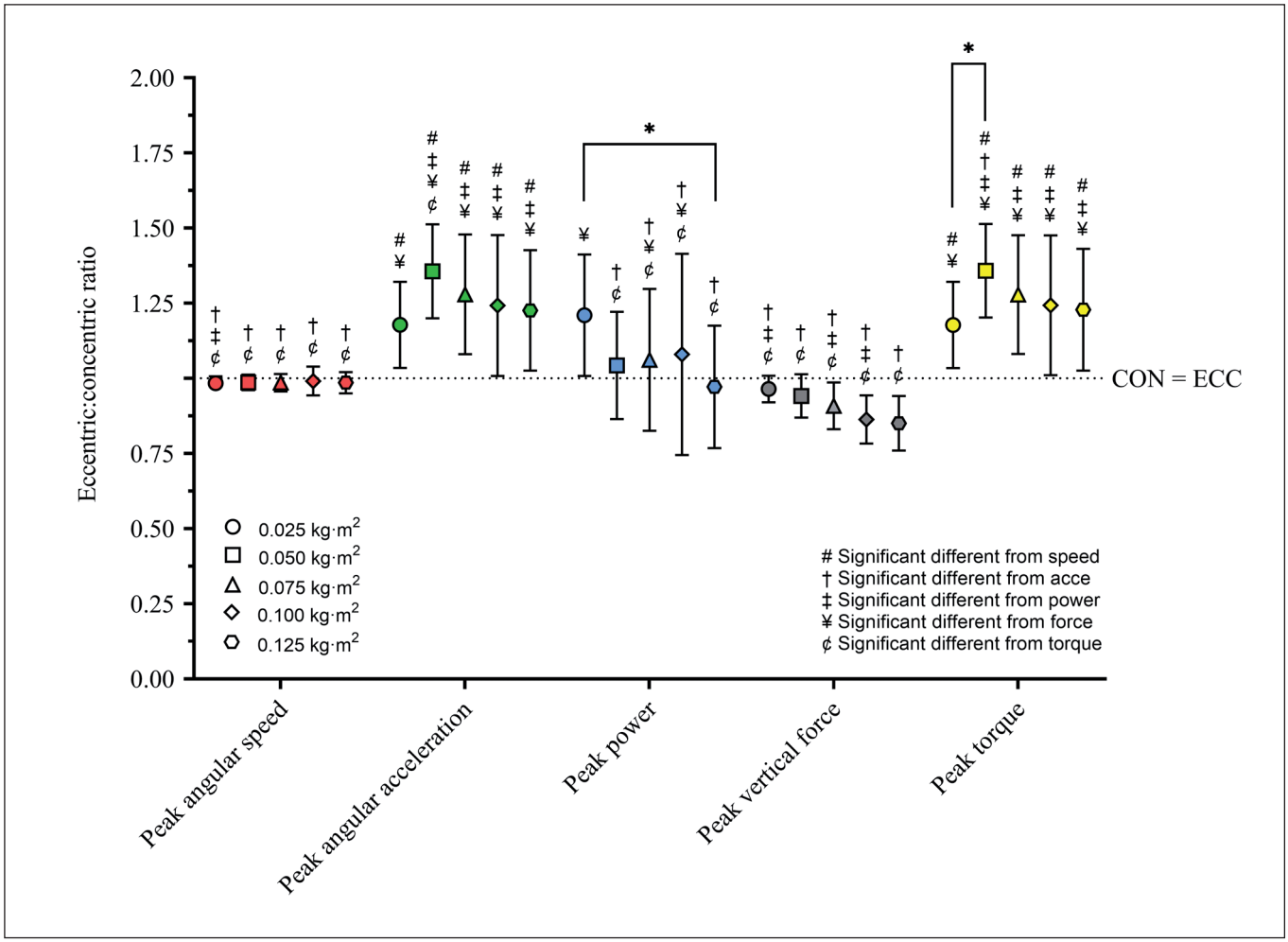


FIG. 2. Eccentric:concentric ratio for each moment of inertia and mechanical variable peak values. The dotted horizontal line represents a ratio equal to 1. Values above this line represents an eccentric overload.

Eccentric:concentric ratio between variables differences

Figures 1 and 2 show the E:C for the mean and peak variables, respectively. The mean and peak variables did not show a significant Load effect, but a Variable significant effect ($p < 0.001$) was detected. For mean variables, E:C was higher than 1 (i.e., eccentric overload) for Mean Angular Acceleration, Mean Torque, Mean Power, and Mean Angular Speed, but lower than 1 (i.e., no eccentric overload) for Mean Vertical Force. For peak variables, E:C was higher than 1 for Peak Acceleration, Peak Torque, and Peak Power, but lower than 1 for Peak Angular Speed and Peak Vertical Force. Only the peak variables showed a Load × Variable significant interaction ($p < 0.001$, $\eta^2_p = 0.26$ – *large*). In this case, Peak Power showed a significant difference between 0.025 kg·m^2 and 0.125 kg·m^2, and Peak Torque between 0.025 kg·m^2 and 0.050 kg·m^2.

Mechanical profiles

Figure 3 shows the mechanical profile between the Vertical Force-Angular Velocity, Torque-Angular Velocity, and Power-Angular Velocity for the concentric and eccentric phases. The concentric Vertical Force-Angular Velocity profile was higher than the eccentric profile for all the load ranges studied. The opposite was shown for the Torque-Angular Velocity profile. Finally, the Power-Angular Velocity profile was higher for the concentric phase, but the velocity was higher. Although the Force-Angular Velocity profile was almost linear, the Torque- and Power-Angular Velocity profiles showed a curvilinear relationship.

DISCUSSION

This study aimed to determine the differences in EO between the moments of inertia and the mechanical outputs used in a flywheel squat. A secondary objective was to compare the force-velocity profile of the concentric and eccentric phases of this exercise. In this research, we showed that 1) EO is recorded preferentially when peak variables are used instead of mean variables; 2) speed derived variables (i.e., angular speed, angular acceleration, power) are more likely to show higher eccentric than concentric outputs, compared

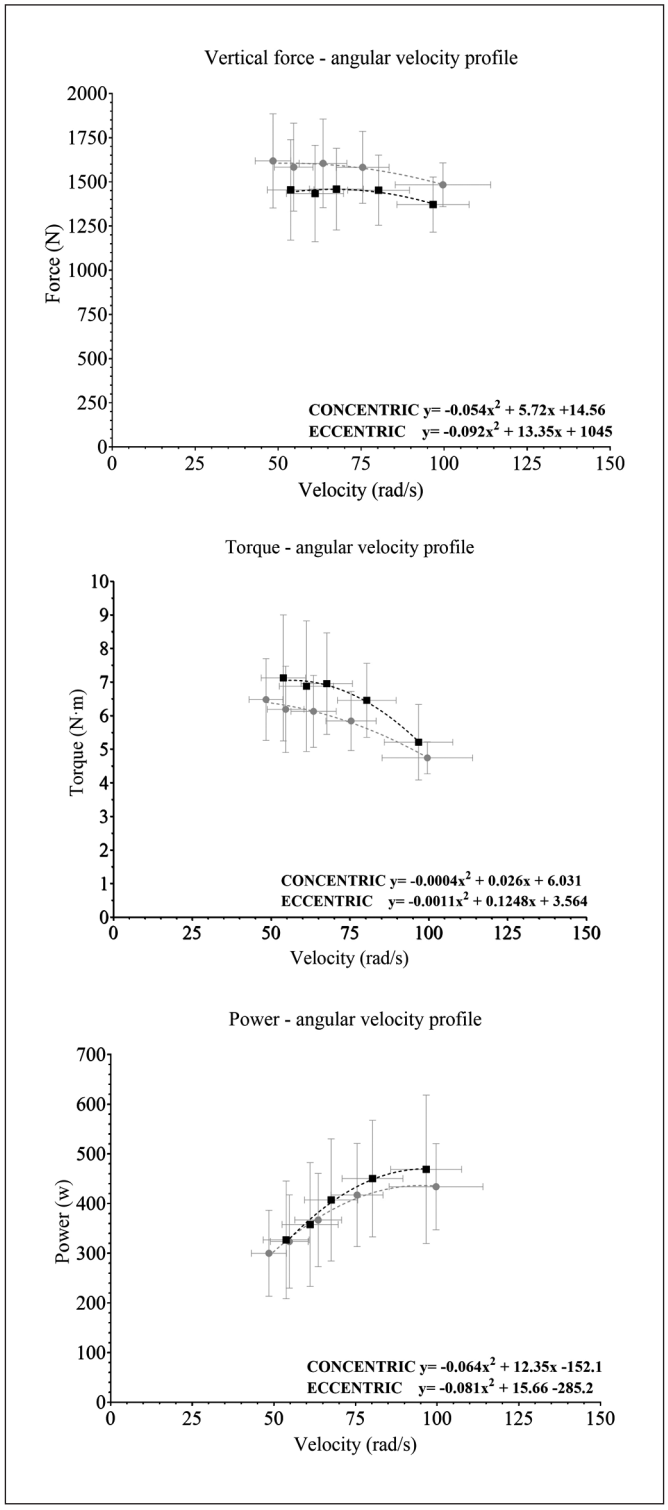


FIG. 3. Force-, Torque-, and Power-Velocity profiles for the concentric (black squares) and eccentric (grey circles) phases. The vertical and the horizontal lines represents the individuals standard deviations for each y-variable (vertical lines) and x-variable (horizontal lines).

to vertical force; 3) the E:C is a suitable parameter to measure EO, with the capability to distinguish levels of EO between loads, especially when peak power is used; 4) the torque-angular velocity profile resulted in a curvilinear relationship, with higher concentric outputs compared to eccentric outputs along the load range studied.

We showed that mean and peak angular acceleration followed the same response pattern across the loads for the first time. As with other training equipment, flywheel resistance devices showed lower peak and mean velocities at higher moments of inertia (4, 14, 23, 35). We found a similar response even though we monitored angular velocity instead of linear velocity as done in other studies (4, 14, 23, 35). In agreement with previous results (13, 25, 35), the mean and peak power decreased when the moment of inertia increased. Furthermore, the angular acceleration showed the largest differences considering Load and Phase. Similar differences were observed with angular acceleration but during leg extension exercise [14]. However, the higher the load, the higher the mean or peak torque measured. Finally, the mean vertical force did not significantly change across loads. Instead, the peak vertical force increased when higher loads were used (Table 2). Similar mean vertical forces were previously observed between different loads in flywheel exercises [16, 18]. For that reason, practitioners may benefit from using low moments of inertia to improve acceleration ability (i.e., 0.025 kg·m^2), which will maximize both concentric and eccentric power outputs, despite the fact that force or torque outputs were lower in those cases. On the other hand, if the intention is to generate high peak force values in both eccentric and concentric phases, it is advisable to use higher moments of inertia, as reported in this study.

Several studies showed the relevance of using flywheel devices in strength and conditioning programs due to their capacity to enhance the eccentric load and related adaptations [5, 23, 24]. Maroto et al. [23] showed the largest changes for Peak Power during the eccentric phase, compared to the concentric phase, after 12 weeks of training using a single-leg flywheel squat exercise. This resulted in moderate increases in tight muscle volume and large increases in maximum repetition and vertical jump performance. Furthermore, increased muscle volume (up to 10%) was observed in the quadriceps muscles during leg extension exercise using a cylindrical flywheel device after 5 weeks of training [24]. Tous-Fajardo et al. [5] introduced the concept of E:C for measuring EO, and subsequently Sabido et al. [11] showed that when E:C was calculated using peak power, the highest values were observed with moments of inertia close to 0.075 kg·m^2, using a cylindrical flywheel quarter squat exercise. In the current study, we show that whether EO is achieved or not depends on the variable and load selected (Figures 1 and 2). Mean variables showed E:C higher than 1, despite only mean angular speed showed a significant difference CON and ECC, probably explained by the high individual variance in these variables. Furthermore, we showed that the peak values showed greater differences between the loads than the mean values and the highest E:C was observed when peak angular acceleration was used to calculate it.

However, Peak Power was also sensible to detect differences between the lower and the highest load used to monitor the EO (Figure 2). Despite peak variables were more sensible to show EO, it is possible that at an individual level, mean variables could also show that. It can be explained by a lower sensibility of the peak variables to show differences in the execution technique, and as a result a higher advantage for monitoring EO using peak variables. More research is needed to confirm these results.

When E:C was calculated with Peak Vertical Force, it decreased when loads increased but it was never higher than 1, which means that no EO was achieved using this variable. To achieve high levels of EO, low inertial loads (i.e., 0.025 $kg \cdot m^2$) may also be used. However, in this research EO could also be observed up to 0.100 $kg \cdot m^2$. Hence Peak Power EO can be achieved across a broad range of loads and the choice of the load depends on the aims of the strength and conditioning program (e.g., focus on speed or force production). Curiously, Sabido et al. [11] found the Peak Power EO close to 0.075 $kg \cdot m^2$, and it might be related to the fact that they used quarter squat while we used half squat. The effect of how deep participants squat in the flywheel exercise on the occurrence of EO needs to be clarified in the future.

To monitor the neuromuscular profile of an athlete, for instance, the force-velocity profile can be used, which shows the relationship between both mechanical variables, reflecting how much force an athlete could exert for a given velocity [25–27]. Profiling exercises can help develop individualized training programs using the slope of the relationship [15] and monitor changes in performance [27]. Typically, these profiles are measured using traditional resistance exercises, where a linear relationship is shown between force and velocity [25]. However, the relationship between power and velocity is curvilinear [25]. In addition, those profiles are calculated during the concentric phase of the movement only. Our results suggest a similar profile for the flywheel squat exercise for concentric and eccentric outputs. This is explained by the very low differences observed between the vertical force loads, which agrees with previous results [16, 18]. On the contrary, greater slopes were observed when linear velocity was used instead of angular velocity in flywheel devices [19]. Although measuring flywheel device performance using the mechanics of linear momentum may help calculate a force-velocity profile slope, it is mostly unpractical and difficult to set a linear encoder, instead, a rotary encoder could be used to measure torque instead of force [7]. In fact, torque can be understood as the equivalent of force exerted on the angular momentum. Furthermore, the force cannot be easily calculated from the speed during flywheel exercises because the width of the shaft varies along with the range of motion of exercise [28]. Our results showed a curvilinear relationship between torque and angular velocity, with higher concentric outputs for all the loads measured. Finally, the power-angular velocity relationship showed that the largest power output was observed at higher velocities (Figure 3). Indeed, those values were higher for the concentric phase, but the lower the angular speed, the smallest the difference between both phases. Monitoring the power-angular velocity may help decide which load may be used for training programs when using flywheel devices to enhance acceleration and deceleration abilities, which is still an underexplored topic [29].

This study has some limitations. First, our results may only apply to squat exercises. Second, the type of flywheel shaft influences the mechanical output, regardless of the moment of inertia [30]. Lastly, this study enrolled a sample of active males participated. Therefore, these findings need to be confirmed in other populations (i.e., female) and different sport levels (e.g., professional athletes). Future research is needed to verify the reliability of these parameters in sports, to verify our findings using different exercises such as flywheel leg curl, flywheel leg press, etc, and also with other flywheel devices (i.e., conical shaft shape).

CONCLUSIONS

In conclusion we found that EO depends on the mechanical output and discrete variables analyzed (peak variables and speed derived variables showed higher EO). Lastly, the torque-angular velocity profile resulted in a curvilinear relationship, with higher concentric outputs than eccentric outputs along with the studied load range. The E:C is a suitable parameter to measure EO, with the capability to distinguish levels of EO between loads, especially when peak power parameters are used.

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Conflict of interest:

The authors declare no conflict of interest.

REFERENCES

1. de Hoyo M, Sañudo B, Carrasco L, et al. Effects of 10-week eccentric overload training on kinetic parameters during change of direction in football players. J Sports Sci. 2016; 34(14):1380–1387.
2. Beato M, Drust B. Acceleration intensity is an important contributor to the external and internal training load demands of repeated sprint exercises in soccer players. Res Sports Med. 2021; 29(1):67–76.
3. Rumpf MC, Lockie RG, Cronin JB, et al. Effect of Different Sprint Training Methods on Sprint Performance Over Various Distances: A Brief Review. J Strength Cond Res. 2016; 30(6):1767–1785.
4. Suchomel TJ, Wagle JP, Douglas J, et al. Implementing Eccentric Resistance Training—Part 1: A Brief Review of Existing Methods. J Funct Morphol Kinesiol. 2019; 4(2):38.
5. Tous-Fajardo J, Maldonado RA, Quintana JM, et al. The flywheel leg-curl machine: offering eccentric overload for

hamstring development. Int J Sports Physiol Perform. 2006; 1(3):293–298.
6. Berg HE, Tesch PA. Force and power characteristics of a resistive exercise device for use in space. Acta Astronaut. 1998; 42(1):219–230.
7. Maroto-Izquierdo S, Raya-González J, Hernández-Davó JL, et al. Load Quantification and Testing Using Flywheel Devices in Sports. Front Physiol. 2021; 12(October):1–5.
8. Muñoz-López A, Fonseca F, Ramirez-Campillo R, et al. The use of real-time monitoring during flywheel resistance training programs: how can we measure the eccentric overload? A systematic review and meta-analysis. Biol Sport. 2021;639–652.
9. Nuñez FJ, Hoyo M de, López AM, et al. Eccentric-concentric Ratio: A Key Factor for Defining Strength Training in Soccer. Int J Sports Med. 2019; 40(12):796–802.
10. Piqueras-Sanchiz F, Sabido R, Raya-González J, et al. Effects of Different Inertial Load Settings on Power Output Using a Flywheel Leg Curl Exercise and its Inter-Session Reliability. J Hum Kinet. 2020; 74(1):215–226.
11. Sabido R, Hernández-Davó JL, Pereyra-Gerber GT. Influence of different inertial loads on basic training variables during the flywheel squat exercise. Int J Sports Physiol Perform. 2018; 13(4):482–489.
12. Martinez-Aranda LMM, Fernandez-Gonzalo R. Effects of inertial setting on power, force, work, and eccentric overload during flywheel resistance exercise in women and men. J Strength Cond Res. 2017; 31(6):1653–1661.
13. Beato M, dello Iacono A. Implementing Flywheel (Isoinertial) Exercise in Strength Training: Current Evidence, Practical Recommendations, and Future Directions. Front Physiol. 2020; 11.
14. Muñoz-López A, Pozzo M, Floria P. Real-time mechanical responses to overload and fatigue using a flywheel training device. J Biomech. 2021; 121:110429.
15. McErlain-Naylor SA, Beato M. Concentric and eccentric inertia–velocity and inertia–power relationships in the flywheel squat. J Sports Sci. 2021; 39(10):1136–1143.
16. Núñez FJ, Galiano C, Muñoz-López A, et al. Is possible an eccentric overload in a rotary inertia device? Comparison of force profile in a cylinder-shaped and a cone-shaped axis devices. J Sports Sci. 2020; 38(14):1624–1628.
17. Muñoz-López A, Floria P, Sañudo B, et al. The Maximum Flywheel Load: A Novel Index to Monitor Loading Intensity of Flywheel Devices. Sensors. 2021; 1–16.
18. Spudić D, Smajla D, Šarabon N. Validity and reliability of force–velocity outcome parameters in flywheel squats. J Biomech. 2020; 107:109824.
19. Spudić D, Cvitkovič R, Šarabon N. Assessment and Evaluation of Force – Velocity Variables in Flywheel Squats: Validity and Reliability of Force Plates, A Linear Encoder Sensor, and A Rotary Encoder Sensor. Appl Sci. 2021; 11(22):10541.
20. Norrbrand L, Pozzo M, Tesch PA. Flywheel resistance training calls for greater eccentric muscle activation than weight training. Eur J Appl Physiol. 2010; 110(5):997–1005.
21. Tesch PA, Fernandez-Gonzalo R, Lundberg TR. Clinical applications of iso-inertial, eccentric-overload (YoYo^{TM}) resistance exercise. Front Physiol. 2017; 8:241.
22. Hopkins WG, Marshall SW, Batterham AM, et al. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1):3–13.
23. Maroto-Izquierdo S, Fernandez-Gonzalo R, Magdi HR, et al. Comparison of the musculoskeletal effects of different iso-inertial resistance training modalities: Flywheel vs. electric-motor. Eur J Sport Sci. 2019; 19(9):1184–1194.
24. Norrbrand L, Fluckey JD, Pozzo M, et al. Resistance training using eccentric overload induces early adaptations in skeletal muscle size. Eur J Appl Physiol. 2008; 102(3):271–281.
25. Cross MR, Brughelli M, Samozino P, et al. Methods of Power-Force-Velocity Profiling During Sprint Running: A Narrative Review. Sports Medicine. Springer International Publishing; 2017. p. 1255–1269.
26. Morin J-BB, Samozino P. Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training. Int J Sports Physiol Perform. 2016; 11(2):267.
27. Iglesias-Soler E, Fernández-Del-Olmo M, Mayo X, et al. Changes in the force-velocity mechanical profile after short resistance training programs differing in set configurations. J Appl Biomech. 2017; 33(2):144–152.
28. Sabido R, Hernández-Davó JL, García-Valverde A, et al. Influence of the Strap Rewind Height during a Conical Pulley Exercise. J Hum Kinet. 2020; 74(1):109–118.
29. Beato M, Maroto-Izquierdo S, Hernández-Davó JL, et al. Flywheel Training Periodization in Team Sports. Front Physiol. 2021; 12:1–6.
30. Muñoz-López A, Galiano C, Nuñez FJ, et al. The flywheel device shaft shape determines force and velocity profiles in the half squat exercise. J Hum Kinet. 2022; 81:15–25.

Is moderate-intensity interval training more tolerable than high-intensity interval training in adults with obesity?

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ABSTRACT: Interval training (IT) has been shown to be a time-effective alternative to traditional training programmes in the management of obesity. Nevertheless, studies comparing the effects of different IT intensities on inflammation, muscle and liver damage, and perceptual responses in people with obesity are relatively scarce. This study aimed to compare the acute effects of two different IT protocols matched by the mean load and duration on biochemical and perceptual responses in sedentary adults with obesity. Twenty-two volunteers (age = 33.40 ± 10.01 years, BMI = 38.29 ± 7.09 kg/m^2) were randomized to perform two conditions: moderate-intensity IT (MIIT) 5 × 3 min (70% of peak power output (PPO))/2 min (45%PPO) and high-intensity IT (HIIT) 8 × 1 min (90%PPO)/2 min (45%PPO). Blood samples were drawn before and after exercise for biochemical and haematological measurements. Rating of perceived exertion (RPE) was assessed during and after exercise. Perceptual pain was evaluated before, throughout and after exercise. C-reactive protein, white blood cells and neutrophils increased only after HIIT ($p < 0.001$, for all). Aspartate aminotransferase, alanine aminotransferase, creatine kinase and lactate dehydrogenase increased in both HIIT and MIIT ($p < 0.001$, for all), without any difference between sessions. HIIT induced a greater increase of blood lactate compared to MIIT ($p < 0.05$). Pain and RPE scores were higher during HIIT vs. MIIT ($p < 0.001$ and $p < 0.01$, respectively). MIIT induced fewer immune system perturbations and less muscle pain and was perceived as more tolerable compared to HIIT session. Therefore, MIIT could be used as a first step to promote body adaptations before starting a HIIT programme in sedentary people with obesity.

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Interval exercise
Muscular damage
Perceived exertion
Inflammation
Obesity

INTRODUCTION

Excess body weight increases the incidence of morbidity and mortality from a myriad of life-threatening diseases [1]. A major link between these various disorders and obesity is a state of chronic low-grade inflammation characterized by infiltration and activation of several pro-inflammatory biomarkers (e.g., interleukin 6 (IL-6), tumour necrosis factor-alpha (TNF-α) and C-reactive protein (CRP)) [1].

Regular exercise can help to lose weight and to attenuate obesity-related comorbidities [2]. Despite the beneficial effects of moderate-intensity continuous exercise (MICT), the majority of adults with obesity fail to meet these recommendations due to various barriers such as physical limitations, and lack of time and motivation [3]. There is growing evidence encouraging the application of interval training (IT) as a time-efficient alternative to MICT for health improvement in the general population [4]. IT consists of intermittent periods of relatively intense effort interrupted with periods of active or passive recovery [4]. Nevertheless, when aiming to compare the

effectiveness of IT in the management of excess body weight and its related health conditions, it has been usual to compare supra-maximal or near-maximal intensities with MICT [5], which are different not only in their intensities but also in the type of stimulus: intermittent versus continuous. Few studies have compared the chronic effects of different IT modes in the management of obesity. In this context, Naves et al. [6] reported that high-intensity IT (HIIT) and sprint IT improved anthropometric and cardiorespiratory fitness even without changes in dietary intake, yet only sprint IT reduced body weight in healthy young women. Other studies have investigated the efficacy of IT in people with obesity by comparing HIIT to moderate-intensity IT (MIIT). Alkahtani et al. [7] demonstrated a similar increase in fat oxidation and decrease in blood lactate (BLa) after both HIIT and MIIT, yet rating of perceived exertion (RPE) decreased to a greater extent following HIIT compared to MIIT. Racil et al. [8] indicated superior beneficial effects of HIIT versus MIIT on the levels of insulin, total cholesterol, and low-density lipoprotein cholesterol, without differences between the HIIT and MIIT groups for high-density lipoprotein cholesterol, insulin resistance and adiponectin. However, studies examining acute biological, metabolic and perceptual responses to different intensities of interval exercise in sedentary adults with high body mass index (BMI) are rare. To the best of the authors' knowledge, only the study of Dorneles et al. [9] has compared the acute effects of HIIT and MIIT on the inflammatory response and muscle damage in males with overweight-obesity (BMI = 31.99 ± 3.93 kg/m^2). The results showed a similar increase of white blood cells (WBC) and creatine kinase (CK) after HIIT versus MIIT, while only HIIT decreased the pro-inflammatory cytokine (i.e. IL-8) level and increased anti-inflammatory mediators (i.e. IL-6 and IL-10), indicating that HIIT was well tolerated by adults with overweight and obesity grade 1. Hence, the question that arises about the tolerance of HIIT in inactive adults having a high BMI is still unanswered. In this context, Kim et al. [10] reported a remarkable increase in muscle soreness and CK levels after a repetitive eccentric exercise in the high BMI group compared to the normal BMI group, indicating that BMI is one of the potential factors affecting muscle damage after intense exercise. Thus, this study aimed to compare the acute effects of HIIT versus MIIT on inflammation, muscle and liver damage, BLa and perceptual responses in sedentary adults with high BMI. We hypothesized that acute changes in markers of inflammation, cellular damage, BLa, perceived pain and RPE would be greater after HIIT compared to MIIT and that MIIT would be more tolerable in sedentary adults with high BMI.

MATERIALS AND METHODS

Participants

Twenty-two sedentary adults with obesity (8 men and 14 women) provided their written informed consent and completed the trial. Participants' characteristics are presented in Table 1. Participants suffering from diabetes, autoimmune diseases, infections, cardiovascular diseases, musculoskeletal impairments, or any comorbidities limiting exercise were excluded. Participants were not engaged in any physical training programmes for the last six months. All female participants were eumenorrheic with menses length between 4 and 6 days and they had not been using hormonal contraceptives during the past six months. They also cautioned against taking any supplements or drugs that could affect the immune system throughout the study. This study was approved by the local Ethics Committee for the Protection of Persons and was conducted in compliance with the ethical guidelines of the Declaration of Helsinki for human experimentation.

TABLE 1. Participants' characteristics.

Characteristic	Mean ± SD
Age (years)	33.40 ± 10.01
Height (cm)	168.95 ± 8.03
Weight (kg)	108.30 ± 24.02
Body mass index (kg/m^2)	38.29 ± 7.09
Body fat (%)	42.01 ± 10.71
Body fat (kg)	46.79 ± 20.43
Fat-free mass (kg)	61.21 ± 10.05
Basal metabolism (kcal)	1909.45 ± 292.36
Waist circumference (cm)	111.88 ± 16.59
Hip circumference (cm)	128.54 ± 17.75
Waist-to-hip ratio	0.87 ± 0.89
Peak power output (W)	138.41 ± 42.91
VO_2 max (L·min^{-1})	2.88 ± 1.09
VO_2 max (mL·kg^{-1}·min^{-1})	26.58 ± 2.11
Resting Heart rate (bpm)	86.12 ± 9.07
Diastolic blood pressure (mmHg)	80.55 ± 11.47
Systolic blood pressure (mmHg)	120.41 ± 12.27

Study design

Participants attended the rehabilitation unit on five occasions, where all assessments and exercise sessions took place. All testing sessions were performed between 7:00 and 10:00 a.m. after an overnight fast. Participants were instructed to abstain from any strenuous exercise for 72 h before all testing sessions and to replicate their food intake as closely as possible on the day before the exercise session. At the first visit, anthropometric measurements were assessed and the maximal graded exercise test was done. During the second and the third visit, two familiarization sessions were performed to familiarize the participants with HIIT and MIIT exercises. During the fourth and fifth visits, patients were randomly allocated to perform a HIIT or MIIT session. Free online software was used to randomize and counterbalance the order of the testing sessions. A seven-day washout period was applied between MIIT and HIIT sessions. The maximal graded exercise test, HIIT and MIIT were all performed using an electromagnetic ergo-cycle (Ergoselect 100, Ergoline, Germany).

Maximal graded exercise test

The test started at 30 W with a progressive increase of 15 W/min [11]. Participants continued cycling until volitional exhaustion and/or attaining at least four of the following criteria: (a) RPE > 9; (b) heart rate > 90% of maximal heart rate; (c) respiratory exchange ratio ≥ 1.15; (d) inability to maintain a cycling cadence between 60 and 70 rpm; (e) VO_2 steady state [12]. After reaching their maximum, a 3-min cool-down period at 0 W was applied. Blood pressure was measured every 2 min with a manual sphygmomanometer. Heart electrographic activity was monitored continuously using a 12-lead electrocardiogram. RPE was assessed at every stage with the 0–10 Borg scale [13]. Gas exchange was measured throughout the test using a gas analyser (Metasys TR-B, Brainware, France). The VO_2 max was determined as the highest attained VO_2 over the last 15 s of the test. The power of the last completed stage was considered as the peak power output (PPO).

IT protocols

In both sessions, a 3-minute warm-up and cool-down of unloaded cycling were performed. The HIIT protocol consisted of 8 bouts of 1 min (90%PPO) alternated with 2 min of active recovery (45%PPO). The MIIT session involved 5 bouts of 3 min (70%PPO) interspersed with 2 min of active recovery (45%PPO). For the same participant, HIIT and MIIT protocols were matched by the mean load (P_{mean}) and duration (≈24 min). P_{mean} was calculated using the formula of Tschakert and Hofmann [14]:

$$P_{mean} = (P_{peak} \times T_{peak} + P_{recovery} \times T_{recovery}) / (T_{peak} + T_{recovery})$$

where P_{peak}, T_{peak}, $P_{recovery}$ and $T_{recovery}$ are the peak workload intensity, the peak workload duration, the recovery load and the recovery duration, respectively (Table 2).

TABLE 2. Characteristics of high-intensity interval training (HIIT) versus moderate-intensity continuous exercise (MIIT).

	HIIT	MIIT
P_{peak} (%PPO)	90	70
T_{peak} (min)	1	3
$P_{recovery}$ (%PPO)	45	45
$T_{recovery}$ (min)	2	2
Sets	8	5
Total duration (min)	24	24
Females' P_{mean} (W)	70.05	70.04
Males' P_{mean} (W)	105.83	105.85
Females and males' P_{mean} (W)	83.06	83.06

Abbreviations: HIIT, high intensity interval training; MIIT, moderate intensity interval training; PPO, peak power output; P_{peak}, peak workload intensity; T_{peak}, peak workload duration; $P_{recovery}$, recovery load; $T_{recovery}$, recovery duration; P_{mean}, mean load.

Anthropometric measurements and body composition

Height was measured to the nearest 0.5 cm using a wall-mounted stadiometer. A non-elastic tape was used to measure waist circumference (WC) and hip circumference (HC) according to the World Health Organization guidelines [15]. Waist-to-hip ratio was defined as WC divided by HC. Weight and body composition were measured using a bioelectrical impedance scale (Tanita BC-418, Tokyo, Japan).

Blood sampling and analysis

Blood samples (8 ml) were drawn pre-exercise and 3–5 min after exercise cessation from the forearm vein in a sitting position. These samples were divided into three distinct blood collection tubes. The first EDTA tube was used to determine WBC, neutrophils, lymphocytes

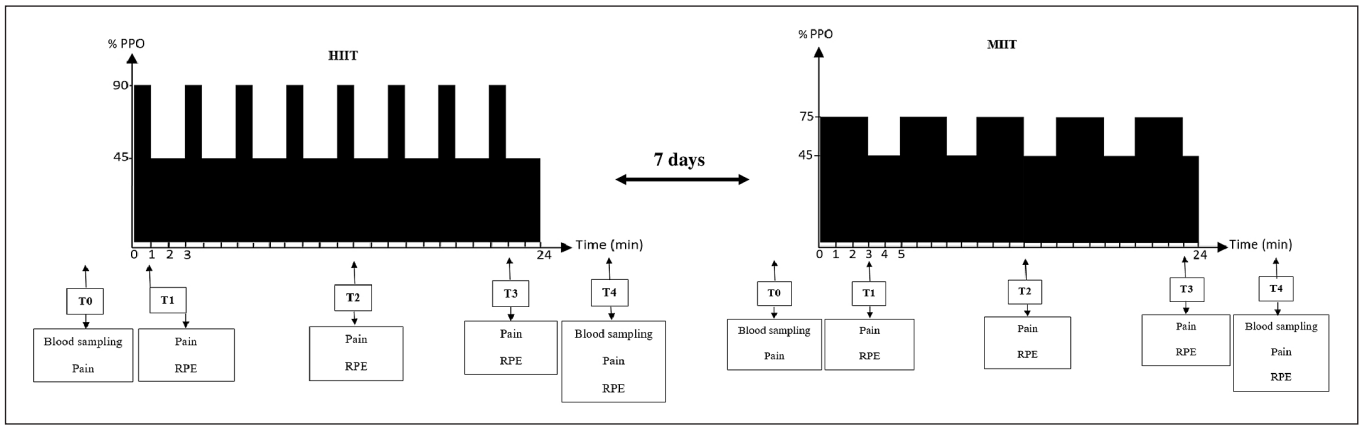


FIG. 1. Simplified study design. HIIT, high-intensity interval training; MIIT, moderate-intensity interval training, T0, pre-exercise; T1, after the first bout; T2, at the middle of the session; T3, after the last bout; T4, 3 min post-exercise; RPE, rating of perceived exertion; PPO, peak power output.

and monocytes using a multichannel automated blood cell analyser: Beckman Coulter Gen system-2 (Coulter T540). The second lithium heparin tube was used for aspartate aminotransferase (AST), alanine aminotransferase (ALT), CK, lactate dehydrogenase (LDH), and CRP analysis. The third sodium fluoride/potassium oxalate tube was used to determine BLa concentrations. Biochemical measurements were done through the Roche Cobas 6000 (c501) analyser. All specimens were placed in an ice bath to be centrifugated at 2500 r/min (× g) at 4°C for 10 min. Aliquots of the resulting plasma were stored at -80°C until analysed. To eliminate inter-assay variance, all samples were analysed in the same assay run. All assays were carried out in duplicate in the same laboratory with simultaneous use of a control serum from Randox. Changes in plasma volume induced by exercise were corrected using the formula of Dill and Costill [16]. All methods used in haematological [17] and biochemical analysis are listed in Table 3.

Perceptual records

Perceptual pain was evaluated by a 10 cm visual analogue scale with 0 = "no pain" and 10 = " "maximum pain" [18]. RPE was assessed by the 0–10 Borg scale with 0 = "extremely easy" and 10 = "extremely hard" [13]. Measurements were done before exercise (T0), immediately after the first bout (T1), in the middle of the session (T2), the last bout (T3) and 3 min after exercise (T4) (Figure 1).

Statistical analysis

Data are presented as mean ± standard error of the mean (SEM) in figures and as mean ± standard deviation (SD) in tables and analysed using IBM SPSS version 23.0 Software (SPSS Inc., Chicago, IL, USA). The normality of data was checked through the Shapiro-Wilk test. When the data were normally distributed, a two-way ANOVA with repeated measures [intensity (HIIT × MIIT) and time (pre-exercise × post-exercise)] was applied. If significant main effects were detected, Bonferroni post-hoc tests were performed. When the Shapiro-Wilk test was significant ($p < 0.05$), the Friedman test was applied. If appropriate, pairwise comparisons were performed using the Wilcoxon test. Effect sizes were calculated through partial eta-squared (ηp^2) for the two-way repeated-measures ANOVA and by Kendall's coefficient of concordance (Kendall's W) when the data were skewed. The level of statistical significance was set at $p < 0.05$.

RESULTS

Twenty-eight adults with obesity volunteered to participate and they were screened for eligibility. Twenty-three participants met all the eligibility criteria and were randomized to perform two different interval exercises, yet twenty-two completed the trial. Figure 2 summarizes the process of selection of volunteers.

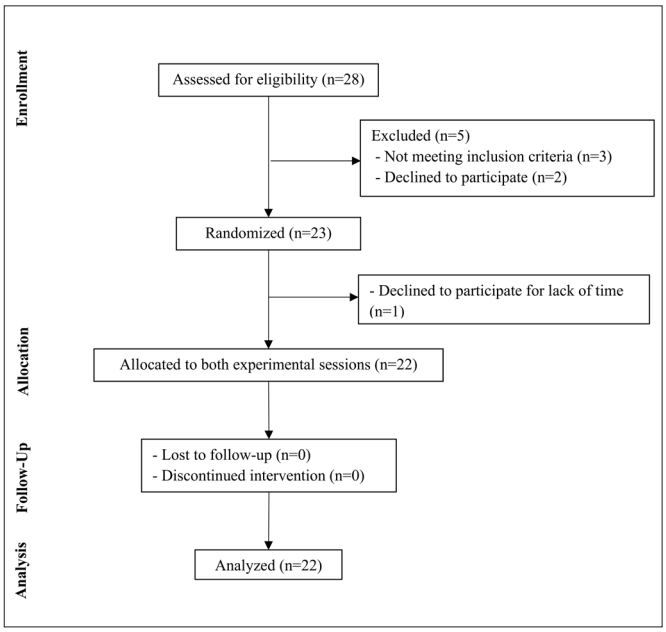


FIG. 2. Flowchart of study participants.

TABLE 3. Different used methods in blood analysis.

Parameter	Abbreviation	Method
C-reactive protein	CRP	Immunoturbidimetric (intra-assay CV = 1.16%)
White blood cells count	WBC	Standard laboratory method of Dacie and Lewis [17]
Aspartate aminotransferase	AST	340 nm kinetics (intra-assay CV = 1.1%)
Alanine aminotransferase	ALT	340 nm kinetics (intra-assay CV = 1.15%)
Creatine Kinase	CK	340 nm kinetics (intra-assay CV = 1.3%)
Lactate dehydrogenase	LDH	340 nm kinetics (intra-assay CV = 0.2%)
Blood lactate	BLa	Lactate oxidase peroxidase method

Abbreviation: CV, coefficient of variation.

Acute effects of HIIT and MIIT on inflammatory and haematological biomarkers

The Friedman test revealed a significant effect (test = 21.54, $p < 0.001$, Kendall's W = 0.33) for CRP levels. Pairwise comparison showed an increase in CRP levels only after HIIT (+10.78%, $p < 0.001$) with a slight, but not significant difference between exercise protocols ($p = 0.07$) (Table 4).

Statistical analysis of WBC showed a significant effect of time ($F_{(1, 21)} = 21.25$, $p < 0.001$, $\eta p^2 = 0.5$) and intensity × time interaction ($F_{(1, 21)} = 14.23$, $p < 0.01$, $\eta p^2 = 0.4$). WBC increased significantly only after HIIT (+14.43%, $p < 0.001$) with a significant difference between exercise sessions ($p < 0.001$). Similarly, neutrophils demonstrated a significant effect of time ($F_{(1, 21)} = 19.29$, $p < 0.001$, $\eta p^2 = 0.48$) and intensity × time interaction ($F_{(1, 21)} = 12.59$, $p < 0.01$, $\eta p^2 = 0.38$). Neutrophils increased only following HIIT (+17.58%, $p < 0.001$) with a significant difference between HIIT and MIIT ($p < 0.001$). No significant effects were observed for monocytes and lymphocytes.

Acute effects of HIIT and MIIT on muscle and hepatic damage biomarkers

Statistical analysis of AST concentrations revealed a significant effect of time ($F_{(1, 21)} = 79.41$, $p < 0.001$, $\eta p^2 = 0.79$), yet no significant effects of intensity or intensity × time interaction were detected. AST increased after HIIT (+10.67%, $p < 0.001$) and MIIT (+7.76%, $p < 0.001$) without significant difference between protocols. Similarly to AST, only a significant effect of time was found ($F_{(1, 21)} = 24.73$, $p < 0.001$, $\eta p^2 = 0.54$) for ALT. ALT levels increased after both HIIT (+6.40%, $p < 0.001$) and MIIT (+4.80%, $p < 0.01$). The Friedman test revealed a significant effect for CK (test = 16.72, $p < 0.001$, Kendall's W = 0.25). The Wilcoxon test showed an increase in CK levels after HIIT (+10.12%, $p < 0.001$) and MIIT (+8.57%, $p < 0.001$) without significant differences across sessions. There was only a significant effect of time ($F_{(1, 21)} = 40.4$, $p < 0.001$, $\eta p^2 = 0.66$) for LDH. The Bonferroni post-hoc test showed a significant increase of LDH after HIIT (+7.85%, $p < 0.001$) and MIIT (+9.67%, $p < 0.001$) without a significant difference between sessions (Table 4).

Acute effects of HIIT and MIIT on BLa level

The Friedman test revealed a significant effect on BLa (test = 52.57, $p < 0.001$, Kendall's W = 0.8). The Wilcoxon test showed an increase in BLa levels after both HIIT (+280.53%, $p < 0.001$) and MIIT (+208.93%, $p < 0.001$) with a greater increase following HIIT when compared to MIIT ($p = 0.04$) (Table 4).

Acute effects of HIIT and MIIT on perceptual responses

Pain scores differed between HIIT and MIIT (test = 152.07, $p < 0.001$, Kendall's W = 0.77). Pain scores were higher in HIIT compared to MIIT at T2 (5.73 ± 0.45 versus 3.73 ± 0.40, $p < 0.001$) and at T3 (6.09 ± 0.44 versus 4.18 ± 0.45, $p < 0.001$) (Figure 3).

The Friedman test showed a significant main effect for RPE (test = 135.53, $p < 0.001$, Kendall's W = 0.68). RPE revealed a greater increase with HIIT at T1 (4.95 ± 0.28 versus 3.09 ± 0.34, $p < 0.01$); T2 (6.23 ± 0.29 versus 4.41 ± 0.40, $p < 0.01$); T3 (7.23 ± 0.32 versus 4.86 ± 0.41, $p < 0.01$); and T4 (7.23 ± 0.24 versus 3.41 ± 0.28, $p < 0.001$) compared to MIIT (Figure 3).

TABLE 4. Haematological and biochemical changes in response to acute high-intensity interval training (HIIT) versus moderate-intensity continuous exercise (MIIT).

	HIIT			MIIT		
Variables	**Pre**	**Post**	**% change**	**Pre**	**Post**	**% change**
CRP (mg·L^{-1})	4.36 ± 2.44	4.83 ± 2.48***	10.78	4.45 ± 2.42	4.54 ± 2.32	2.02
WBC (10^3/μl)	7.83 ± 2.37	8.96 ± 2.42***	14.43	7.74 ± 2.65	7.97 ± 2.43###	2.97
Neutrophils (10^3/μl)	4.55 ± 1.73	5.35 ± 1.89***	17.58	4.48 ± 1.82	4.71 ± 1.65###	5.13
Lymphocytes (10^3/μl)	2.41 ± 0.66	2.58 ± 0.75	7.05	2.44 ± 0.77	2.45 ± 0.76	0.41
Monocytes (10^3/μl)	0.55 ± 0.18	0.57 ± 0.16	3.64	0.54 ± 0.22	0.54 ± 0.18	0.00
AST (U/l)	17.05 ± 3.29	18.87 ± 3.47***	10.67	17.14 ± 2.72	18.47 ± 2.86***	7.76
ALT (U/l)	20.46 ± 7.01	21.77 ± 7.28***	6.40	19.99 ± 5.63	20.95 ± 6.53**	4.80
CK (U/l)	128.45 ± 44.08	141.45 ± 52.69***	10.12	118.82 ± 59.60	129 ± 68.86***	8.57
LDH (U/l)	186.59 ± 33.40	201.23 ± 33.98***	7.85	181 ± 34.97	198.5 ± 37.28***	9.67
BLa (mmol·L^{-1})	1.13 ± 0.37	4.30 ± 2.71***	280.53	1.12 ± 0.38	3.46 ± 1.82 ***, #	208.93

Data are presented as mean ± SD. **Abbreviations:** HIIT, high-intensity interval training; MIIT, moderate-intensity interval training; WBC, white blood cells; CRP, c-reactive protein; AST, aspartate aminotransferase; ALT, alanine aminotransferase; CK, creatine kinase; LDH, lactate dehydrogenase; BLa, blood lactate. **, ***: significant difference between pre-post exercise ($p<0.01$, $p<0.001$, respectively). #, ###: significant difference between HIIT-MIIT ($p<0.05$ and $p<0.001$, respectively).

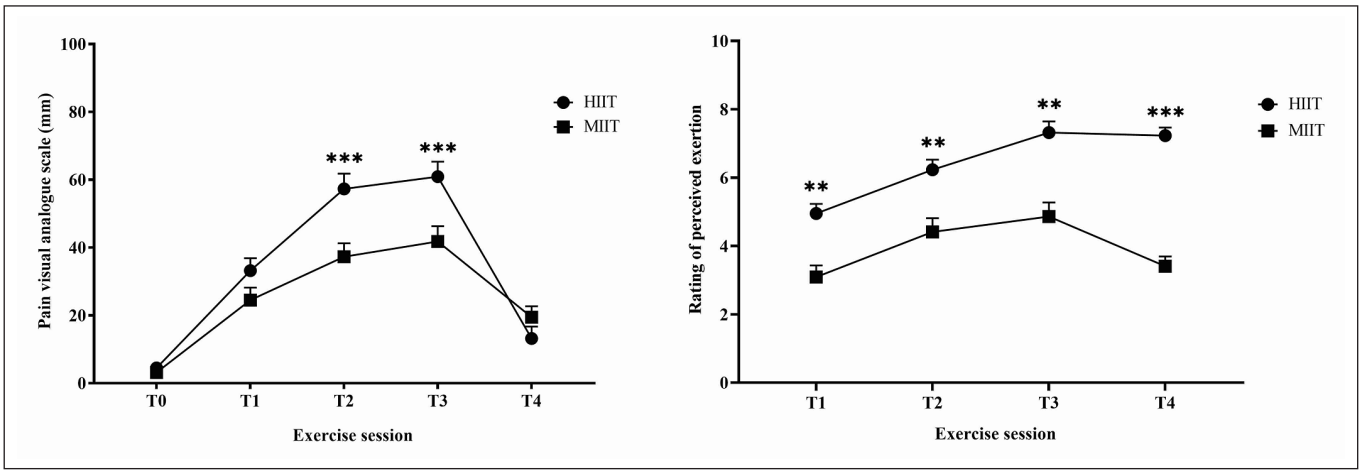


FIG. 3. Changes in perceived pain and in rating of perceived exertion in response to acute HIIT and MIIT. Data are presented as mean ± SEM. Abbreviations: RPE, rating of percieved exertion; HIIT, high-intensity interval training; MIIT, moderate-intensity interval training; T1, after the first bout; T2, at the middle of the session; T3, after the last bout; T4, 3 min post-exercise. **, ***: significant difference between HIIT-MIIT at the same time point ($p < 0.01$, $p < 0.001$ respectively).

DISCUSSION

The present study aimed to compare the acute effects of two different interval exercise modes (HIIT and MIIT), matched for duration and total workload on immune, haematological, biochemical, and perceptual responses in sedentary adults with obesity. The main findings of this study were as follows: only HIIT induced a significant increase in inflammatory markers (CRP, WBC and neutrophils), both HIIT and MIIT increased markers of cellular damage (AST, ALT, CK and LDH) and greater metabolic (BLa) and perceptual (pain and RPE) responses were recorded following HIIT compared to MIIT in sedentary adults with obesity.

In the present study, the increase in CRP levels only following the HIIT session agrees with the findings of Fernandes et al. [19], who observed an increase in CRP following acute cycling exercise (65% VO_2peak for 50 min) in overweight patients with coronary artery disease. It is well known that obesity is associated with a low-grade systemic inflammation characterized by increased levels of pro-inflammatory cytokines including IL-6 and IL-1β, which are the main CRP enhancers [20]. Admittedly, strenuous exercise induces an increase in circulating pro-inflammatory cytokines such as IL-1β and TNF-α as well as a potent increase in IL-6 [21–23]. However, Kaspar et al. [24] reported unchanged levels of CRP after one session of HIIT and MICT in healthy, normal-weight males. A possible explanation for these equivocal outcomes is that baseline CRP levels are already elevated in people with obesity [20] and that HIIT was strenuous enough to exacerbate the inflammation.

An increase in WBC was observed only after HIIT, indicating that this increase in response to interval exercise can be dependent on its intensity, which could be mediated by a greater increase of catecholamine levels and their interaction with beta-adrenergic receptors after sympathetic nervous system activation [25]. Likewise, Neves et al. [26] found an intensity dependence for WBC immediately after exercise when comparing low- versus high-intensity continuous exercise bouts, in healthy normal-weight men. In the present study, the leukocytosis in response to HIIT was basically due to neutrophilia. Similarly, Durrer et al. [27] reported a rapid increase of neutrophil number after a HIIT session in patients living with obesity and type 2 diabetes. It is known that acute exercise induces a rapid initial increase in circulating neutrophils possibly attributable to shear stress and catecholamines, followed by a delayed elevation through neutrophil release from the bone marrow likely mediated by cortisol [28–30]. Indeed, obesity is linked to a vegetative nervous system imbalance, characterized by high sympathetic nervous system activity and low parasympathetic nervous system activity [31], which could be aggravated following intense exercise. In fact, differences in acute immune system responses to HIIT and MIIT could be in part explained by a greater increase in the sympathetic nervous activity following HIIT compared to MIIT, since the magnitude of the sympathetic response to one exercise session depends on exercise intensity (i.e., the higher the exercise intensity, the greater the sympathetic activity) [32]. Increased sympathetic nervous system activity causes an increase in the secretion of catecholamines, which are highly implicated in the mobilization of leukocytes [25]. Another mechanism that could explain these findings is the increase of hypothalamic–pituitary–adrenal axis activity in response to one session of HIIT but not MIIT, which was demonstrated to be moderated by exercise intensity [33]. In fact, it has been reported that only a HIIT session induced an increase in plasma adrenocorticotropin levels when compared to one session of MIIT [33] or MICT [34]. The increase in adrenocorticotropin levels in response to pituitary gland stimulation by corticotropin-releasing hormone triggers the adrenal glands to raise cortisol levels, which is strongly implicated in leukocyte trafficking [25].

Inflammation following vigorous exercise has previously been linked to cell damage [35]. Exercise-induced muscle injury stimulates a variety of skeletal muscle cell types, including immune cells, to begin tissue repair and regeneration [36]. In the present study, an immediate elevation in all biomarkers of muscle damage (e.g. CK, LDH) after both interval exercises was reported. These findings are in line with those of Wiewelhove et al. [37] demonstrating that short-maximal and long-submaximal HIIT sessions induced an increase in CK levels in intermittent sports athletes. Dorneles et al. [9] observed an increase in CK levels immediately after one session of HIIT and MIIT, yet LDH increased only following HIIT in males with overweight/obesity. This disagreement regarding the increased level of LDH after MIIT in our study could be due to differences in the duration of work/rest intervals used in MIIT [38]. In fact, when the exercise load surpasses the muscle's ability or when performing an unaccustomed exercise, both CK and LDH leak from the muscle cells into interstitial fluid and enter the bloodstream through the lymphatic system [35, 39]. Our findings showed a similar elevation of ALT and AST after both exercise modes. AST is found in the liver as well as in skeletal muscle and other tissues, while ALT is mainly present in the liver with smaller amounts in other tissues including skeletal muscle [40]. Thus, in the absence of liver diseases, and when confirmed with a simultaneous increase in levels of CK and LDH, AST and ALT should refer to muscle injury instead of liver injury [41]. One session of unaccustomed high-intensity exercise can induce disruption of the sarcolemma and liberate intramuscular protein including aminotransferases into the serum [42]. Interestingly, it has been reported that obesity could negatively affect markers of cell damage following intense exercise [43]. Previous studies reported that the group with a high body fat percentage [43] or BMI [10] had a greater increase in markers of cell damage after intense repetitive exercise (i.e., eccentric exercise) compared to their lean counterparts. In fact, it has been demonstrated that excessive fat accumulation increases fatty acyl chain saturation in the sarcolemma as well as phospholipid packing density, resulting in a rigid cell membrane that is more vulnerable to damage [44]. Moreover, obesity-related low-grade inflammation and oxidative stress facilitate the infiltration of phagocytes of injured muscle tissues, resulting in further cell disruption [45]. Another predictor of muscle damage is BLa [46]. In this study, a higher BLa level was observed after the HIIT session than after the MIIT session. According to the suggested model for HIIT categorization by Laursen and Buchheit [47], MIIT can be classified as aerobic since the post-exercise level of BLa was greater than 3 mmol/L and HIIT as moderately anaerobic since BLa was greater than 4 mmol/L; hence a higher BLa accumulation could be due to a greater draw on the anaerobic glycolytic system for energy production during HIIT. In addition, Warr-di Piero et al. [48] reported a higher BLa concentration after one HIIT session involving long interval durations (90 s/90 s and 130 s/130 s) compared to short intervals (10 s/10 s and 50 s/50 s) performed at 100% of maximal aerobic speed. These results do not support our findings regarding the effect of work interval duration on BLa as work bouts in HIIT were one-third shorter than MIIT but performed at a greater workload (i.e. 90%PPO versus 70%PPO), which suggests that not only the duration of work interval but also the work intensity could affect BLa concentration.

Regarding perceptual responses, our findings showed a greater RPE and pain in the HIIT session versus the MIIT session. In agreement with the findings of Wiewlhove et al. [37], pain scores were higher after all-out sprint IT than after long submaximal interval exercises. It has been previously reported that strenuous exercise inducing an elevation in muscle damage markers is associated with increased perceived pain and soreness after exercise cessation [49]. HIIT was perceived as "very difficult" and MIIT was perceived as "moderate" by inactive adults with obesity despite lower actual work (i.e. 8 min in HIIT versus 15 min in MIIT). Although Warr-di Piero et al. [48] demonstrated higher RPE during long versus short HIIT, it is worth mentioning that work duration was extended from one protocol to another while the work intensity was constant (100% of maximum aerobic speed), which could increase the RPE by participants. Our findings are in line with those of Wood et al. [50] reporting higher RPE in sprint IT versus HIIT, which may be due to a greater contribution of the higher intensity of IT in determining perceptual responses.

Nevertheless, the current study has some limitations. First, the measurements of biochemical markers were done only before and immediately after exercise. Second, the number of participants was relatively small. Third, we did not control for the effect of menstrual cycle phases on inflammatory responses, yet all sessions were not carried out during menses. Indeed, discrepancies between findings have been reported in previous studies conducted on eumenorrheic women, demonstrating no effect of menstrual cycle on CRP and TNF-α [51], while another study showed that levels of CRP vary across the menstrual cycle and reach the highest levels during menses [52]. Further studies are needed to increase the follow-up time after exercise and to study the chronic effect of MIIT and HIIT in inactive adults living with obesity.

CONCLUSIONS

The present study demonstrates that one IT session induced an increase in biochemical and perceptual responses and these alterations depend on IT intensity, with a larger, acute increase after HIIT. The MIIT session induced fewer immune system perturbations and less muscle fatigue and was perceived as more tolerable compared to HIIT. Therefore, in sedentary people with obesity, MIIT could be used as a first step to favour body adaptations to a further HIIT programme.

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Conflict of interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

REFERENCES

1. Ellulu MS, Patimah I, Khaza'ai H, Rahmat A, Abed Y. Obesity and inflammation: the linking mechanism and the complications. Arch Med Sci. 2017; 13(4):851–63.
2. Myers J, Kokkinos P, Nyelin E. Physical Activity, Cardiorespiratory Fitness, and the Metabolic Syndrome. Nutrients. 2019; 11(7):1652.
3. Afshar S, Seymour K, Kelly SB, Woodcock S, van Hees VT, Mathers JC. Changes in physical activity after bariatric surgery: using objective and self-reported measures. Surg Obes Relat Dis. 2017; 13(3):474–83.
4. Martland R, Mondelli V, Gaughran F, Stubbs B. Can high-intensity interval training improve physical and mental health outcomes? A meta-review of 33 systematic reviews across the lifespan. J Sports Sci. 2020; 38(4):430–69.
5. MacInnis MJ, Gibala MJ. Physiological adaptations to interval training and the role of exercise intensity. J Physiol. 2017; 595(9):2915–30.
6. Naves JPA, Viana RB, Rebelo ACS, de Lira CAB, Pimentel GD, Lobo PCB, et al. Effects of High-Intensity Interval Training vs. Sprint Interval Training on Anthropometric Measures and Cardiorespiratory Fitness in Healthy Young Women. Front Physiol. 2018; 9:1738.
7. Alkahtani SA, King NA, Hills AP, Byrne NM. Effect of interval training intensity on fat oxidation, blood lactate and the rate of perceived exertion in obese men. Springerplus. 2013; 2:532.
8. Racil G, Ben Ounis O, Hammouda O, Kallel A, Zouhal H, Chamari K, et al. Effects of high vs. moderate exercise intensity during interval training on lipids and adiponectin levels in obese young females. Eur J Appl Physiol. 2013; 113(10):2531–40.
9. Dorneles GP, Haddad DO, Fagundes VO, Vargas BK, Kloecker A, Romão PR, et al. High intensity interval exercise decreases IL-8 and enhances the immunomodulatory cytokine interleukin-10 in lean and overweight-obese individuals. Cytokine. 2016; 77:1–9.
10. Kim J, So WY. High Body Mass Index Is Associated with the Extent of Muscle Damage after Eccentric Exercise. Int J Environ Res Public Health. 2018; 15(7).
11. Stegen S, Derave W, Calders P, Van Laethem C, Pattyn P. Physical fitness in morbidly obese patients: effect of gastric bypass surgery and exercise training. Obes Surg. 2011; 21(1):61–70.
12. Pescatello LS, Riebe D, Thompson PD. ACSM's guidelines for exercise testing and prescription: Lippincott Williams & Wilkins; 2013.
13. Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc. 1982; 14(5):377–81.
14. Tschakert G, Hofmann P. High-intensity intermittent exercise: methodological and physiological aspects. Int J Sports Physiol Perform. 2013; 8(6):600–10.
15. Organization WH. Waist circumference and waist-hip ratio: report of a WHO expert consultation, Geneva, 8–11 December 2008. 2011.
16. Dill DB, Costill DL. Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. J Appl Physiol. 1974; 37(2):247–8.
17. Dacie JV, Lewis SM. Practical Haematology. 7th ed. Edinburgh: Churchill Livingstone; 1991. p. 54–79.
18. Huskisson EC. Measurement of pain. J Rheumatol. 1982; 9(5):768–9.
19. Lara Fernandes J, Serrano CV, Jr., Toledo F, Hunziker MF, Zamperini A, Teo FH, et al. Acute and chronic effects of exercise on inflammatory markers and B-type natriuretic peptide in patients with coronary artery disease. Clin Res Cardiol. 2011; 100(1):77–84.
20. Asghar A, Sheikh N. Role of immune cells in obesity induced low grade inflammation and insulin resistance. Cell Immunol. 2017; 315:18–26.
21. Pedersen BK, Bruunsgaard H, Klokker M, Kappel M, MacLean DA, Nielsen HB, et al. Exercise-induced immunomodulation--possible roles of neuroendocrine and metabolic factors. Int J Sports Med. 1997; 18 Suppl 1:S2–7.
22. Pedersen BK, Toft AD. Effects of exercise on lymphocytes and cytokines. Br J Sports Med. 2000; 34(4):246–51.
23. Ostrowski K, Rohde T, Asp S, Schjerling P, Pedersen BK. Pro- and anti-inflammatory cytokine balance in strenuous exercise in humans. J Physiol. 1999; 515 (Pt 1):287–91.
24. Kaspar F, Jelinek HF, Perkins S, Al-Aubaidy HA, deJong B, Butkowski E. Acute-Phase Inflammatory Response to Single-Bout HIIT and Endurance Training: A Comparative Study. Mediators Inflamm. 2016; 2016:5474837.
25. Simpson RJ, Kunz H, Agha N, Graff R. Exercise and the Regulation of Immune Functions. Prog Mol Biol Transl Sci. 2015; 135:355–80.
26. Neves P, Tenorio T, Lins TA, Muniz MTC, Pithon-Curi TC, Botero JP, et al. Acute effects of high- and low-intensity exercise bouts on leukocyte counts. J Exerc Sci Fit. 2015; 13(1):24–8.
27. Durrer C, Francois M, Neudorf H, Little JP. Acute high-intensity interval exercise reduces human monocyte Toll-like receptor 2 expression in type 2 diabetes. Am J Physiol Regul Integr Comp Physiol. 2017; 312(4):R529–R38.
28. Walsh NP, Gleeson M, Shephard RJ, Gleeson M, Woods JA, Bishop NC, et al. Position statement. Part one: Immune function and exercise. Exerc Immunol Rev. 2011; 17:6–63.
29. Pyne DB. Regulation of neutrophil function during exercise. Sports Med. 1994; 17(4):245–58.
30. McCarthy DA, Dale MM. The leucocytosis of exercise. A review and model. Sports Med. 1988; 6(6):333–63.
31. Hillebrand S, de Mutsert R, Christen T, Maan AC, Jukema JW, Lamb HJ, et al. Body fat, especially visceral fat, is associated with electrocardiographic measures of sympathetic activation. Obesity (Silver Spring). 2014; 22(6):1553–9.
32. Hautala AJ, Kiviniemi AM, Tulppo MP. Individual responses to aerobic exercise: the role of the autonomic nervous system. Neurosci Biobehav Rev. 2009; 33(2):107–15.
33. Yamauchi T, Harada T, Kurono M, Matsui N. Effect of exercise-induced acidosis on aldosterone secretion in men. Eur J Appl Physiol Occup Physiol. 1998; 77(5):409–12.
34. Peake JM, Tan SJ, Markworth JF, Broadbent JA, Skinner TL, Cameron-Smith D. Metabolic and hormonal responses to isoenergetic high-intensity interval exercise and continuous moderate-intensity exercise. Am J Physiol Endocrinol Metab. 2014; 307(7):E539–52.
35. Peake JM, Neubauer O, Della Gatta PA, Nosaka K. Muscle damage and inflammation during recovery from exercise. J Appl Physiol (1985). 2017; 122(3):559–70.
36. Hyldahl RD, Hubal MJ. Lengthening our perspective: morphological, cellular, and molecular responses to eccentric exercise. Muscle Nerve. 2014; 49(2):155–70.
37. Wiewelhove T, Fernandez-Fernandez J, Raeder C, Kappenstein J, Meyer T, Kellmann M, et al. Acute responses and muscle damage in different high-intensity interval running protocols. J Sports Med Phys Fitness. 2016; 56(5):606–15.
38. Laursen P, Buchheit M. Science and application of high-intensity interval training. Champaign: Human Kinetics; 2019. 672 p.
39. Brancaccio P, Lippi G, Maffulli N. Biochemical markers of muscular damage. Clin Chem Lab Med. 2010; 48(6):757–67.
40. Banfi G, Colombini A, Lombardi G, Lubkowska A. Metabolic markers in sports medicine. Adv Clin Chem. 2012; 56:1–54.
41. Nathwani RA, Pais S, Reynolds TB, Kaplowitz N. Serum alanine aminotransferase in skeletal muscle diseases. Hepatology. 2005; 41(2):380–2.

42. Villavicencio Kim J, Wu GY. Body Building and Aminotransferase Elevations: A Review. J Clin Transl Hepatol. 2020; 8(2):161–7.
43. Yoon EJ, Kim J. Effect of Body Fat Percentage on Muscle Damage Induced by High-Intensity Eccentric Exercise. Int J Environ Res Public Health. 2020; 17(10).
44. Knoblauch MA, O'Connor DP, Clarke MS. Obese mice incur greater myofiber membrane disruption in response to mechanical load compared with lean mice. Obesity (Silver Spring). 2013; 21(1):135–43.
45. Kawamura T, Suzuki K, Takahashi M, Tomari M, Hara R, Gando Y, et al. Involvement of Neutrophil Dynamics and Function in Exercise-Induced Muscle Damage and Delayed-Onset Muscle Soreness: Effect of Hydrogen Bath. Antioxidants (Basel). 2018; 7(10).
46. Manojlovic V, Erculj F. Using blood lactate concentration to predict muscle damage and jump performance response to maximal stretch-shortening cycle exercise. J Sports Med Phys Fitness. 2019; 59(4):581–6.
47. Laursen P, Buchheit M. Science and application of high-intensity interval training: Human Kinetics; 2019.
48. Warr-di Piero D, Valverde-Esteve T, Redondo-Castan JC, Pablos-Abella C, Sanchez-Alarcos Diaz-Pintado JV. Effects of work-interval duration and sport specificity on blood lactate concentration, heart rate and perceptual responses during high intensity interval training. PLoS One. 2018; 13(7):e0200690.
49. Harty PS, Cottet ML, Malloy JK, Kerksick CM. Nutritional and Supplementation Strategies to Prevent and Attenuate Exercise-Induced Muscle Damage: a Brief Review. Sports Med Open. 2019; 5(1):1.
50. Wood KM, Olive B, LaValle K, Thompson H, Greer K, Astorino TA. Dissimilar Physiological and Perceptual Responses Between Sprint Interval Training and High-Intensity Interval Training. J Strength Cond Res. 2016; 30(1):244–50.
51. Romero-Parra N, Barba-Moreno L, Rael B, Alfaro-Magallanes VM, Cupeiro R, Díaz Á E, et al. Influence of the Menstrual Cycle on Blood Markers of Muscle Damage and Inflammation Following Eccentric Exercise. Int J Environ Res Public Health. 2020; 17(5).
52. Gaskins AJ, Wilchesky M, Mumford SL, Whitcomb BW, Browne RW, Wactawski-Wende J, et al. Endogenous reproductive hormones and C-reactive protein across the menstrual cycle: the BioCycle Study. Am J Epidemiol. 2012; 175(5):423–31.

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Laboratory-based determinants of simulated time trial performance in cyclists

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ABSTRACT: Different laboratory-based variables are individually associated with cycling performance, but scarce evidence exists on which of them, when all assessed in combination, could best explain cycling performance. The present study aimed to examine the combined association between laboratory-based endurance, strength/power and body composition indicators with time trial performance in high-level cyclists. Ninety-four male cyclists were recruited (age: 20 ± 3.5 years, maximum oxygen uptake [$\dot{V}O_{2max}$]: 77.7 ± 5.4 ml·kg^{-1}·min^{-1}). Participants performed a maximal incremental cycling test for the assessment of endurance indicators (peak power output [PPO], $\dot{V}O_{2max}$, ventilatory threshold [VT] and respiratory compensation point [RCP]), and an incremental loading test to assess muscle strength and power-related outcomes (1-repetition maximum, mean maximal power) in the squat, lunge and hip-thrust exercises. Body composition was assessed by dual energy X-ray absorptiometry. On a separate visit, participants performed a simulated 8-minute time trial to assess cycling performance (determined as the mean power output attained). Strong-to-very-strong correlations were found between all endurance indicators and time trial performance (most *r*-values ranging between 0.68–0.92), whereas weaker correlations were found for strength/power (*r*-values < 0.5) or body composition (*r*-values < 0.7) indicators. Multivariate regression analyses revealed that VT, RCP and PPO explained together 92% of the variance in time trial performance ($p < 0.001$), with no significant contribution of the remaining variables. Although different endurance, strength/power and body composition individually correlate with simulated time trial performance in high-level cyclists, the former (and particularly VT, RCP and PPO) show the strongest association when all studied in combination. These findings underscore the importance of endurance capabilities (above strength/power or body composition) for maximizing time trial performance.

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Testing

INTRODUCTION

Endurance and, particularly, cycling performance is conditioned by a complex interplay between several factors, including race characteristics, tactics and environmental factors [1]. Chief among these factors is the individual's fitness status, with three characteristics traditionally highlighted as the main determinants of endurance performance: the maximal 'aerobic' capacity of the individual (usually assessed through the determination of maximal oxygen consumption [$\dot{V}O_{2max}$] or peak power output [PPO] on an incremental test), the individual workload representing the boundary between heavy and severe intensity domains (which can be assessed through different markers such as critical power [CP], ventilatory threshold [VT], or the so-called lactate threshold), and exercise efficiency (i.e., the oxygen cost to generate a given power output [PO]) [2]. Indeed, several studies — although in most cases using small sample sizes and not analyzing professional cyclists as participants — support the use of laboratory-based endurance indicators (notably, $\dot{V}O_{2max}$, PPO, VT) as predictors of cycling performance [3–10].

Besides the aforementioned endurance indicators, growing evidence suggests that muscle strength/power also plays a major role in cycling performance. For instance, Kordi et al. recently reported that knee extension maximum voluntary torque was positively associated with both CP and with the amount of work completed above CP (known as W', and considered as a marker of the so-called 'anaerobic' capacity) [11], and Cesanelli et al. reported a positive association between lower-limb maximal strength (i.e., 1-repetition maximum) and both the functional threshold power and the lactate threshold [12]. Indeed, strength training has proven beneficial for the improvement of not only muscle strength, but also of cycling and, particularly, time trial performance [13, 14], which seems to be

partly due to beneficial effects on endurance indicators (e.g., PPO, VT) and neuromuscular variables (e.g., rate of force development, pedal stroke efficacy) [15–18]. However, other authors have failed to find a significant association between muscle strength measures (e.g., back squat 1-repetition maximum [1RM], knee extension maximum voluntary torque) and endurance indicators of cycling performance such as CP [19, 20].

Cycling performance can also be conditioned by other fitness-related factors, such as body composition. Increases in lean mass (and consequently body mass) have been traditionally regarded by cyclists as a detrimental adaptation because of the negative influence of gravity on performance (i.e., speed), particularly during uphill cycling [21]. In support of this, a recent study reported that performance improvements across one season in professional cyclists were mostly due to reductions in body mass, and not to increases in absolute PO values [22]. It must be noted, however, that a higher muscle mass can result in a higher absolute PO and speed, at least under those conditions in which gravity exerts a smaller influence (i.e., on flat roads). Indeed, quadriceps' or thigh muscle mass has been identified as one of the main determinants of PPO and W' in cyclists [19, 23–25]. Moreover, time trial performance has been reported to improve with strength training along with concomitant increases in muscle mass, with the improvement of both variables correlated [26]. Therefore, evidence overall suggests that body composition plays a major individual role on cycling performance. Yet, the interplay between body composition and endurance indicators in the prediction of cycling performance when assessed in combination remains unclear.

Although controversy exists in some reports, numerous variables seem therefore individually associated with cycling performance. However, which of these variables best explains cycling performance when all assessed in combination remains unknown, as physiological variables are usually interrelated and their interplay is complex [27]. For instance, it is possible that greater muscle strength levels or a larger muscle mass are associated with a higher cycling performance largely based on their indirect effects on endurance indicators (e.g., PPO, VT), but they might not actually predict cycling performance when assessed in combination with major endurance indicators. Identifying the physiological determinants of cycling performance is relevant, as it might help in performance prediction or talent identification, and could aid in guiding coaches and athletes in the design of training programs focused on those variables that appear more strongly correlated. Moreover, most studies to date have been conducted on recreational cyclists, with little evidence available on the predictors of performance in large cohorts of professional cyclists. The aim of the present study was to assess the individual and combined association between laboratory-based endurance, strength and body composition indicators and cycling performance (assessed through a simulated time trial), with an attempt to develop a multivariate model to predict elite cycling performance.

MATERIALS AND METHODS

Study design

Participants visited the laboratory on three days interspersed by 48 hours and approximately at the same time of the day (temperature = 20 ± 3°C, humidity = 25 ± 3%). They were instructed to maintain their normal dietary pattern and to refrain from intense exercise and consuming ergogenic aids/caffeine 48 hours before each testing session. In the first visit, participants underwent body composition assessment and a maximal incremental cycling test. During the second visit, they completed strength tests. A simulated 8-minute time trial was performed in the last visit (see below for further details).

Participants

Ninety-four male road cyclists volunteered to participate in this study (aged 20 ± 3.5 years [range 16–37], body mass 63.9 ± 6.7 kg, $\dot{V}O_{2max}$ 77.7 ± 5.4 mL·kg^{-1}·min^{-1}). All participants competed actively at the international or national level in the Professional, U23 or Junior categories. According to the guidelines proposed by de Pauw et al [28], these cyclists were overall considered to be of the highest performance level (i.e., Level 5). To be included in the study, cyclists had to be free of musculoskeletal injuries or other conditions that could hinder their participation. All participants were informed of the study procedures, benefits and risks and provided written informed consent. For those participants aged < 18 years, informed consent was signed by their parents or guardians. The study was approved by the Ethical Committee of the Alcorcón University Hospital (approval number 19/86). All procedures were conducted following the standards established by the Declaration of Helsinki and its later amendments.

Procedures

Body composition

Height was measured using a wall stadiometer (Seca 437). Body composition (whole body fat and muscle mass, and bone mineral content) was measured by dual energy X-ray absorptiometry (DXA; Hologic QDR series Discovery; Bedford, MA). Assessments were performed at least two days after the last exercise session. Participants were recommended to maintain a similar eating and sleeping routine the day before each testing session and were advised to be euhydrated.

Incremental cycling test

Cyclists performed a graded exercise test on their own bikes, which were placed on an indoor trainer (Hammer, CycleOps, Madison, WI) that has been proven valid to measure PO [29]. Participants started with a standardized 10-minute warm-up at 75 W, before completing a maximal incremental cycling test with an initial workload of 75 W, which increased by 5 W every 12 seconds (i.e., following a ramp-like protocol) until volitional exhaustion or when pedaling cadence fell below 60 rpm for more than 10 seconds. Gas exchange data were collected breath-by-breath (Ultima Series

Medgraphics; Cardiorespiratory Diagnostics, Saint Paul, MN). The VT was determined as the workload at which an increase in both the ventilatory equivalent for oxygen ($VE{\cdot}\dot{V}O_2^{-1}$) and end-tidal partial pressure of carbon dioxide ($PetCO_2$) occurred with no concomitant increase in the ventilatory equivalent for carbon dioxide ($VE{\cdot}VCO_2^{-1}$). The respiratory compensation point (RCP, also termed 'second ventilatory threshold') corresponded to the work rate at which both $VE{\cdot}\dot{V}O_2^{-1}$ and $VE{\cdot}VCO_2^{-1}$ increased together with a decrease in $PetCO_2$ [30]. PPO was defined as the highest PO value reached during the test, and $\dot{V}O_{2max}$ was defined as the highest $\dot{V}O_2$ value (mean of 30 s) attained during the test.

Muscle strength/power

Forty-eight hours after the incremental test, participants performed an incremental loading test to assess muscle strength and power-related outcomes in the squat, lunge and hip-thrust exercises. Exercises were performed on a Smith machine (Multipower Fitness Line; Peroga, Murcia, Spain). Bar mean propulsive power (MPP) during the concentric phase was measured with a validated linear position transducer (T-Force System; Ergotech, Murcia, Spain) [31]. The initial weight was 20 kg (i.e., only the bar), and the load was increased by 10 kg until a decrease in MPP was observed in two consecutive loads. Participants performed three consecutive repetitions with each load, and a 2-minute rest was allowed between loads. The highest MPP registered for each exercise was analyzed and 1RM was estimated as explained elsewhere [13, 14].

Simulated time trial

During the third visit, cyclists performed an 8-minute time trial after a standardized 10-minute warm-up at 60% of their PPO. The simulated time trial was performed on the same bike and using the same aforementioned indoor trainer as for the incremental cycling test. Participants were instructed to attain the highest mean PO possible, and they were allowed to adjust resistance by changing the gears of the bicycle. They received no instructions regarding pacing and were blinded to PO values during the trial, and they were not allowed to stand on the pedals. An 8-minute time trial was chosen because all participants were familiar with this effort duration, it represents an effort commonly performed by cyclists during competition (e.g., during a Prologue), and it has been reported as a valid indicator of performance, being correlated with different laboratory-based performance indicators [32–34].

Statistical analysis

Data are presented as mean ± SD. Normality (Kolmogorov–Smirnov test) and homoscedasticity (Levene's test) of the data were checked prior to any statistical treatment. The relationship between endurance, strength and body composition indicators with simulated time trial performance (average W or W/kg) was analyzed with Pearson's correlation coefficients (r); *r*-values of 0.1, 0.3, 0.5, 0.7, and 0.9 were considered small, moderate, strong, very strong and extremely strong, respectively [35]. Stepwise multivariate linear regression analysis was performed to determine the variables that best explained time trial performance. All variables were included in the model to avoid selection bias, and variance inflation factors (VIF) and tolerance values were checked to inspect for multicollinearity (i.e., VIF < 10 and tolerance > 0.1). Statistical analyses were performed with a specific statistical software package (SPSS 26.0, Inc., Chicago, IL) setting the alpha for significance at 0.05.

TABLE 1. Association between laboratory-based endurance indicators and absolute (average W) and relative performance (average W/kg) in an 8-minute time trial

Predictor variable	Mean ± SD	Time trial (W)		Time trial (W/kg)	
		r	*p*-value	r	*p*-value
PPO (W)	430 ± 47	0.923**	< 0.001	0.343**	0.001
Relative PPO (W/kg)	6.80 ± 0.51	0.382**	< 0.001	0.863**	< 0.001
$\dot{V}O_{2max}$ (L/min)	5.02 ± 0.57	0.828**	< 0.001	0.256*	0.013
Relative $\dot{V}O_{2max}$ (mL/kg/min)	77.9 ± 5.4	0.458**	< 0.001	0.675**	< 0.001
PO at RCP (W)	367 ± 46	0.851**	< 0.001	0.381**	< 0.001
Relative PO at RCP (W/kg)	5.81 ± 0.58	0.340**	0.001	0.756**	< 0.001
$\dot{V}O_2$ at RCP (%$\dot{V}O_{2max}$)	92.4 ± 3.7	0.277**	0.007	0.284**	0.006
PO at VT (W)	261 ± 35	0.816**	< 0.001	0.495**	< 0.001
Relative PO at VT (W/kg)	4.14 ± 0.49	0.294**	0.004	0.762**	< 0.001
$\dot{V}O_2$ at VT (%$\dot{V}O_{2max}$)	70.6 ± 6.2	0.056	0.593	0.256*	0.013

Significant associations: * $p < 0.05$; ** $p < 0.01$. Abbreviations: PO, power output; PPO, peak power output; RCP, respiratory compensatory threshold; $\dot{V}O_{2max}$, peak oxygen uptake; VT, ventilatory threshold.

TABLE 2. Association between muscle strength/power indicators and absolute (average W) and relative performance (average W/kg) in an 8-minute time trial

Predictor variable	Mean ± SD	Time trial (W)		Time trial (W/kg)	
		r	*p*-value	r	*p*-value
Squat 1RM (kg)	83 ± 16	0.365**	< 0.001	0.104	0.320
Squat relative 1RM [kg / body mass (kg)]	1.30 ± 0.24	-0.004	0.972	0.238*	0.021
Squat MMP (W)	518 ± 121	0.436**	< 0.001	0.103	0.324
Squat relative MMP [W / body mass (kg)]	8.11 ± 1.67	0.136	0.191	0.228*	0.027
Hip thrust 1RM (kg)	101 ± 29	0.275**	0.007	0.000	0.997
Hip thrust relative 1RM [kg / body mass (kg)]	1.59 ± 0.45	0.203*	0.050	-0.067	0.523
Hip thrust MMP (W)	454 ± 121	0.264*	0.010	-0.027	0.796
Hip thrust relative MMP [W / body mass (kg)]	7.16 ± 1.93	0.180	0.083	-0.088	0.397
Split squat 1RM (kg)	58 ± 17	0.028	0.790	-0.240*	0.020
Split squat relative 1RM [kg / body mass (kg)]	0.91 ± 0.29	-0.047	0.655	-0.284**	0.006
Split squat MMP (W)	324 ± 107	0.002	0.988	-0.294**	0.004
Split squat relative MMP [W / body mass (kg)]	5.13 ± 1.82	-0.068	0.514	-0.327**	0.001

Significant associations: * $p < 0.05$; ** $p < 0.01$. Abbreviations: 1RM, one-repetition maximum; MMP, maximum mean power.

TABLE 3. Association between body composition indicators and absolute (average W) and relative performance (average W/kg) in an 8-minute time trial

Predictor variable	Mean ± SD	Time trial (W)		Time trial (W/kg)	
		r	*p*-value	r	*p*-value
Body mass (kg)	63.9 ± 6.7	0.696**	< 0.001	-.233*	0.024
BMC (kg)	2.26 ± 0.37	0.522**	< 0.001	-0.132	0.205
BMC (%)	3.56 ± 0.41	0.127	0.221	0.069	0.511
Fat mass (kg)	10.9 ± 2.1	0.262*	0.011	-0.451**	< 0.001
Fat mass (%)	17.1 ± 2.3	-0.114	0.275	-0.415**	< 0.001
Muscle mass (kg)	50.1 ± 5.1	0.740**	< 0.001	-0.136	0.190
Muscle mass (%)	79.2 ± 2.3	0.122	0.243	0.466**	< 0.001

Significant associations: * $p < 0.05$; ** $p < 0.01$. Abbreviations: BMC, bone mineral content.

RESULTS

Participants' PO during the time trial averaged 347 ± 42 W (5.49 ± 0.5 W/kg). Strong-to-very-strong correlations were found between all endurance indicators and time trial performance expressed in both absolute (W) and relative units ($W \cdot kg^{-1}$) (*r*-values ranging from 0.68 to 0.93) (Table 1). By contrast, weaker correlation coefficients were found between time trial performance and strength/power (*r*-values < 0.5, Table 2) or body composition indicators (*r*-values < 0.7, Table 3).

Multivariate regression analyses including all variables as potential predictors showed that PPO, VT and RCP explained together 92% of the variance in time trial performance (all of them expressed in absolute units [W]) ($R^2 = 0.917$, $p < 0.001$), with the three variables contributing significantly to the model (Figure 1, Table 4). No signs of strong multicollinearity were found for the variables included in the model (VIF and tolerance between 4.4–7.2 and 0.14–0.23, respectively). Similarly, the model including PPO, VT and RCP (in this case expressed in relative units [W/kg]) was also the one that best explained the variance in time trial performance when expressed in relative units ($R^2 = 0.887$, $p < 0.001$), with the three variables contributing significantly to the model (Figure 1, Table 4). Again, no signs of strong multicollinearity were found for the variables included in the model (VIF and tolerance ranging between 4.2–5.9 and 0.17–0.24, respectively).

TABLE 4. Multivariate models predicting simulated time trial performance

Performance	Predictors	β (SE)	Standardized β	*p*-value	R^2 (adjusted R^2)	Model *p*-value
Average W	PPO (W)	0.557 (0.068)	0.649	< 0.001	0.920 (0.917)	< 0.001
	VT (W)	0.212 (0.077)	0.169	0.008		
	RCP (W)	0.159 (0.068)	0.172	0.022		
Average W/kg	PPO (W/kg)	0.566 (0.074)	0.649	< 0.001	0.891 (0.887)	< 0.001
	VT (W/kg)	0.175 (0.082)	0.151	0.036		
	RCP (W/kg)	0.161 (0.070)	0.176	0.024		

Abbreviations: β, regression coefficient; PPO, peak power output; RCP, respiratory compensation point; VT, ventilatory threshold.

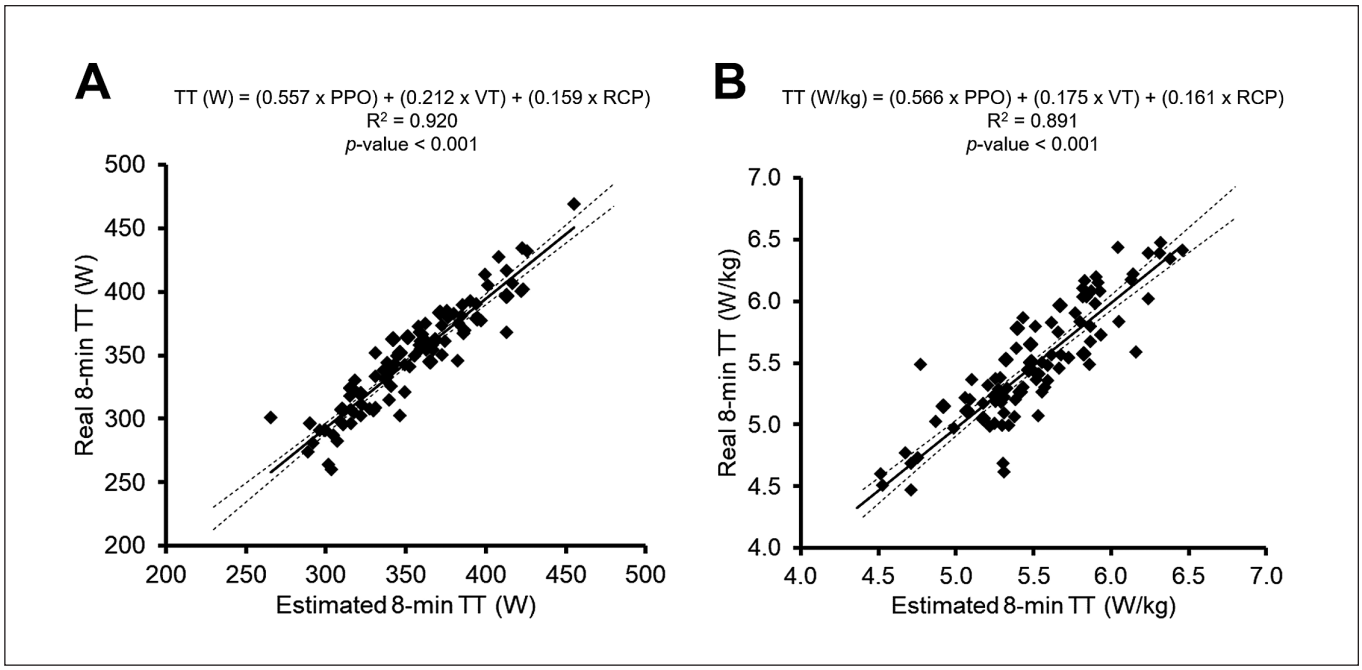


FIG. 1. Association between the time trial (TT) performance estimated with the multivariate model and the actual time trial performance expressed both in absolute (average W, panel A) and relative (average W/kg, panel B) units.
Note: Solid and dashed lines represent the line of identity and 95% confidence interval, respectively. Abbreviations: PPO, peak power output; RCP, respiratory compensation point; VT, ventilatory threshold.

DISCUSSION

The main finding of the present study is that, while different laboratory-based endurance, strength and body composition indicators appear individually correlated with time trial performance, when all assessed in combination the former (and particularly PPO, VT and RCP) show the strongest correlation, explaining up to 92% of the variance in time trial performance in multivariate analysis. Strength and body composition indicators do not seem to further improve the predictive accuracy of the model.

A large body of knowledge supports the individual association between several laboratory-based endurance indicators and time trial performance. In the present study, we found that both $\dot{V}O_{2max}$ and particularly PPO – both indicative of cyclists' maximal aerobic capacity – were strongly related to time trial performance, and the multivariate model indeed revealed that PPO was the variable that best predicted time trial performance. In line with this finding, previous evidence showed that PPO is strongly associated not only with $\dot{V}O_{2max}$ [8], but also with performance in time trials of different durations [4, 5, 8, 9]. For instance, strong correlations ($r > 0.8$) have been reported between PPO and 16-km [9], 20-km [8], 1-hour [4], or 90-minute time trial performance [7]. Of note, PPO has been reported to be more strongly correlated with time trial performance than $\dot{V}O_{2max}$ [4, 5, 7]. In addition to maximal aerobic capacity, the so-called 'anaerobic' threshold has been proposed to be

a cornerstone of endurance performance [2], and our findings confirm this notion, with both VT and RCP showing strong correlations with time trial performance and contributing significantly to the multivariate model. This finding is supported by previous studies reporting strong correlations – stronger indeed that other indicators such as $\dot{V}O_{2max}$ – between threshold-related parameters (e.g., lactate or ventilatory thresholds) and time trial performance [4–7]. For instance, Nichols et al. [6] reported a stronger correlation between threshold-derived parameters and time trial performance than between $\dot{V}O_{2max}$ and time trial performance. In the same line, Lucia et al. found that PO at the VT, but not PPO or $\dot{V}O_{2max}$, was associated with performance in a 50-km time trial during the Tour de France [10]. Moreover, in line with our findings, Støren et al. found that PPO, $\dot{V}O_{2max}$. and the lactate threshold were strongly associated with performance on a 15-km time trial [36].

In contrast to endurance-related indicators, more controversy exists about the influence of strength/power on cycling and, particularly, time trial performance. There is evidence that maximal strength could be positively associated with cycling performance, at least in short-duration maximal efforts. For instance, lower-limb muscle strength has been positively associated with W' [11, 19], which suggests that improving muscle strength could be beneficial for short-duration efforts (e.g., sprinting). In turn, there is mixed evidence on the association between maximum torque and CP, with the latter being more related to endurance performance. For example, Kordi et al. [19] reported that knee extensor maximum torque was associated with W', but not with CP [19]. Byrd et al. [20] also found a significant association between back squat 1RM and W', but no associations were found between back squat or other strength-related outcomes (e.g., knee extension torque at different angles) and CP. In support of these findings, we found overall weak correlations ($r < 0.5$) between strength/power indicators and time trial performance, and these variables did not significantly contribute to the multivariate model. In a group of regional and national-level road cyclists, Støren et al. found no association between strength/power variables (e.g., Wingate test, half squat test) and performance on a simulated 15-km time trial [36]. It must be noted, nonetheless, that while strength/power values might not be associated *per se* with cycling performance [36], resistance training has proven beneficial for cyclists, which seems to be partly due to a beneficial effect on neuromuscular variables (e.g., rate of force development, pedal stroke efficacy) [15, 16, 18]. However, the present findings suggest that the benefits of strength (and consequently of resistance training) should not overshadow the key role of endurance training for improving time trial performance.

Another major finding of the present study is that body composition parameters were overall weakly correlated with time trial performance, with the strongest correlations found between muscle mass (in kg) and absolute power output ($r = 0.74$). Supporting this finding, previous evidence suggests that muscle mass indicators (e.g., quadriceps or thigh muscle cross-sectional area or volume) are positively associated with power production capacity, at least for short-duration efforts (e.g., W', PPO) [19, 23, 24]. In addition, strength training has been reported to improve cycling performance despite concomitant increases in muscle mass or muscle cross-sectional area [21], with changes in muscle cross-sectional area being positively correlated with improvements in time trial performance (assessed as relative PO) [26]. However, some debate exists on the association between changes in body composition and actual cycling performance. Although increases in muscle mass can covary with a greater PO production, an increased body mass might negatively affect riding speed due to the influence of gravity, particularly on the steepest roads. Indeed, relative PPO, and not absolute PPO, has been reported to better explain performance during uphill climbing [37]. Thus, whereas a decrease in fat mass is likely associated with an improved cycling performance, as confirmed in the present study by the negative association found between fat mass and relative power output, the association between muscle mass and performance remains unclear. Indeed, no associations were reported between muscle mass indicators and other markers of endurance performance such as CP [19]. Thus, our findings suggest that high absolute muscle mass values can be beneficial for absolute power production capacity regardless of fat mass, whereas the combination of low fat mass levels, along with high relative muscle mass levels (as a %), seems optimal for maximizing relative power output. Notwithstanding this, none of the analyzed body composition parameters contributed significantly to the multivariate model.

Some limitations of the present study should be acknowledged, notably its cross-sectional design, which precludes from drawing cause-effect conclusions. Indeed, despite the wide body of cross-sectional evidence suggesting a link between laboratory-based indicators and cycling performance, the scarce longitudinal evidence available suggests that these variables might have a limited accuracy for predicting future success in young cyclists [38]. Another potential limitation is that we assessed cycling performance through the PO attained on a simulated time trial in order to control, as much as possible, for all confounding variables (e.g., environmental conditions) but the assessment of speed on a real outdoor time trial could yield different results given the influence of other parameters such as aerodynamics (and consequently of body surface area). Indeed, the PO attained during a time trial is not necessarily associated with real performance (i.e., speed), and a previous study found that PPO was strongly associated with PO during a 16-km time trial, but not with the time needed to complete the trial [9]. Another limitation is the lack of control for potentially confounding variables such as motivation, or the absence of data on other important predictor variables such as exercise economy or muscle cross-sectional area, which have also been proposed as major indicators of cycling performance [2, 19, 23–25]. Moreover, the present findings might only be applicable to short-time trials, such as the one performed here (e.g., prologues, individual pursuit races), and might not necessarily be applicable to longer trials. It is also worth noting that the

presence of multicollinearity cannot be completely ruled out, although the VIF and tolerance values observed (< 8 and > 0.14, respectively) suggest that there was not strong multicollinearity. Also, although we checked the linear association between numerous variables, future research should analyze whether nonlinear models can provide a better predictive accuracy. In turn, the large size (n = 94) and the high performance level of the analyzed sample can be considered major strengths, as well as the broad range of analyzed predictors.

PRACTICAL APPLICATIONS

The present findings suggest that, although muscle strength and body composition indicators are individually associated with time trial performance, when multiple indicators are assessed in combination endurance ones are the strongest predictors, with other variables not meaningfully improving predictive accuracy. Particularly, given that PPO, VT and RCP explain most of the variance in time trial performance, our findings might support the routine assessment of these parameters for the monitoring of cyclists' performance. Moreover, although the important role of muscle strength and body composition on cycling performance should not be disregarded, our results suggest that their benefits are mostly due to indirect effects on PPO, VT and RCP. Therefore, coaches and cyclists might preferably focus on the latter variables if their goal is to improve time trial performance, as these parameters appear as the main determinants.

CONCLUSIONS

Different laboratory-based endurance, muscle strength and body composition indicators can be individually correlated with time trial performance, but the former present the strongest correlation and the combination of PPO, VT and RCP explains most of the variance (~92%) in time trial performance. These findings underscore the importance of endurance for predicting time trial performance, with muscle strength/power or body composition indicators *per se* not meaningfully improving the predictive accuracy.

Conflict of Interest

The authors declare no conflicts of interest.

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REFERENCES

1. Phillips KE, Hopkins WG. Determinants of Cycling Performance: a Review of the Dimensions and Features Regulating Performance in Elite Cycling Competitions. Sport Med – Open. 2020; 6(1).
2. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. J Physiol. 2008; 586(1):35–44.
3. Amann M, Subudhi AW, Foster C. Predictive validity of ventilatory and lactate thresholds for cycling time trial performance.pdf. Scand J Med Sci Sports. 2006; 16:27–34.
4. Bishop D, Jenkins DG, Mackinnon LT. The relationship between plasma lactate parameters, Wpeak and 1-h cycling performance in women. Med Sci Sports Exerc. 1998; 30(8):1270–5.
5. Bishop D, Jenkins DG, McEniery M, Carey MF. Relationship between plasma lactate parameters and muscle characteristics in female cyclists. Med Sci Sports Exerc. 2000; 32(6):1088–93.
6. Nichols JF, Phares SL, Buono MJ. Relationship between blood lactate response to exercise and endurance performance in competitive female master cyclists. Int J Sports Med . 1997; 18(6):458–63.
7. Bentley DJ, Mcnaughton LR, Thompson D, Vleck VE, Batterham AM. Peak power output, the lactate threshold, and time trial performance in cyclists. Med Sci Sports Exerc. 2001; 33(12):2077–81.
8. Hawley JA, Noakes TD. Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. Eur J Appl Physiol Occup Physiol. 1992; 65(1):79–83.
9. Balmer J, Davison RCR, Bird SR. Peak power predicts performance power during an outdoor 16.1-km cycling time trial. Med Sci Sports Exerc. 2000; 32(8):1485–90.
10. Lucia a, Hoyos J, Pérez M, Santalla a, Earnest CP, Chicharro JL. Which laboratory variable is related with time trial performance time in the Tour de France? Br J Sports Med. 2004; 38(5):636–40.
11. Kordi M, Simpson LP, Thomas K, Goodall S, Maden-Wilkinson T, Menzies C, Howatson G. The Relationship Between Neuromuscular Function and the W' in Elite Cyclists. Int J Sports Physiol Perform. 2021; 16(11):1656–62.
12. Cesanelli L, Ammar A, Arede J, Calleja-González J, Leite N. Performance indicators and functional adaptive windows in competitive cyclists: Effect of one-year strength and conditioning training programme. Biol Sport. 2022; 39(2):329–40.
13. Valenzuela PL, Gil-Cabrera J, Talavera E, Alejo LB, Montalvo-Pérez A, Rincón-Castanedo C, Rodríguez-Hernández I, Lucia A, Barranco-Gil D. On- versus off-bike power training in professional cyclists: A randomized controlled trial. Int J Sports Physiol Perform. 2021; 16(5):674–81.
14. Gil-Cabrera J, Valenzuela PL, Alejo LB, Talavera E, Montalvo-Pérez A, Lucia A, Barranco-Gil D. Traditional versus optimum power load training in professional cyclists: A randomized controlled trial. Int J Sports Physiol Perform. 2021; 16(4):496–503.
15. Rønnestad BR, Hansen J, Hollan I, Ellefsen S. Strength training improves performance and pedaling characteristics in elite cyclists. Scand J Med Sci Sport. 2015; 25(1):e89–98.
16. Rønnestad BR, Hansen J, Nygaard H. 10 Weeks of Heavy Strength Training Improves Performance-Related Measurements in Elite Cyclists. J Sports Sci. 2017; 35(14):1435–41.
17. Rønnestad BR, Hansen EA, Raastad T. Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. Eur J Appl Physiol. 2010; 108(5):965–75.
18. Kordi M, Folland JP, Goodall S,

Menzies C, Patel TS, Evans M, Thomas K, Howatson G. Cycling-specific isometric resistance training improves peak power output in elite sprint cyclists. Scand J Med Sci Sport. 2020; 30(9):1594–604.
19. Kordi M, Menzies C, Parker Simpson L. Relationship between power–duration parameters and mechanical and anthropometric properties of the thigh in elite cyclists. Eur J Appl Physiol. 2018; 118(3):637–45.
20. Byrd MT, Wallace BJ, Clasey JL, Bergstrom HC. Contributions of Lower-Body Strength Parameters to Critical Power and Anaerobic Work Capacity. J strength Cond Res. 2021; 35(1):97–101.
21. Mujika I, Rønnestad BR, Martin DT. Effects of increased muscle strength and muscle mass on endurance-cycling performance. Int J Sports Physiol Perform. 2016; 11(3):283–9.
22. Leo P, Spragg J, Mujika I, Menz V, Lawley JS. Power Profiling in U23 Professional Cyclists During a Competitive Season. Int J Sports Physiol Perform. 2021; 16(6):881-889.
23. Miura A, Endo M, Sato H, Sato H, Barstow TJ, Fukuba Y. Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. Eur J Appl Physiol. 2002; 87(3):238–44.
24. Kordi M, Folland J, Goodall S, Haralabidis N, Maden-Wilkinson T, Sarika Patel T, Leeder J, Barratt P, Howatson G. Mechanical and morphological determinants of peak power output in elite cyclists. Scand J Med Sci Sport. 2020; 30(2):227–37.
25. Douglas J, Ross A, Martin JC. Maximal muscular power: lessons from sprint cycling. Sport Med – Open. 2021; 7(1):48.
26. Vikmoen O, Ellefsen S, Trøen, Hollan I, Hanestadhaugen M, Raastad T, Rønnestad BR. Strength training improves cycling performance, fractional utilization of $\dot{V}O_{2max}$ and cycling economy in female cyclists. Scand J Med Sci Sport. 2016; 26(4):384–96.
27. Jacobs RA, Rasmussen P, Siebenmann C, Díaz V, Gassmann M, Pesta D, Gnaiger E, Nordsborg NB, Robach P, Lundby C. Determinants of time trial performance and maximal incremental exercise in highly trained endurance athletes. J Appl Physiol. 2011; 111(5):1422–30.
28. De Pauw K, Roelands B, Cheung SS, De Geus B, Rietjens G, Meeusen R. Guidelines to classify subject groups in sport-science research. Int J Sports Physiol Perform. 2013; 8(2):111–22.
29. Lillo-Bevia J, Pallarés J. Validity and Reliability of the Cycleops Hammer Cycle Ergometer. Int J Sport Physiol Perform. 2018; 13(7):853–9.
30. Lucía A, Hoyos J, Pérez M, Chicharro JL. Heart rate and performance parameters in elite cyclists: a longitudinal study. Med Sci Sports Exerc. 2000; 32(10):1777–82.
31. Sánchez-Medina L, González-Badillo JJ. Velocity loss as an indicator of neuromuscular fatigue during resistance training. Med Sci Sport Exerc. 2011; 43(9):1725–34.
32. Klika, R J, Alderdice MS, Kvale JJ, Kearmey JT. Efficacy of cycling training based on a power field test. J Strength Cond Res. 2007; 21(1):265–9.
33. Gavin TP, Van Meter JB, Brophy PM, Dubis GS, Potts KN, Hickner RC. Comparison of a Field-Based Test to Estimate Functional Threshold Power and Power Output at Lactate Threshold. J Strength Cond Res. 2012; 26(2):416–21.
34. Sanders D, Taylor RJ, Myers T, Akubat I. A field-based cycling test to assess predictors of endurance performance and establishing training zones. J Strength Cond Res. 2017; 34(12):3482-3488.
35. Hopkins W, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1):3–12.
36. Støren Ø, Ulevåg K, Larsen MH, Støa EM, Helgerud J. Physiological determinants of the cycling time trial. J Strength Cond Res. 2013; 27(9):2366–73.
37. Antón MM, Izquierdo M, Ibáñez J, Asiain X, Mendiguchía J, Gorostiaga EM. Flat and uphill climb time trial performance prediction in elite amateur cyclists. Int J Sports Med. 2007; 28(4):306–13.
38. Menaspà P, Sassi A, Impellizzeri FM. Aerobic fitness variables do not predict the professional career of young cyclists. Med Sci Sports Exerc. 2010; 42(4):805–12.

Hamstring muscle fibre typology is not associated with hamstring strain injury history or performance in amateur male soccer players: a retrospective magnetic resonance spectroscopy study

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ABSTRACT: Hamstring strain injuries (HSI) are still the most common injuries in soccer. Recent research has been focusing on the role of hamstring muscle morphology and architecture. The hamstring's fibre type composition might play a role as well, but this has never been investigated in the light of HSI risk in an athletic population. The purpose of this study was to investigate the association between hamstring muscle fibre type, hamstring strain injury history (HSIH), performance and isokinetic strength in a population of amateur male soccer players. In this cross-sectional observational study, 44 male soccer players (22 with and 22 without HSIH) participated. The research consisted of a non-invasive fibre composition evaluation using proton magnetic resonance spectroscopy (^{1}H-MRS), functional performance (evaluated by means of maximal jumping height, maximal sprinting speed and hamstring muscle strength endurance (single leg hamstring bridge testing)), and isokinetic strength testing. The results revealed that hamstring carnosine concentration demonstrated a high inter-individual variability within this soccer population and was not significantly associated with either HSIH or with any of the functional performance parameters. The only secondary outcome measure presenting a significant association with the intramuscular carnosine content was the hamstrings' explosive strength production capacity, objectified by means of the time to peak torque (TPT), measured concentrically at an angular velocity of 240 degrees/second (°/s) during isokinetic strength testing. This TPT was significantly shorter in players presenting higher carnosine concentrations ($p = 0.044$). The findings indicate that in male amateur soccer players (1) the hamstrings have no distinct fibre type dominance and (2) fibre typology in this population does not relate to HSIH or performance.

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INTRODUCTION

Running-related hamstring strain injuries (HSI) continue to present high occurrences and reoccurrences in male soccer [1]. Next to the already repeatedly investigated athlete- and performance-related risk factors making the individual athlete more susceptible to HSI (age, injury history, (eccentric) muscle strength) [2–4], hamstring muscle fibre typology is believed to play a role in this [4]. Previous research on hamstring muscle fibre type composition suggested that the hamstrings are particularly susceptible to strain injuries, due to the fact that they consist of a high portion of fast twitch (FT) fibres, compared to other lower limb muscle groups [5–8]. Although fast twitch fibres have beneficial contractile characteristics (e.g. short time to peak tension) – facilitating the athlete's explosiveness – they have a limited oxidative potential which limits both aerobic and repeated anaerobic exercise capacity due to lactate accumulation [9]. This could promote earlier fatigue onset and intramuscular acidification and increase their risk of strain injury during repeated high speed running [7, 10]. Moreover, FT fibres are more susceptible to structural damage induced by (eccentric) exercise compared to slow twitch (ST) fibres because of ultrastructural differences between both fibre groups, making FT fibres less resistant to strain (narrow Z-disks, lower molecular weight, lower isoform expression) [11]. Unlike the existing evidence and scientific background on fibre structure and architectural muscle-tendon features, studies on hamstring muscle fibre type composition are scarce and non-existent in the context of hamstring strain injury risk assessment, and have never been studied in athletic populations vulnerable to hamstring injury. One very recent study assessed the association between the soleus muscle's carnosine content and the hamstring injury risk in professional male soccer players using a prospective design [12]. The results revealed that athletes with high intramuscular carnosine contents indicative for FT fibre dominance had a five-times greater risk of sustaining a hamstring injury compared

to athletes presenting low carnosine contents, matching with slow twitch (ST) dominant fibre distributions. Although other researchers suggested the existence of an across-muscle phenotype with respect to fibre type proportions within one individual, indicative for a fairly homogeneous fibre type distribution across skeletal muscles within one subject [13], the role of the fibre type composition of the hamstring muscle unit itself in its particular vulnerability to strain injury has never been investigated.

The present study intends to examine to what extent hamstring muscle fibre type distribution is associated with hamstring injury history and athletic performance in a population of amateur male soccer players. This will be done using proton magnetic resonance spectroscopy (^{1}H-MRS). This is a soft-tissue specific quantitative (metabolic and functional) MR technique that allows quantification of concentrations of particular metabolites. The dipeptide carnosine is a metabolite, of which the intramuscular concentrations have been established to be twice as high in fast twitch compared to slow twitch muscle fibres [14–15]. Previous research has validated this ^{1}H-MRS technique as an alternative for invasive muscle sampling procedures with histochemical staining in the light of muscle fibre type identification [14].

The aim of the present study is to 1) identify the hamstring muscle's fibre composition by means of ^{1}H-MRS in a sample of amateur male soccer players; 2) assess the possible association between hamstring muscle fibre composition and hamstring strain injury history (HSIH); and 3) investigate the association between hamstring muscle fibre composition and athletic performance capacity, since both have been associated with HSI risk, which would imply both features to be mutually related as well.

MATERIALS AND METHODS

Male soccer players, active in the amateur competition of Belgium, were addressed and informed as regards the purpose and content of this study via social media and by directly reaching out to some clubs affiliated to the head researcher's private network. As this study intended to assess the association between hamstring fibre composition HSIH and athletic performance parameters, both soccer players with and without a (soccer-related) recent HSI history were recruited. Participants were selected as such, in order to end up with a sample with an equal representation of players with and without a history of HSI. This recent history of HSI needed to concern a non-contact soccer-related HSI occurring during training or match play, within the last two seasons. In order to be eligible for participation in the injury history group, these injuries needed to be confirmed by a medical doctor and needed to have prohibited the player from participating in regular training and match activities for at least one week. Participants categorized in this hamstring injury group needed to be fully recovered, participating in weekly training and competition sessions and free of any complaint or residual dysfunction/functional limitation at the time of testing. All male athletes between the age of 18 and 35 years (in order to exclude the presence of a potentially biasing effect of underlying age-related musculoskeletal disorders) were eligible for participation if they:

- Had been active in soccer competition for at least 5 years
- Had a weekly soccer exposure consisting of at least 2 training sessions and one match session
- Did not systematically participate in additional strength training or weight lifting in addition to their weekly soccer training (which might potentially influence intramuscular carnosine concentration)
- Had no recent injury (within the last 5 years) of orthopaedic surgery or severe musculoskeletal trauma necessitating them to stop soccer practice for a period longer than 3 months
- Were fully fit, free from any pain or complaint and 'ready to compete' at the time of participation
- Did not take any food supplements which might possibly influence the intramuscular carnosine content (beta-alanine) [15]
- Did not report being vegetarian or vegan, as these dietary measures might have an impact on the intramuscular carnosine concentration as well.

After being checked for eligibility to participate, willing candidates were contacted by phone and e-mail in order to verify their availability within the testing period (October, November and December 2020).

Ultimately, 44 male soccer players participated in this study, of whom 22 had and 22 lacked a history of HSI (matched controls). Participants within the control group were matched with participants in the HSIH group by means of age, height and weight. Details on anthropometric features and hamstring injury history can be seen in Table 1. Within the injury group, injuries were located at the level of the proximal myotendinous junction of the BF_{LH} in 40% of cases (mostly with involvement of the common tendon with the semitendinosus (SemiT)), at the level of the BF_{LH} muscle in 25% of cases and at the level of the SemiT muscle in 35% of cases. These details were gathered by means of a participant's self-report, with additional availability of conforming medical imaging. Average time since the last HSI was 12.8 (± 9.3) months, and most of the candidates reported having sustained this HSI in the dominant leg (73%).

Eligible candidates were invited to the Ghent University Hospital Campus to take part in a comprehensive testing procedure consisting of (1) proton magnetic resonance spectroscopy (^{1}H-MRS) for quantification of the hamstring's intramuscular carnosine content (measured in the SemiT) and (2) a functional performance and isokinetic strength testing battery.

This study was approved by the Ethics Committee of the Ghent University Hospital (approval number B670201941764, dd. 18/11/2019).

Each participant signed an informed consent form prior to participation in this study's testing series. The duration of the entire testing procedure was approximately 1.5 hours per participant. After completing an extensive administrative survey regarding their athletic experience/background and (hamstring) injury history, participants were systematically submitted to the MRS testing procedure first, followed

TABLE 1. Participant Details.

	HSI History group (n = 22)	Control group (n = 22)
Age (years, mean ± SD)	24.95 ± 3.47	22 ± 1.57
Bodyweight (kilograms, mean ± SD)	78.32 ± 8.80	74.98 ± 6.73
Height (meters, mean ± SD)	1.81 ± 0.06	1.81 ± 0.06
Time passed since last HSI (months, mean ± SD)	12.8 ± 9.3	/
Dominant leg involvement (%)	73	/

Note: HSI, Hamstring Strain Injury; n, sample size; SD, Standard Deviation; %, Percentage

TABLE 2. MR Spectroscopy sequence (Single voxel point-resolved spectroscopy (PRESS) sequence and acquisition details.

^{1}H-MRS acquisition parameters	Muscle (Semitendinosus)	Water Reference
Relaxation Time (ms)	4500	4500
Echo Time (ms)	30	30
Number of averages	64	8
Water suppression	Water Saturated	None
Spectral bandwidth (Hz)	2000	2000
Voxel size (mm^3)	$(40 \times 13 \times 19) = 9880$	$(40 \times 13 \times 19) = 9880$

Note: ^{1}H-MRS, Proton Magnetic Resonance Spectroscopy; Hz, Hertz; mm, millimeters; mm^3, cubic millimeters; MR, Magnetic Resonance; ms, milliseconds; °, degrees

by the performance and isokinetic strength testing procedures. This standardized testing sequence was chosen as we wanted to collect baseline resting state MR images and spectroscopy spectra, in order to avoid bias induced by the potential influence of mechanical and metabolic muscle activation on the ^{1}H-MRS characteristics.

A particular, soft-tissue-specific, MR sequence (3 Tesla (T) whole body MRI scanner (Prisma, Siemens)) was used in order to acquire hamstring muscle fibre architecture-related data in this study (point resolved spectroscopy sequence (PRESS)) [16]. Details on muscle fibre composition were gathered using a proton spectroscopy (proton magnetic resonance spectroscopy (^{1}H-MRS)) sequence measuring the muscle tissue's carnosine content, which provided the opportunity to make assumptions regarding the muscle's fibre type dominance based on the intramuscular carnosine content, relative to the content of a water reference [12, 17–18]. Prior to this spectroscopy sequence, coronal and transverse plane T1 weighted images were taken for subsequent voxel positioning in the semitendinosus muscle. This spectroscopy sequence was systematically run on a homogeneous muscle tissue voxel, positioned in the centre of the proximal upper third of the semitendinosus muscle (SemiT). The SemiT muscle was selected instead of the (most frequently injured) biceps femoris long head (BF_{LH}) muscle, as this resulted in better shimming results and superior field homogeneity within the voxel of interest, most likely due to the fact that the SemiT muscle consists of fewer intramuscular tendon and fascia tissues compared to the more tendinous BF_{LH}, making it more suitable for spectroscopy analysis. Fibre type composition was expected to be highly similar within the same muscle group within one subject (due to the presence of an across-muscle fibre composition phenotype), which has been reported by previous research as well [10, 13].

For this scanning procedure, participants were positioned supine on the scanning table, with the feet primarily directed into the scanning entrance. The spine coil was used as the primary sender coil, while a flex coil was fixed around the back of the participant's dominant thigh acting as a receiving coil for both T1 and H-MRS sequences. The participants were instructed to lie down as still as possible throughout the entire scanning procedure. To reduce the risk of motion artefacts, the researcher applied sand bags to fix the dominant limb in its isocentre position on the scanning table. A detailed overview of the technical particularities of the spectroscopy (PRESS) sequence can be seen in Table 2.

These measurements were conducted in the athlete's dominant thigh (side preferably used to kick) only, as bilateral image acquisition was not possible due to the extent of the respective field of view (FOV) and associated issues related to coil size and scanning time. The total scan time was approximately 15 minutes, taking into account the additional time needed for optimal slice and voxel positioning and shimming (i.e. increasing the magnetic field homogeneity to increase the signal to noise ratio (SNR) and hence the resolution and quality of the spectrum).

After MR imaging, participants were submitted to a performance screening battery consisting of a repeated maximal 25 m sprint, a repeated counter movement jump (CMJ) for maximal vertical jumping height, a single leg hamstring bridge test (SLHB) for the investigation of hamstring strength endurance, as well as a maximal isokinetic strength investigation of the hamstrings using isokinetic dynamometry (IKD). Each participant was submitted to this performance screening in the same standardized sequence ((1) sprint, (2) CMJ, (3) SLHB, (4) IKD). This order was chosen to guarantee maximal explosiveness during the sprint and CMJ tests, without any influence of fatigue due to preceding strength performances. As fatigue most definitely affects maximal isokinetic muscle strength measured by means of IKD evaluation, this last performance test was proceeded by a short recovery period of 30 minutes for each participant. This was done in order to decrease and standardize the potential effect of fatigue of the IKD test results.

Prior to performance and consecutive strength analyses, participants were instructed to perform a 5 minute (min) warm-up by running at a comfortable steady pace (8–10 km/h). These performance measures were conducted indoors and participants wore indoor soccer shoes to complete these testing series.

For the 25 m sprint acceleration test, participants were instructed to cover respective distance as fast as possible, starting from a stationary position. This was repeated 6 times. Between each sprinting trial, participants were instructed to return to the starting point by jogging at a comfortable pace (6-8 km/h), after which they were told to immediately position themselves in the stationary starting position again to perform the consecutive sprint. Sprinting speed was measured using the Witty timing Gate Photocell system (Microgate, Bolzano, Italy), using 3 pairs of gates positioned at 0 m, 10 m and 25 m of the linear running trajectory. Photocells were placed at respective positions, in order to primarily track starting speed and acceleration capacity, rather than maximal sprinting speed. The protocol consisted of 6 sprints with some recovery though no actual rest in between trials, in order to match with the mechanical and metabolic demands of soccer and the associated HSI risk. Both average and minimal (i.e. best) sprint times (expressed in seconds (s)) for the 0–10 m, 10–25 m and 0–25 m distances were taken for data analysis.

Maximal vertical jumping capacity was evaluated by means of a five-fold CMJ with rapid rebound in between consecutive jumps. For this CMJ analysis, the Optogait System (Microgate, Bolzano, Italy) was used. The athletes were instructed to stand between both bars in a neutral starting position, feet placed at shoulder width and equally supporting on both legs. Afterwards, the athlete was instructed to perform 5 consecutive maximal CMJs between both bars, aiming to jump as high as possible with the legs extended in the airborne phase, landing steadily in between consecutive jumps. Both average and maximal (i.e. best) jumping heights (expressed in metres, as well as average and maximal jumping power (expressed in watts) were taken for data analysis.

Local hamstring muscle strength endurance was investigated by means of a single leg hamstring bridge test (SLHB) performed by the dominant leg, until full exhaustion was reached. Only the dominant leg was evaluated, as we only collected ^{1}H-MRS data on the athlete's dominant side as well. This test was initially described by Freckleton and colleagues and was performed using the same standardized guidelines and instructions [19]. The number of repetitions the participants were able to perform adequately (without loss of quality or control, or demonstration of compensations) until reaching full exertion was taken for data analysis.

Concentric and eccentric hamstring muscle strength features were evaluated at angular velocities of 60 and 240°/s for the concentric isokinetic sequences (5 and 10 maximal repetitions (reps) respectively), and 30 and 120°/s for the eccentric sequences (3 and 5 maximal reps respectively). Different angular velocities were used in order to investigate both features of maximal strength and explosive strength in concentric and eccentric contraction modes. All measurements were carried out on the same Biodex Isokinetic Dynamometer (Biodex 4 Pro System, Biodex Medical Systems, Inc. NY, USA). Participants were positioned on the IKD chair in a standardized sitting position with 90° of knee and hip flexion, using straps to assure a fixed testing position. The dynamometer axis was aligned with the knee axis and the lower leg was fixated accordingly. After taking care of the protocol and range of motion (ROM) settings, which allowed maximal concentric and eccentric peak torque analysis throughout a fixed knee flexion-extension testing range of 100°, lower leg weight was measured for gravity correction. Consecutively, isokinetic strength testing for the different contraction modes and angular velocities was performed, in which each participant was allowed three practice trials per strength testing condition prior to actual isokinetic strength evaluation. As this study intended to assess the association between hamstring muscle fibre type dominance and isokinetic strength profile, this isokinetic strength testing procedure was only carried out for the participant's dominant leg. For each one of the isokinetic testing protocols mentioned above, average hamstring peak torque/bodyweight (PT/BW; expressed in Nm/kg), and average time to peak torque (TPT; expressed in ms), were taken for statistical analysis. These particular outcome measures were chosen to investigate both maximal (average peak torque) and explosive (time to peak torque) muscle strength capacity.

To quantify the SemiT muscle's carnosine content, the integral of the C2-H peak (at ~8 ppm) was quantified relative to the water peak integral (at 4.7 ppm), multiplied by 1 000 000, and calculated as arbitrary units [14, 20]. Given the quite high variability in hamstring muscle fibre type in male athletes, and in order to allow subsequent categorization of data in order to identify the participants' hamstrings as being predominantly slow twitch, intermediate type or fast twitch, Z-scores were calculated using mean and standard deviations of the above-mentioned carnosine concentration outcomes, based on the normal distribution. For methodological details we refer to previous work [12, 21–22].

Because of poor quality of some of the carnosine and water spectra collected by means of H-MRS, data on carnosine content of 5 of the 44 participants were not taken for statistical analysis (2 participants in control and 3 participants in the HSIH group).

For each of the continuous and dependent outcome parameters, descriptive statistics were explored and data distributions were checked for normality. The primary outcome measure was the potential difference in relative SemiT carnosine contents between groups (HSI history versus matched controls), for which Student's independent t-testing was performed. This possible association was also investigated by means of chi-square analysis, using the carnosine concentration's derived Z-scores, to compare to what extent the cell count representation in the slow twitch, intermediate type and fast twitch muscle type groups differed significantly between the HSIH group and the control group. Participants were estimated to have predominantly (1) slow twitch, (2) intermediate type or (3) fast twitch fibre typologies if their Z-scores were (1) < -.05, (2) > -0.05 and < 0.05, and (3) > 0.05, respectively. Effect sizes for between-group differences were quantified using post-hoc Bonferroni corrections in these chi-square procedures.

After this HSIH based carnosine content comparison, correlation and linear regression analyses were performed in order to quantify potential associations between the hamstring muscle's relative carnosine content, functional performance and isokinetic hamstring strength features (secondary outcome measure). These associations were examined with Pearson's correlation coefficient (r) and ANOVA hypothesis tests.

All statistical procedures were carried out within the interface of SPSS Statistics Version 25 (IBM SPSS Statistics 25). Significance levels were set at $\alpha = 0.05$.

RESULTS

Between-group comparison in terms of demographics revealed that age differed significantly between groups (means and standard deviations (SD) of 22 ± 1.57 and 24.95 ± 3.47 years in control and HSIH groups, respectively, $p = 0.001$), while height (means and SDs of 1.81 ± 0.06 and 1.81 ± 0.06 m in control and HSIH groups, respectively, $p = 0.76$) and bodyweight (means and SDs of 74.89 ± 6.89 and 78.32 ± 8.80 kg in control and HSIH groups, respectively, $p = 0.17$) were very similar. Age was demonstrated not to be related to carnosine content within this sample of amateur soccer payers ($r = 0.13$, $p = 0.43$).

Between-group comparison revealed no differences in relative carnosine content (expressed in arbitrary units [(C2-H peak/water peak)*1000000]) or associated Z-score, either for the continuous ($p = 0.34$) or categorical statistical analyses ($p = 0.21$). The data distribution of this relative carnosine concentration parameter, used to make estimations as regards fibre type, presented a remarkably high variability in both the control and the HSIH groups (coefficient of variation (CV) = 31.2%) (Figure 1). Table 3 demonstrates the fibre type distribution within the entire sample, without making further subdivision based on HSIH.

Correlation and chi-square analyses in the search of any associations between the hamstring muscle's fibre typology and the functional performance characteristics revealed no associations between the intramuscular carnosine content and either the SLHB, maximal sprint acceleration or CMJ capacity within this sample. This was the case for correlation analysis taking into account the carnosine concentration as a continuous parameter, as well as for the ANOVA analysis assessing possible differences in performance estimates based on fibre type category. (Table 4)

Correlation analysis did not reveal any associations between relative carnosine content and isokinetic thigh strength, whereas the ANOVA analyses (hamstring strength as a function of categorized Z-cores) did reveal a significant between-group difference for the hamstring's time to peak torque measured concentrically at a 240°/s

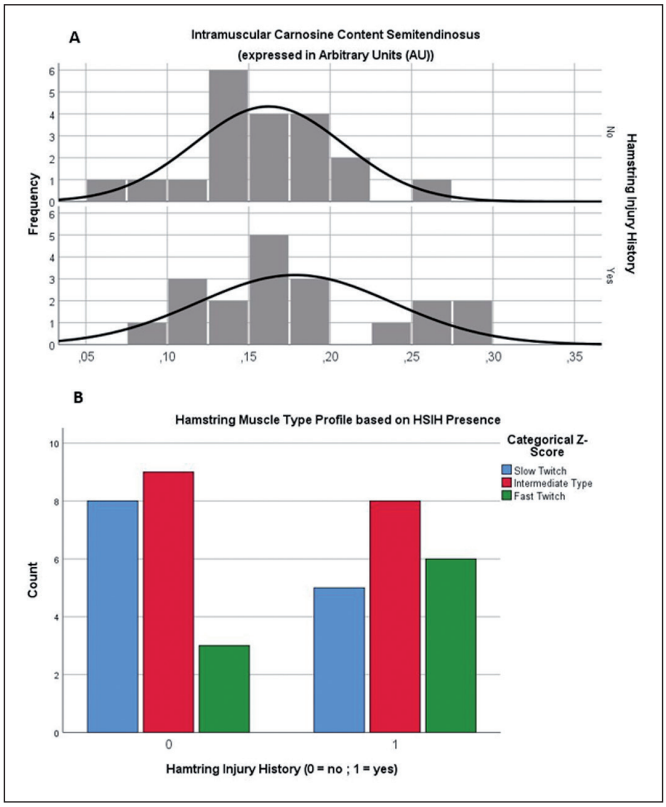


FIG. 1. A) Data distribution of the relative carnosine content variable in both the control and HIH groups. Z-score transformation was used in order to categorize players in the fast twitch ($Z > 0.5$), intermediate type ($0.5 < Z > -0.5$) or slow twitch ($Z < -0.5$) hamstring muscle fibre type groups. **B)** Distribution of 3 major Z-score groups within both the control and HSIH groups. Chi-square testing revealed no significant differences in categorical Z-score counts based on HSIH presence. ($p = 0.21$).
Note: Std. Dev., standard deviation; N, sample size; HIH, hamstring injury history; HSIH, hamstring strain injury history; %, percentage.

TABLE 3. Fiber type distribution within entire study sample.

	Sample of Male Amateur SOCCER Players (n = 39)
Slow twitch fiber dominant (z < -0.5) (count (%))	13 (33)
Intermediate type dominant (-0.5 < z > 0.5) (count (%))	17 (44)
Fast twitch fiber dominant (z > 0.5) (count (%))	9 (23)

Note: n, study sample; %, percentage. Z < -0.5 = predominantly Slow Twitch Fibers; 0.5 < Z > -0.5 = Intermediate Type; Z > 0.5 = Predominantly Fast Twitch Fibers.

TABLE 4. Performance outcomes in function of Fiber Type Category for SLHB, Sprint, Vertical Jump and Isokinetic Strength analyses with accompanying levels of significance (in-between-group differences using ANOVA and post hoc Bonferonni hypothesis tests).

	Slow Twitch (ST) (n = 13)	Intermediate Type (IT) (n = 17)	Fast Twitch (FT) (n = 9)	ANOVA's p	Bonferonni's p
Single Leg Hamstring Bridge (dominant leg) (number of reps)	36 ± 14	30 ± 6	31 ± 13	0.353	/
Average sprint time 0–10m (s)	1.86 ± 0.11	1.81 ± 0.08	1.87 ± 0.05	0.105	/
Minimal sprint time 0–10m (s)	1.77 ± 0.10	1.75 ± 0.06	1.80 ± 0.08	0.310	/
Average sprint time 10–25m (s)	2.00 ± 0.12	2.00 ± 0.09	2.05 ± 0.06	0.414	/
Minimal sprint time 10–25m (s)	1.91 ± 0.10	1.93 ± 0.07	1.97 ± 0.07	0.196	/
Average sprint time 0–25m (s)	3.86 ± 0.22	3.81 ± 0.15	3.92 ± 0.09	0.257	/
Minimal sprint time 0–25m (s)	3.69 ± 0.19	3.70 ± 0.11	3.79 ± 0.12	0.230	/
Average vertical jumping height (m)	40.12 ± 5.72	37.61 ± 5.42	37.50 ± 3.70	0.384	/
Maximal vertical jumping height (m)	40.82 ± 8.69	40.56 ± 6.03	39.79 ± 4.69	0.940	/
Average vertical jumping power (W)	22.98 ± 5.05	19.94 ± 3.25	21.21 ± 3.06	0.139	/
Maximal vertical jumping power (W)	26.11 ± 8.30	20.90 ± 3.50	22.64 ± 3.69	0.061	0.058 (ST vs IT)
Average PT/BW Hamstrings Con @60°/s (Nm/kg)	1.35 ± 0.26	1.38 ± 0.30	1.39 ± 0.28	0.956	/
TPT Hamstrings Con @60°/s (ms)	547 ± 124	557 ± 164	619 ± 235	0.602	/
APT Hamstrings Con @60°/s (°)	53 ± 10	57 ± 13	56 ± 16	0.656	/
Average Power Hamstrings Con @60°/s (W)	80.3 ± 12.8	80.5 ± 21.2	76.6 ± 21.9	0.873	/
TW/BW Hamstrings Con @60°/s (J/kg)	7.99 ± 1.79	8.39 ± 2.51	7.52 ± 1.68	0.610	/
Average PT/BW Hamstrings Con @240°/s (Nm/kg)	0.84 ± 0.19	0.85 ± 0.19	1.01 ± 0.22	0.119	/
TPT Hamstrings Con @240°/s (ms)	244 ± 38	199 ± 57	188 ± 50	0.025	0.044 (ST vs FT)
APT Hamstrings Con @240°/s (°)	64 ± 7	58 ± 11	52 ± 16	0.081	0.084 (ST vs FT)
Average Power Hamstrings Con @240°/s (W)	111.7 ± 21.0	121.5 ± 31.0	132.9 ± 36.3	0.283	/
TW/BW Hamstrings Con @240°/s (J/kg)	8.19 ± 2.04	8.59 ± 2.40	9.38 ± 2.35	0.496	/
Average PT/BW Hamstrings Ecc @30°/s (Nm/kg)	2.15 ± 0.41	2.21 ± 0.35	2.20 ± 0.57	0.937	/
TPT Hamstrings Ecc @30°/s (ms)	2737 ± 319	2741 ± 318	2735 ± 0.57	0.993	/
APT Hamstrings Ecc @30°/s (°)	21 ± 9	23 ± 10	20 ± 6	0.668	/
Average Power Hamstrings Ecc @30°/s (W)	60.0 ± 8.1	65.2 ± 12.3	60.0 ± 13.6	0.397	/
TW/BW hamstrings Ecc @30°/s (J/kg)	520.1 ± 79.6	567.5 ± 137.6	495.1 ± 128.4	0.478	/
Average PT/BW Hamstrings Ecc @120°/s (Nm/kg)	1.80 ± 0.32	1.81 ± 0.46	1.94 ± 0.58	0.750	/
TPT Hamstrings Ecc @120°/s (ms)	673 ± 108	649 ± 97	646 ± 114	0.794	/
APT Hamstrings Ecc @120°/s (°)	29 ± 11	32 ± 12	32 ± 15	0.703	/
Average Power Hamstrings Ecc @120°/s (W)	151.2 ± 35.6	177.9 ± 37.6	163.8 ± 45.6	0.212	/
TW/BW Hamstrings Ecc @120°/s (J/kg)	8.33 ± 2.00	9.23 ± 2.08	9.33 ± 2.90	0.508	/

Note: APT, Angle of Peak Torque; BW, Body Weight; Con, Concentric; Ecc, Eccentric; J, Joule; kg, kilogram; m, meters; m, meters; ms, milliseconds; n, sample size; Nm, Newton meter; p, probability; PT, Peak Torque; reps, repetitions; s, seconds; TPT, Time to Peak Torque; TW, Total Work; vs, versus; W, Watts; °, degrees.

angular velocity ($p = 0.025$). The FT dominant participants demonstrated the shortest TPT and the ST dominant participants presenting the longest TPT, with the intermediate type participants scoring somewhere in between. Post hoc pairwise comparisons with Bonferroni correction revealed that this difference was located between the ST and FT fibre category groups, presenting times to peak torque of 244 ± 38 ms and 188 ± 50 ms, respectively ($p = 0.044$) (Table 4).

DISCUSSION

This is the first study investigating hamstring muscle fibre typology non-invasively by means of ^{1}H-MRS, in function of both HSIH and performance in a sample of male soccer players. The results revealed that the hamstring's carnosine content, investigated in the proximal part of the SemiT, was highly variable in male amateur soccer players and did not present a particularly uniform carnosine concentration but a rather large inter-individual variability, indicative for the absence of distinctly predominant fibre typology. Interestingly, this carnosine concentration did not present any association with HSIH, nor with any of the functional performance-related outcomes. Only the TPT of the hamstring muscles measured concentrically at 240°/s presented a significant association with muscle fibre typology, as it was found to be significantly shorter in players with a fast twitch dominant fibre type, compared to players with a slow twitch fibre dominance.

The first important finding of this study is that the hamstring muscle group of this study sample of amateur soccer players presented high inter-individual variability in intramuscular carnosine content. This carnosine content distribution indicates that the hamstring muscles within this study sample present a rather intermediate fibre typology profile and can probably not be considered a fast twitch fibre dominant muscle group. These findings are in contrast with what has been stated in previous literature, i.e. that the hamstrings mainly consist of fast twitch fibres (ca. 55%), making them particularly vulnerable to eccentric induced muscle damage (EIMD) and fatigue, and therefore highly susceptible to strain injury in explosive field sports exposing them to repeated bouts of high speed running [5, 7, 10, 23]. Albeit valuable to provide some kind of a normative database, this theoretical framework has very little to do with the actual HSI risk profile in soccer, as it was composed based on in vitro research on necrotic hamstring muscle tissue in cadavers [10]. In their study, Garret and colleagues explored hamstring muscle fibre composition in 7 different sites across the hamstring muscle unit, which revealed a type II (FT) muscle fibre representation of 55% and 54% in the proximal and distal regions of the BFLH, 55% and 60% in the proximal and distal regions of the SemiT, and 51% and 51% in the proximal and distal regions of the semimembranosus, respectively. Based on these findings, together with a relevant preliminary cadaver study and referred work [5, 7], we are not able to make estimations on the role of fibre type composition in the hamstring's strain injury risk as the research investigated metabolically inactive muscle tissue in the elderly, without any association with the soccer related loading mechanism or hamstring injury occurrence. Nonetheless, it provided us with insights as regards the (varying) profile of the distribution with the bi-articular hamstring muscle unit, and provided scientific evidence for our methodological approach selecting a voxel in the proximal SemiT for ^{1}H-MRS measurements, as the fibre distribution at this particular location was established to be highly similar to the one in the (proximal) BFLH region. The present results should be interpreted carefully and do not allow us to use proximal SemiT carnosine content identification for general hamstring muscle group fibre type determination. Future studies should include voxel selection in proximal, mid-section and distal hamstring muscle regions as well. Interestingly, however, the results of the present study are in line with the findings of recent in vivo work of Evangelidis and colleagues [24], who evaluated BF_{LH} fibre distribution (by means of sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE)), muscle volume and maximal and explosive knee flexor strength in a sample of 31 healthy male volunteers (non-athletic). They found a balanced muscle fibre composition in the BF_{LH}, consisting of 47% type I (slow twitch) muscle fibres, 36% type IIa (intermediate twitch) muscle fibres and 17% type IIx muscle fibres (fast twitch). Beside this renewing insight, they also found no association between muscle fibre type and maximal or explosive knee flexor strength. In their study, the large inter-individual variation in fibre type most possibly has an important share in these findings, which is most likely to be the case for the present study findings as well. Indeed, Our study results indicated that the hamstring muscle's relative carnosine content demonstrated a large CV (31.2%) as well, implying a large spread and heterogeneity in muscle fibre type composition within this study's sample of amateur soccer players. This large CV probably co-explains the absence of associations with HSIH and performance (as is the case for the above-mentioned study as well) [24], particularly given the fact that the selected study sample was rather limited in size and consisted of amateur athletes rather than professionals. The sample of Evangelidis consisted of recreationally active men, while ours consisted of amateur male soccer players. Evangelidis et al. concluded that the BF_{LH} should not be considered a fast twitch muscle fibre dominant muscle entity, and that its fibre composition is probably not part of its particular vulnerability to strain injury in their particular study sample.

The second and most important finding of this study is that estimated hamstring muscle fibre typology in amateur male soccer players did not present any association with HSIH. This is the opposite of what was expected based on existing theoretical frameworks [7, 10], and recently published work on the association between calf muscle carnosine content and hamstring strain injury risk [12]. These authors used the same ^{1}H-MRS procedure to determine the intramuscular carnosine content using the uni-articular soleus muscle instead of the hamstrings in a cohort of professional male soccer players who were prospectively monitored for hamstring injury occurrence over a period of 3 consecutive competition seasons. Similarly to our study, they established that male professional

soccer players exhibit a widely varying muscle fibre composition (44% slow twitch, 40% intermediate type and 15% fast twitch). Contrary to our findings, however, the results of their prospective analysis did indicate that athletes with a fast typology had a 5-fold higher risk of sustaining an index HSI compared to athletes with a predominantly slow twitch fibre profile. Although these findings seem conflicting, they are most likely to be explained by the essential difference in study samples. Lievens et al. assessed a cohort of professional male soccer players, who are equally exposed to highly strict and standardized training and competition sessions throughout a professionally composed competition season. Our sample consisted of amateur male soccer players, for whom soccer exposure by means of training and match participation is known to differ essentially between clubs and individual players. Moreover, other features such as weekly diet, weekly activity levels and participation in other recreational sports will influence the amateur athlete's injury risk and performance profile probably to a higher extent than the player's muscle fibre content, which might be slightly dependent on these differential soccer exposure and general behavioural features as well. We suggest that in amateur sports, too many other factors influence the player's injury risk and performance capacity due to the relatively low exposure rates throughout a competition season and large variety in behaviour outside of soccer specific training and competition times. Another, probably less pivotal, reason for the different findings in the study of Lievens et al. is that these authors particularly wanted to identify whether the overall (muscle group-independent) skeletal muscle fibre typology (in professional male soccer players) assessed in the soleus muscle was related to hamstring strain injury susceptibility. Our study specifically wanted to verify to what extent the hamstring's proper muscle fibre composition should be held accountable for the unremittingly high hamstring strain injury incidence (in amateur soccer players). The authors of the present study suggest that the fact that Lievens et al. found FT dominant players to be more susceptible to HSI might presumably partly be explained by the fact that these players possess more explosiveness, agility and speed, increasing the amount of mechanical strain imposed on the hamstrings during sport-specific manoeuvres. In accordance with this line of reasoning, the authors also suggested that players with a fast twitch dominant calf-muscle profile might present a higher HSI injury risk due to lower fatigue tolerance and the detrimental influence of fatigue on neuromuscular coordination capacity, potentially putting the hamstrings at increased risk for strain injury during high load lengthening contractions as is the case in high speed running. The present study did not find any associations between ^{1}H-MRS-estimated hamstring muscle fibre typology and HSIH. Nevertheless, a higher percentage of fast twitch fibres in the hamstring muscle of the individual amateur soccer player might predispose his hamstrings relatively more to HSI occurrence, but there is currently no evidence to state that this trend applies to the hamstring muscle unit as such. It is also important to note that within the population of recreational athletes, significant associations between maximal and explosive knee flexor strength and muscle thickness (objectified by means of T1 magnetic resonance imaging) were identified [26,30]). Other features of muscle architecture (e.g. muscle thickness and fascicle length) are therefore more likely to have an influence on the HSI risk in the recreationally active population, as these features significantly related to strength performance capacity as well [24, 26].

As regards our third and final hypothesis, no clear associations could be established between hamstring muscle fibre type and functional performance or isokinetic strength profile. Data analysis only established a significant association between the SemiT's carnosine content and the hamstring muscle's time to peak torque variable measured concentrically at 240°/s, which was established to be significantly shorter in participants presenting higher SemiT carnosine contents. Given this was the first study assessing the association between hamstring muscle fibre type and performance in a population of amateur soccer players, comparison with existing research is impossible. Albeit not in a sample of football players, the results of Evangelidis and colleagues are in line with our findings, demonstrating no association between maximal or explosive hamstring muscle strength and fibre typology [24]. Other fairly recent ^{1}H-MRS based fibre type determination studies assessing the relationship between intramuscular calf muscle carnosine content and athletic performance did find some significant associations between some particular speed-related performance characteristics and higher Z-scores/carnosine contents, albeit to a limited extent [17–18, 25]. The fact that we did not find any association between muscle fibre typology and performance, whereas previous work using almost the same methodological approach did, might again be the consequence of the differences between amateur and professional athletes. Athletic performance, in particular explosiveness, is dependent on many more factors (e.g. neuromuscular control, muscle strength, plyometric capacity, reaction speed) than muscle fibre typology alone. As these others features are adequately and highly similarly trained in professional athletes, the effect of muscle fibre type on athletic performance is considered to be much more important in professional compared to amateur athletes. Professional athletes are exposed to the same athletic exposure and possess similar motor skills, trained at an almost identical level (within the same sports domain). This is not the case for amateur athletes, where performance is expected to be primarily dependent on (1) physical fitness, (2) sports exposure, diet and behaviour, and (3) medical history and sports experience, with the underlying muscle fibre type only being a small part of his performance capacity profile. Beside differing athletic profiles between amateur and elite players, differences between carnosine content in SemiT and soleus muscle may play a role in finding different results here as well. Therefore, future work should ideally look into associations between fibre typology, injury susceptibility and performance, assessing different muscle groups and several intramuscular locations within those muscles.

As far as the role of hamstring muscle fibre type is concerned, the authors would not recommend further studies on its value in

sport-specific injury risk in amateur athletes. The present results suggest that in amateur soccer players, hamstring muscle fibre type demonstrates very high inter-individual variability and is not related to performance, and can therefore probably not be considered a strong risk factor for running-related hamstring strain injuries in the recreationally active population.

Strengths and Limitations

Despite being the very first study assessing the role of hamstring muscle fibre type composition in function of HSIH and performance in male soccer players, it is not without limitations. First, this was a retrospective study and therefore the present results do not allow the identification of any cause-effect relationships as regards the role of muscle fibre type in strain injury vulnerability. Second, our sample size was fairly limited. Given the high variability in carnosine content established within our selection of male soccer players, a bigger sample might have augmented the sensitivity and specificity of our findings (certainly as we had to exclude carnosine-content related data of 5 of the 44 participants – 3 in the HSIH group and 2 in the control group). We based our sample size on the ones documented in previous work using ^{1}H-MRS for the quantification of intramuscular carnosine contents in athletes for fibre type determination [14]. Using the effect sizes documented in the respective study, power and associated sample size calculations demonstrated a power-associated β-value of at least 0.80, using an average participant count of $n = 17$ in each of the included groups (total sample count of $n = 34$). Given the fact that these authors worked with more distinct metabolic athletic profiles (sprinters, marathon runners and athletes with a mixed explosive/endurance loading profile) [14], CV of the carnosine contents are assumed to be lower within athletic groups, allowing lower effect sizes to make valid conclusions. Given the fact that soccer players are repeatedly exposed to a mix of explosive and endurance related loading efforts, they are expected to present less distinct metabolic muscle fibre type features and a CV as regards their carnosine concentrations was to be expected. Future research investigating muscle fibre composition using ^{1}H-MRS in athletic populations with mixed metabolic loading profiles, might therefore benefit from larger sample sizes. Third, H-MRS analysis was performed selecting a standardized muscle voxel positioned centrally (transverse plane) in the proximal third (coronal and sagittal planes) of the SemiT in the dominant (i.e. preferred kicking) leg of the participants. We chose to do so because we wanted to (1) avoid biased results based on the factor dominance and (2) maximize the ^{1}H-MRS spectra's quality and improve the results of the shimming procedure to allow maximal magnetic field homogeneity within the voxel of interest (pilot investigations on the most frequently injured BF_{LH} revealed issues in the shimming procedure, making correct spectroscopy measurements and interpretation of these results hardly feasible). Taking into account the side and muscle location subject to the last HSI in the HSIH group within the voxel selection for consecutive spectroscopy analysis (and choosing similar muscle locations in the control group) might have resulted in different findings and insights (although previous work demonstrated muscle fibre composition to be identical when comparing both limbs) [27]. The authors are however fairly certain to have opted for the best approach in terms of research quality and associated validity and reliability, as opting to include differential muscle locations in both the dominant and non-dominant legs within an athletic sample already consisting of a substantial amount of inter-individual variability as far as muscle fibre architecture is concerned would make interpretation of the results very complex or even impossible. Because we also wanted to investigate the associations between hamstring fibre composition and athletic performance/strength, we are certain we made the correct choice standardizing in terms of body side and muscle location for the ^{1}H-MRS procedure. Lastly, it must be acknowledged that the TPT measure is less reliable at high measuring speeds [28]. This is also why this finding was considered negligible and the authors concluded that performance presented no association with SemiT's carnosine content.

CONCLUSIONS

Hamstring muscle fibre composition was established to be highly variable in male amateur soccer players and presented no association with HSIH or with athletic performance evaluated by means of sprints, vertical jump or hamstring strength endurance capacity or any isokinetic hamstring strength parameters. These study findings indicate that (in male amateur soccer) (1) the hamstring muscles do not seem to have a particular fibre type dominance and present substantial inter-individual variability (2) fibre composition does not relate to hamstring injury occurrence or athletic performance or hamstring strength in amateur male soccer players. Based on the results, the authors suggest that hamstring muscle fibre type should probably not be considered a substantial risk factor contributing to the hamstrings' susceptibility to strain injury in amateur male soccer players.

Practical implications

- Hamstring muscle fibre type, evaluated in the proximal part of the semitendinosus muscle, is not associated with their strain injury risk or athletic performance in amateur male soccer players.
- In amateur sports, many other confounding factors are believed to influence the player's performance capacity and injury risk profile. These factors are mostly related to large variation in athletic behaviour and background (both medical and sports related) at the recreational level of soccer competition.
- There is no need to focus on potential differences in muscle fibre type when wanting to organize muscle injury prevention at the amateur level.
- The large variability in fibre typology in between amateur soccer players indicates that recovery sessions should ideally be organized at the level of the individual athlete (and his typology), as generic recovery content can questionably sufficiently address both the fast and slow twitch dominant players.

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Conflict of interest

The authors declared no conflict of interests.

REFERENCES

1. Ekstrand J, Bengtsson H, Waldén M, Davison M, Khan KM, Hägglund M. Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: the UEFA Elite Club Injury Study from 2001/02 to 2021/22. Br J Sports Med. 2022. DOI: bjsports-2021-105407.
2. Freckleton G, Pizzari T. Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis. Br J Sports Med. 2013; 47:351–358.
3. Green B, Bourne MN, van Dyk N, et al. Recalibrating the risk of hamstring strain injury (HSI): A 2020 systematic review and meta-analysis of risk factors for index and recurrent hamstring strain injury in sport. Br J Sports Med. 2020; 54:1081–1088.
4. van Beijsterveldt AM, van de Port IG, Vereijken AJ, Backx FJ. Risk factors for hamstring injuries in male soccer players: a systematic review of prospective studies. Scand J Med Sci Sports. 2013; 23(3):253–62.
5. Huygaerts S, Cos F, Cohen D et al. Does Muscle–Tendon Unit Structure Predispose to Hamstring Strain Injury During Running? A Critical Review. Sports Med. 2021; 51:215–224.
6. Dahmane R, Djordjevic S, Smerdu V. Adaptive potential of human biceps femoris muscle demonstrated by histochemical, immunohistochemical and mechanomyographical methods. Med Biol Eng Comput. 2006; 44(11):999–1006.
7. Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: factors that lead to injury and re-injury. Sports Med. 2012; 42(3):209–26.
8. Fournier G, Bernard C, Cievet-Bonfils M, Kenney R, Pingon M, Sappey-Marinier E, Chazaud B, Gondin J, Servien E. Sex differences in semitendinosus muscle fiber-type composition. Scand J Med Sci Sports. 2022 Apr; 32(4):720–727. doi: 10.1111/sms.14127.
9. Zierath JR, Hawley JA. Skeletal muscle fiber type: influence on contractile and metabolic properties. PLoS Biol. 2004 Oct; 2(10):e348. doi: 10.1371/journal.pbio.0020348.
10. Garrett WE, Califf JC, Bassett FH. Histochemical correlates of hamstring injuries. Am J Sports Med. 1984; 12(2):98–103.
11. Qaisar R, Bhaskaran S, Van Remmen H. Muscle fiber type diversification during exercise and regeneration. Free Radic Biol Med. 2016; 98:56–67. doi: 10.1016/j.freeradbiomed.2016.03.025.
12. Lievens E, Van Vossel K, Van de Casteele F, Wezenbeek E, Deprez D, Matthys S, De Winne B, McNally S, De Graaf W, Murdoch JB., Bourgois JG., Witvrouw E., Derave W. Muscle fibre typology as a novel risk factor for hamstring strain injuries in professional football (soccer): a prospective cohort study. Sports Med. 2021; 52(1):177-185. doi: 10.1007/s40279-021-01538-2.
13. Vikne H, Gundersen K, Liestøl K, Maelen J, Vøllestad N. Intermuscular relationship of human muscle fiber type proportions: slow leg muscles predict slow neck muscles. Muscle Nerve. 2012; 45(4):527–35.
14. Baguet A, Everaert I, Hespel P, et al. A New Method for Non-Invasive Estimation of Human Muscle Fiber Type Composition. PLOS ONE. 2011; 6(7): e21956.
15. Harris RC, Wise JA, Price KA, Kim HJ, Kim CK, Sale C. Determinants of muscle carnosine content. Amino Acids. 2012; 43(1):5–12.
16. Klose U. Measurement sequences for single voxel proton MR spectroscopy. Eur J Radiol. 2008; 67(2):194–201.
17. Bex T, Baguet A, Achten E, Aerts P, De Clercq D, Derave W. Cyclic movement frequency is associated with muscle typology in athletes. Scand J Med Sci Sports. 2017; 27(2):223–229.
18. Mallett A, Bellinger P, Derave W, et al. Muscle Fiber Typology and Its Association With Start and Turn Performance in Elite Swimmers. Int J Sports Physiol Perform. 2021; 16(6):834–840.
19. Freckleton G, Cook J, Pizzari T. The predictive validity of a single leg bridge test for hamstring injuries in Australian Rules Football Players. Br J Sports Med. 2014; 48(8):713–7.
20. Schache AG, Dorn TW, Blanch PD, Brown NA, Pandy MG. Mechanics of the human hamstring muscles during sprinting. Med Sci Sports Exerc. 2012; 44(4):647–58.
21. Lievens E, Van Vossel K, Van de Casteele F, Krššák M, Murdoch JB, Befroy DE, Derave W. Cores of Reproducibility in Physiology (CORP): quantification of human skeletal muscle carnosine concentration by proton magnetic resonance spectroscopy. J Appl Physiol 2021; 131(1):250-264. doi: 10.1152/japplphysiol.00056.2021.
22. Ozdemir MS, Reyngoudt H, De Deene Y, et al. Absolute quantification of carnosine in human calf muscle by proton magnetic resonance spectroscopy. Phys Med Biol. 2007; 52(23):6781–94.
23. Choi SJ. Differential susceptibility on myosin heavy chain isoform following eccentric-induced muscle damage. J Exerc Rehabil. 2014; 10(6):344–348.
24. Evangelidis PE, Massey GJ, Ferguson RA, Wheeler PC, Pain MTG, Folland JP. The functional significance of hamstrings composition: is it really a "fast" muscle group? Scand J Med Sci Sports. 2017; 27(11):1181–1189.
25. Bellinger P, Bourne M, Duhig S, et al. Relationships between Lower Limb Muscle Characteristics and Force-Velocity Profiles Derived during Sprinting and Jumping. Med Sci Sports Exerc. 2021; 53(7):1400-1411. doi: 10.1249/MSS.0000000000002605.
26. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. Br J Sports Med. 2016; 50(24):1524–1535. doi: 10.1136/bjsports-2015-095362.
27. Horwath O, Envall H, Röja J, et al. Variablity in vastus lateralis fiber type distribution, fiber size and myonuclear content along and the between legs. J Appl Physiol. 2021;131(1):158-173. doi: 10.1152/japplphysiol.00053.2021.
28. Bernard PL, Amato M, Degache F, et al. Reproducibility of the time to peak torque and the joint angle at peak torque on knee of young sportsmen on the isokinetic dynamometer. Ann Phys Rehabil Med. 2012; 55(4):241–251.

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.

REFERENCES

1. FIFA. Physical Analysis of The Fifa Women's World Cup France 2019[tm]. 2019.
2. Vescovi JD, Fernandes E, Klas A. Physical Demands of Women's Soccer Matches: A Perspective Across the Developmental Spectrum. Front sports act living. 2021;3.
3. Mohr M, Krustrup P, Andersson H, Kirkendal D, Bangsbo J. Match Activities of Elite Women Soccer Players at Different Performance Levels. J Strength Cond Res. 2008; 22(2):341–9.
4. Faude O, Koch T, Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. J. Sports Sci. 2012; 30(7):625–631.
5. Panduro J, Ermidis G, Røddik L, Vigh-Larsen JP, Madsen EE, Larsen MN, Pettersen SA, Krustrup P, Randers MB. Physical performance and loading for six playing positions in elite female football: full-game, end-game, and peak periods. Scand J Med Sci Sports. 2021; 00:1–12.
6. Bradley PS, Bendiksen M, Dellal A, et al. The Application of the Yo-Yo Intermittent Endurance Level 2 Test to Elite Female Soccer Populations. Scand J Med Sci Sports. 2014; 24(1):43–54.
7. Krustrup P, Mohr M, Ellingsgaard H, Bangsbo J. Physical demands during an elite female soccer game: Importance of training status. Med Sci Sports Exerc. 2005; 37(7):1242–1248.
8. Hewitt A, Norton K, Lyons K. Movement profiles of elite women soccer players during international matches and the effect of opposition's team ranking. J Sports Sci. 2014; 32(20):1874–1880.
9. Vescovi JD, Falenchuk O. Contextual factors on physical demands in professional women's soccer: Female Athletes in Motion study. Eur J Sport Sci. 2019; 19(2):141–146.
10. Trewin J, Sar Meylan CÉ, Varley MC, Cronin J, Ling D. Effect of match factors on the running performance of elite female soccer players. J Strength Cond Res. 2018; 32(7):2002–2009.
11. Haugen TA, Tønnessen E, Seiler S. Speed and Countermovement-Jump Characteristics of Elite Female Soccer Players, 1995–2010. Int J Sports Physiol Perform. 2012; 7(4):340–349.
12. Haugen TA, Tønnessen E, Hem E, Leirstein S, Seiler S. VO_2max characteristics of elite female soccer players, 1989–2007. Int J Sports Physiol Perform. 2014; 9(3):515–521.
13. Krustrup P, Zebis M, Jensen JM, Mohr M. Game-induced fatigue patterns in elite female soccer. J Strength Cond Res. 2010; 24(2):437–41.
14. Jackman SR, Scott S, Randers MB, Ørntoft CØ, Blackwell J, Zar A, Helge EW, Mohr M, Krustrup P. Musculoskeletal health profile for elite female footballers versus untrained young women before and after 16 weeks of football training. J. Sports Sci. 2013;31(13), 1468–1474.
15. Emmonds S, Nicholson G, Begg C, Jones B, Bissas A. Importance of physical qualities for speed and change of direction ability in elite female soccer players. J Strength Cond Res. 2019; 33(6):1669–1677.
16. Aquino R, Carling C, Maia J, Palucci Vieira LH, Wilson RS, Smith N, Almeida R, Gonzalves LGC, Kalva-Filho CA, Garganta J, Puggina EF. Relationships between running demands in soccer match-play, anthropometric, and physical fitness characteristics: a systematic review. Int J Perform Anal Sport. 2020; 20(3):534–555.
17. Gonçalves L, Clemente FM, Barrera JI, Sarmento H, González-Fernández FT, Palucci Vieira LH, Figueiredo AJ, Clark CCT, Carral JMC. Relationships between Fitness Status and Match Running Performance in Adult Women Soccer Players: A Cohort Study. Medicina. 2021; 57(6):617.
18. Villaseca-Vicuña R, Otero-Saborido FM, Perez-Contreras J, Gonzalez-Jurado JA. Relationship between Physical Fitness and Match Performance Parameters of Chile Women's National Football Team. Int J Environ Res Public Health. 2021; 18(16):8412.
19. McCormack WP, Stout JR, Wells AJ, Gonzalez AM, Mangine GT, Fragala MS, Hoffman JR. Predictors of high-intensity running capacity in collegiate women during a soccer game. J Strength Cond Res. 2014; 28(4):964–70.
20. Silva JR, Magalhaes J, Ascensao A, Seabra, AF, Rebelo AN. Training status and match activity of professional soccer players throughout a season. J Strength Cond Res. 2013; 27(1):20–30.
21. Oliveira R, Francisco R, Fernandes R, Martins A, Nobari H, Clemente F, Brito J. In-season body composition effects in professional women soccer players. Int J Environ Res Public Health. 2021; 18; 12023.
22. Rienzi E, Drust B, Reilly T, Carter JEL, Martin. Investigation of Anthropometric and Work-Rate Profiles of Elite South American international soccer players. J Sports Med Phys Fitness. 2000; 40(2):162–9.
23. Sporis G, Dujic I, Trajkovic N, Milanovic Z, Madic D. Relationship Between Morphological Characteristics and Match Performance in Junior Soccer Players. Int J Morphol. 2017; 35(1):37–41.
24. Radzimiński Ł, Szwarc A, Padrón-Cabo A, Jastrzębski Z. Correlations between body composition, aerobic capacity, speed and distance covered among professional soccer players during official matches. J Sports Med Phys Fitness. 2020; 60(2):257–262
25. Mckay AKA, Stellingwerff T, Smith ES, Martin DT, Mujika I, Goosey-Tolfrey VL, Sheppard J, Burke LM. Defining Training and Performance Caliber: A Participant Classification Framework. 2022; 29; 1–15.
26. Scott MTU, Scott TJ, Kelly VG. The Validity and Reliability of Global Positioning Systems in Team Sport. J Strength Cond Res. 2016; 30(5):1470–1490.
27. Huggins RA, Giersch GEW, Belval LN, Benjamin CL, Curtis RM, Sekiguchi Y, Peltonen J, Casa DJ. The Validity and Reliability of Global Positioning System Units for Measuring Distance and Velocity During Linear and Team Sport Simulated Movements. J Strength Cond Res. 2020; 34(11):3070–3077.
28. Fernandes-da-Silva J, Castagna C, Teixeira AS, Carminatti LJ, Guglielmo LGA. The peak velocity derived from the Carminatti Test is related to physical match performance in young soccer players. J Sports Sci. 2016; 34(24):2238–2245.
29. O'Donoghue PG. Time-motion analysis of work-rate in English FA Premier League soccer. Int J Perform Anal Sport. 2002; 2(1):36–43.
30. Wing CE, Turner AN, Bishop CJ. The Importance of Strength and Power on Key Performance Indicators in Elite Youth Soccer. J Strength Cond Res. 2020; 34(7):2006–2014.
31. Samozino P, Morin JB, Hintzy F, Belli A. A simple method for measuring force, velocity and power output during squat jump. J Biomech. 2008; 41(14):2940–2945.
32. Östenberg A, Roos H, Östenberg A. Injury risk factors in female European football. A prospective study of 123 players during one season. J Med Sci Sports. 2000; 10:279–285.
33. DeLang MD, Rouissi M, Bragazzi NL, Chamari K, Salamh PA. Soccer footedness and between-limbs muscle strength: Systematic review and meta-analysis. Int J Sports Physiol Perform. 2019; 14(5):551–562.
34. Vesterinen V, Häkkinen K, Laine T, Hynynen E, Mikkola J, Nummela A. Predictors of individual adaptation to high-volume or high-intensity endurance training in recreational endurance runners. Scand J Med Sci Sports. 2016; 26(8):885–893.
35. Sillanpää E, Häkkinen A, Häkkinen K. Body composition changes by DXA, BIA and skinfolds during exercise training in women. Eur J Appl Physiol. 2013; 113(9):2331–2341.
36. Vikmoen O, Raastad T, Ellefsen S, Rønnestad BR. Adaptations to strength

training differ between endurance-trained and untrained women. Eur J Appl Physiol. 2020 Jul; 120(7):1541–1549.
37. Risberg MA, Steffen K, Nilstad A, Myklebust G, Kristianslund E, Moltubakk MM, Krosshaug T. Normative quadriceps and hamstring muscle strength values for female, healthy, elite handball and football players. J Strength Cond Res. 2018; 32(8):2314–2323.
38. Aagaard P, Andersen JL, Dyhre-Poulsen P, Leffers, AM, Wagner A, Magnusson SP, Halkjaer-Kristensen J, Simonsen EB. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. J Physiol. 2001; 534(2):613–623.
39. Watson J, Weir J, Maughan RJ, Watson JS. Muscle strength and cross-sectional area in man: a comparison of strength-trained and untrained subjects. Br J Sports Med. 1984; 18(3):149–57.

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Quantification of training load across two competitive seasons in elite senior and youth male soccer players from an English Premiership club

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ABSTRACT: This study aimed to compare the daily training load (TL) in first-team and U-18 soccer players from an English Premiership club. 36 first-team (age 23.2 ± 5.9 years, weight 75.2 ± 8.1 kg, height 1.83 ± 0.06 m), and 22 U-18 players (age 17.5 ± 1.1 years, weight 71.1 ± 8.2 kg, height 1.78 ± 0.08 m) participated. GPS metrics were measured during all pitch training sessions throughout the 2020–21 and 2021–22 seasons. Linear mixed-effect model analyses revealed that, irrespective of training day, U-18 players covered greater total and explosive distance than first-team players, and performed a higher number of accelerations and decelerations, whereas first-team players covered greater sprint distance. Irrespective of the team, all examined variables were greater at match-day (MD)-3, while the number of accelerations and decelerations were higher at MD-4. Significant team-by-training day interactions revealed that U-18 players covered greater total and high-intensity distances than first-team players at MD-4, MD-2, and MD-1, whereas first-team players covered greater total and high-intensity distances at MD-3. Sprint distance was greater for first-team players at MD-3 and MD-4, while explosive distance was greater for U-18 players at MD-2. Also, U-18 players performed a higher number of accelerations than first-team players at MD-3 and MD-2, and a higher number of decelerations at MD-4. The present results provide novel information on TL patterns in English Premiership soccer and contribute to understanding how training methods to physically develop players are implemented in different countries and leagues.

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INTRODUCTION

Soccer is a sport that is intermittent in nature with short periods of high-intensity activity separated by longer periods of low-intensity actions [1]. Knowledge of these characteristics are vitally important to adequately prepare players for the demands of match-play and have implications for training prescription [2]. The occurrence of these high-intensity activities during match-play has increased over the last few decades [3, 4], thus driving the development of specific training to allow players to cope with these ever-evolving demands. The progress of these physical demands has aligned with advancements in technology which have enhanced the ability of practitioners to quantify these aspects of physical performance during soccer training and, consequently, it allowed better training prescription, load adjustment and thus adequate preparation of players for match-play [5].

The increasement in physical demands and availability of technology has led to a rise in the popularity of quantifying player activities during training on a daily basis [6]. The quantification of physical training demands is commonly referred as training load (TL) [7]. Training load can be subdivided into external and internal dimensions. External load refers to the locomotive profile of individual players during training, while internal load refers to the individual physiological response to external load [8, 9]. In elite contemporary soccer clubs, both external and internal load are monitored respectively using various microelectromechanical systems and heart-rate telemetry systems to quantify the overall load placed on players during training and match-play [10].

The quantification of external and internal intensity under differing conditions and across various sessions and seasonal periods

(pre-, in-season mesocycles) have been systematic reviewed and employed various monitoring methods such as total distance, high-speed running, sprinting, accelerations and decelerations in professional [11] and youth male soccer players [12]. However, the same study [11] highlighted a limitation that the varying training made it difficult to provide benchmark values for the key external and internal measures, which was also emphasised as several competition levels and countries were included. Notwithstanding, another study that was not included in the previous systematic review [12] found limited variation of running and accelerometry-based measures considering playing position, stage of the season and loading during mid-week training with the exception of the two days prior to the match [13].

Furthermore, to our knowledge, only limited studies [14, 15] have attempted to quantify the TL of elite senior (first-team) and youth (U-18 team) soccer players from the same club and scarce studies are known when analysing both teams match data [16, 17]. Currently, scant literature is available comparing differences in TL between competition levels (first-team versus U-18 team) [14, 15]. This is significant as soccer players differ greatly between age groups [11–14], standards (top-class and moderate professional soccer players) [18], and the playing style of any given team [19].

In terms of developing soccer players, it may be important to understand the differences in TL between elite senior and youth players from the same club to allow practitioners to appropriately inform this process. While Buchheit et al. [20] presented physical match data of elite youth soccer players (U-13 to U-18), this study did not provide an understanding of the weekly TL throughout the season to adequately prepare these players for their match demands. Although, more recently TL comparisons have been conducted in first and youth team players [14, 15], albeit across limited periods (4 weeks) [15] and mainly examining locomotive metrics (distances covered) [14], while other accelerometry-based measures could provide impactful information for coaches. There are small discrepancies between the velocity thresholds used in the previous studies [14, 15] and those used in the general literature around soccer performance which makes a comparison of the data difficult. Specifically, the study of Houtmeyers et al. [14] found that total distance and low-intensity running (12–15 km/h) was higher for U-19 players when compared to first-team players, while distances of running at 15–20 and 20–25 km/h were similar for both teams. Moreover, first-team players covered higher running distances at > 25 km/h than U-19 players. The study of Copalle et al. [15] also showed that running distances (16–19.9 km/h, > 20 km/h and > 25 km/h) were significantly higher in U-19 players when compared to the first-team, with small effect sizes.

Examining data from different countries and leagues is vital to improving our understanding of various training methods to physically develop players [16]. Although recent research into TL in senior [11] and youth [21, 22] male soccer players have extended the existing literature, more is warranted to fully understand the different demands between young and adult players and practically apply the findings. Vigh-Larsen et al. [17] compared the U-17, U-19 and first-team from the same Danish SuperLiga club and found a higher number of accelerations and decelerations for the U-19 team when compared with both the U-17 and first-team during match-play, while no differences were found for distance covered during high-intensity running or sprinting. However, currently accelerations and decelerations have not been previously compared in youth and first-team players during training activities across consecutive seasons. Thus, it is important to quantity TL across a season and identify any differences in TL between competition levels to provide practitioners with detailed information to allow specific sessions to be designed and delivered [16].

Therefore, the aims of this study were to compare the TL among different training days and between elite senior (first-team) and youth (U-18 team) soccer players over two competitive seasons (2020–21 and 2021–2022) from an English Premiership club. Our hypothesis was that varying TL data will be evident according to the typical microcycle structure of an elite English Premiership soccer club. Moreover, based on previous studies [14, 15], it was hypothesised that first-team players will display lower loads than U-18.

MATERIALS AND METHODS

Participants

58 professional outfield soccer players from an English Premiership club were involved in the study. Data from the complete 2020–21 and 2021–22 seasons included 36 senior players (first-team squad) (age 23.2 ± 5.9 years, weight 75.2 ± 8.1 kg, height 1.83 ± 0.06 m), and 22 youth players (U-18 youth squad) (age 17.5 ± 1.1 years, weight 71.1 ± 8.2 kg, height 1.78 ± 0.08 m). The inclusion criteria for the study included: (i) listed on the roster of the first-team or U-18 squad of the English Premiership club at the start of the 2020–21 and/or 2021–22 seasons, (ii) regularly trained with the respective team (first-team or U-18), (iii) participated in at least 80% of training sessions and matches, (iv) did not use dietary supplements during the study, (v) who were uninjured over the course of the study, and (vi) who did not participate in another training program along with this study. Additionally, the exclusion criteria for the study included: (i) long-term injured player data, (ii) player joining the team late in either of the study seasons, (iii) lack of full, complete data for training or match-play, (iv) an in-sufficient number of satellite connection signals, and (v) goalkeepers, due to the different variations in the physical demands with outfield players.

Players were assigned to one of five positions as match demands for these differ significantly. The methodology of differentiating specialised positions was adapted from previous research [23]. As various situational factors have an influence on the style of play that can be modulated by different tactical roles [24], context was considered whilst using a player's average position in an attempt to determine a player's relevant tactical role in the team [25]. All participants examined were classified based on their regular playing position at the start of each season and remained consistent throughout the study

period: centre-backs (CB; n = 14, senior n = 8 and youth n = 6), wing-backs (WB; n = 8, senior n = 6 and youth n = 2), centre midfielders (CM; n = 13, senior n = 9 and youth n = 4), wide midfielders (WM; n = 15, senior n = 9 and youth n = 6), and strikers (ST; n = 8, senior n = 4 and youth n = 4). Goalkeepers were excluded from the investigation due to the specific nature of their match activity and their low running demands [26, 27]. All data collected resulted from normal analytical procedures regarding player monitoring over the competitive season, nevertheless, written informed consent was obtained from all participants. Informed written consent was provided by the parents of participants under 18 years of age. The study was conducted according to the requirements of the Declaration of Helsinki and was approved by the local Ethics Committee of the University of Central Lancashire (N 0104 dated 7/12/20) and the English Premiership club from which the subjects volunteered [28]. To ensure confidentiality, all data were anonymised prior to analysis.

Training information

Training data were collected over a two-year period across the 2020–21 and 2021–22 competitive seasons. Only team pitch-based training sessions were included for analysis. All other sessions, individual training sessions, recovery sessions, and rehabilitation training sessions were excluded [29, 30]. The planning of all soccer content was cyclical in nature and reflective of modern methods of periodisation in elite soccer and thus the external physical load experienced by players was undulating across a microcycle leading to match-play. The number of days between matches differed [31, 32] and training sessions in elite soccer microcycles have recently been classified based on days prior to a match (MD minus (-)) or post-match (MD plus (+)) [33]. All training sessions were integrated to include technical, tactical, physical and mental components. All players completed one to two strength and power gym-based sessions per microcycle incorporating upper and lower body and core exercises, although these sessions were not included in the analyses as mentioned earlier [29, 30]. All physical TL data was collected at the club's official training facility.

Both teams only participated in one competitive league match during a microcycle and thus the structure of the training days was standardised across both teams and seasons. The first and second days post-match (MD+1 and +2) were a day off and therefore no GPS data was available. Additional fitness sessions for non-starters were limited to the immediate post-match period and GPS data was collected but not included in the study analysis. The start of the next MD microcycle was MD-4, four days prior to competition, and focussed on drills designed to develop players' strength, power and ability to repeatedly produce explosive actions. This session was devised to improve technical and tactical understanding when 'out-of-possession' whilst developing the necessary physical qualities to produce high accelerations and decelerations without decrement. Individual and unit (defence, midfield, attack) practices followed by positional games and small-sided games with goalkeepers in restricted pitch dimensions were delivered. Three days pre-match (MD-3) aimed to tactically prepare players when 'in-possession' whilst developing position-specific high-intensity and sprint running capabilities. Practices entailed full-pitch attacking tactical patterns (10v0, 10v4) and large numbered games regularly concluding in 11v11 format (> 8v8 plus goalkeepers). The structure of MD-2, two days prior to the match, concentrated on repeating technical-tactical information at low-intensity in various functional pitch areas and dimensions and thus was regarded as an 'under-loaded' session considering all key GPS metrics. This session included position-specific passing patterns and then divided players into unit-specific drills for defending or attacking. The final session of the weekly microcycle, MD-1, was standardised with no variety and drills intended to provide neural stimulation to players whilst also finalising tactical situations and set-plays. For the purposes of this study, the tactical periodisation approach and subsequent TL from all MD-4, MD-3, MD-2, and MD-1 training sessions performed by both teams across the 2020–2021 and 2021–2022 seasons were standardised and examined. For the reliability and validity of the study, only data from players who performed the full session duration have been used, withdrawing the data from goalkeepers and players whose TL was manipulated due to fatigue management or injury. A total number of 493 team training sessions (first-team, n = 268; U-18, n = 225), were examined, of which 158 were MD-1 sessions (first-team, n = 88; U-18, n = 79), 126 were MD-2 sessions (first-team, n = 74; U-18, n = 52), 113 were MD-3 sessions (first-team, n = 57; U-18, n = 56), and 95 were MD-4 sessions (first-team, n = 49; U-18, n = 46). A total of 6828 individual player training session data points were included (MD-1, n = 2354; MD-2, n = 1754; MD-3, n = 1485; MD-4, n = 1235).

Data collection

Physical data were consistently monitored across both study seasons during all training sessions and match-play using a 18 Hz Global Positioning System (GPS) technology tracking system (Apex Pod, version 4.03, 50 gr, 88 × 33 mm; Statsports; Northern Ireland, UK) that has been previously validated in a student population for tracking distance covered and peak velocity during simulated team sports and linear sprinting [34]. All devices were activated 30-minutes before data collection to allow the acquisition of satellite signals and to synchronise the GPS clock with the satellite's atomic clock [35]. Quantifying the devices' accuracy indicated a 2.5% estimation error in distance covered, with accuracy improving as the distance covered increased and the speed of movement decreased [36]. To avoid inter-unit error, each player wore the same device during the study period [37, 38], although the present GPS system has previously reported excellent inter-unit reliability [39]. Specifically designed vests were used to hold the devices, located on the player's upper torso, and anatomically adjusted to each player, as previously described [40]. To avoid potential inter-unit variation players wore the same GPS unit for each training session and match [40]. The GPS signal quality and horizontal dilution of position was connected to

a mean number of 21 ± 3 satellites, range 18–23, while HDOP for both seasons was 0.9 (first-team) and 1.3 (U-18), respectively. On completion of each session, GPS data were extracted using proprietary software (Apex, 10 Hz version 4.3.8, Statsports Software; Northern Ireland, UK) as software-derived data is a more simple and efficient way for practitioners to obtain data in an applied environment, with no differences reported between processing methods (software-derived to raw processed) [41]. The dwell time (minimum effort duration) was set at 0.5 s to detect high-intensity running and 1 s to detect sprint distance efforts, in-line with manufacturers recommendations and default settings to maintain consistent data processing [40]. Furthermore, the internal processing of the GPS units utilised the Doppler shift method to calculate both distance and velocity data which is shown to display a higher level of precision and less error compared with data calculated via positional differentiation [42]. Statsports provided written permission to allow all data to be used for research purposes.

The total distance covered (m); high-intensity distance (m; total distance covered 5.5–7 $m \cdot s^{-1}$); sprint distance (m; total distance covered > 7 $m \cdot s^{-1}$ were examined and have been established based on previous studies [31, 43]. The following physical variables were also quantified in this study: explosive distance (m; distance covered with acceleration above 1.12 m/s^{-2}); the number of very high-intensity accelerations (> +3 $m \cdot s^{-2}$ with minimum duration of 0.5 s); the number of very high-intensity decelerations (< -3 $m \cdot s^{-2}$ with minimum duration of 0.5 s) [13, 37].

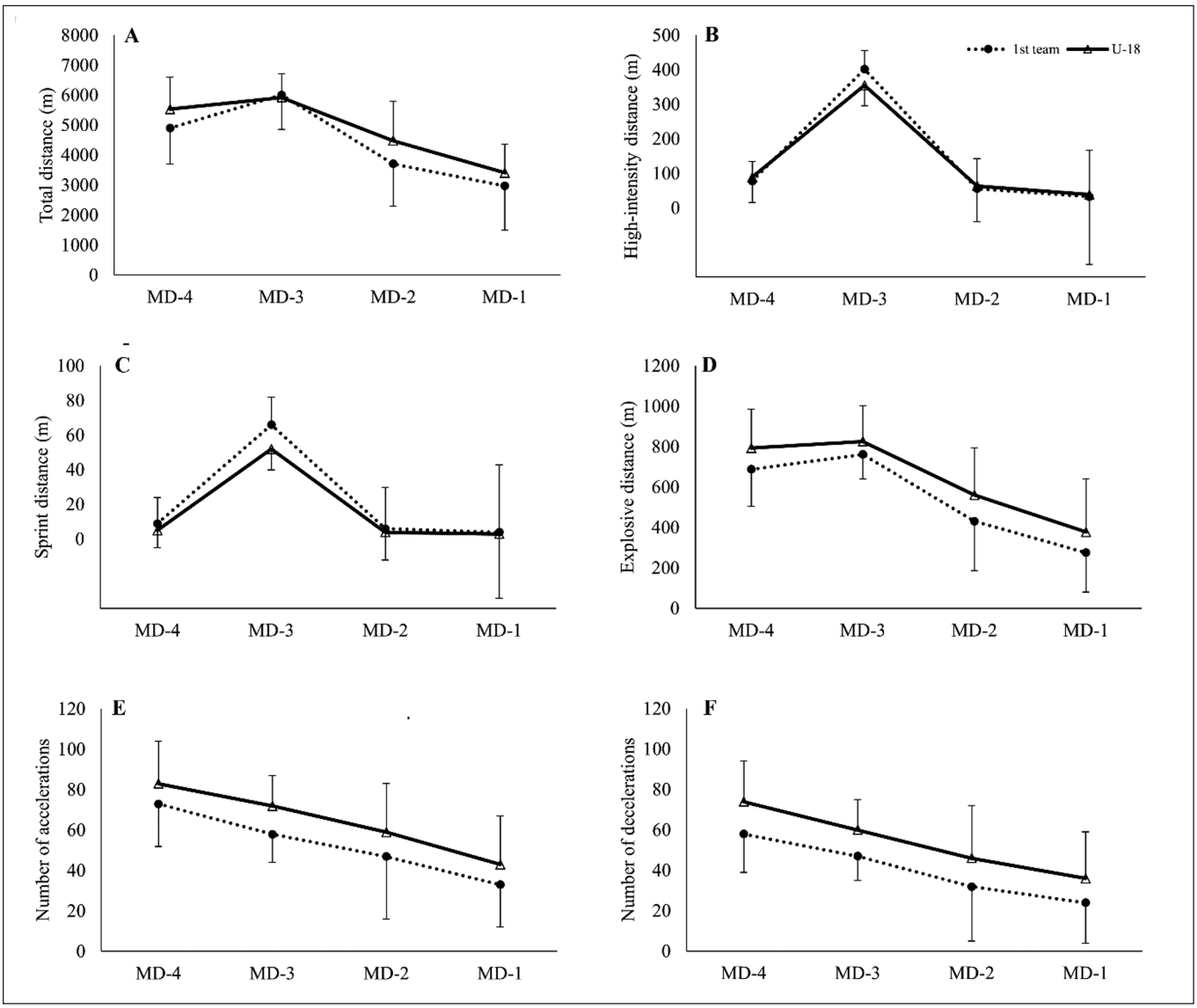


FIG. 1. Mean and standard deviation values of total distance (A), high-intensity distance (B), sprint distance (C), explosive distance (D), the number of accelerations (E), and the number of decelerations (F) across the training microcycle from the two examined teams. The dotted line with black circles: first-team; solid line with white triangles: U-18.

Statistical analyses

Data are displayed as the mean ± standard deviation. Linear mixed-effect models with random intercepts for individual players' ID were used to assess the effects of the team (first-team / U-18), training day (MD-4, MD-3, MD-2, MD-1), and their interaction on the examined GPS metrics. When there was a significant effect of the team and/or training day and/or their interaction, post-hoc Tukey's HSD tests for pairwise comparisons were performed to examine which categories differed and determine the source of the interaction. The Cohen's d effect-size (ES) statistic was calculated to determine the magnitude of effects by the difference of two population means which are then divided by the standard deviation from the data. Absolute differences between teams were standardised by the respective between-player standard deviation of each outcome variable to determine an effect size (ES). Standardised differences were evaluated as trivial (< 0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0), very large (2.0–4.0), and extremely large (> 4.0) [38]. The statistical analyses were performed in R language and environment for statistical computing (version 4.2.0, The R Foundation for Statistical Computing, Vienna, Austria), using the packages nlme and lsmeans [44]. For all analyses, statistical significance was set at $p < 0.05$.

TABLE 1. Estimated differences between teams for the examined metrics on all training days. CI: confidence interval; ES: effect size

		First-team / U-18 estimated difference (95% CI)	p value	ES
Total Distance (m)	**MD-4**	-435 (-696 to -173)	< 0.001	1.08
	MD-3	+279 (+27 to +532)	0.018	0.70
	MD-2	-590 (-842 to -339)	< 0.001	1.47
	MD-1	-235 (-467 to -4)	0.043	0.59
High-intensity distance (m)	**MD-4**	-7 (-30 to +15)	0.976	0.33
	MD-3	49 (28 to +71)	< 0.001	2.23
	MD-2	-6 (-27 to +16)	0.993	0.26
	MD-1	-3 (-23 to +17)	1.000	0.14
Sprint distance (m)	**MD-4**	+5 (0 to +11)	0.047	1.00
	MD-3	+15 (+10 to +20)	< 0.001	2.84
	MD-2	+4 (-1 to +9)	0.279	0.73
	MD-1	+2 (-3 to +7)	0.885	0.38
Explosive distance (m)	**MD-4**	-36 (-84 to +11)	0.278	0.42
	MD-3	+5 (-41 to +52)	1.000	0.06
	MD-2	-58 (-104 to -12)	0.004	0.66
	MD-1	-29 (-72 to +14)	0.431	0.34
Number of accelerations	**MD-4**	-5 (-10 to 0)	0.103	0.47
	MD-3	-9 (-14 to -4)	< 0.001	0.91
	MD-2	-6 (-11 to -1)	0.006	0.61
	MD-1	-4 (-8 to +1)	0.305	0.35
Number of decelerations	**MD-4**	-6 (-11 to -1)	0.003	0.56
	MD-3	-2 (-7 to +2)	0.821	0.21
	MD-2	-4 (-9 to +1)	0.171	0.36
	MD-1	-1 (-6 to +3)	0.992	0.11

RESULTS

Figure 1 shows the mean and standard deviation values of the examined GPS metrics from both teams across the MD-4 to MD-1 training days.

The linear mixed-effect model analyses revealed a significant ($p < 0.01$) main effect of the team for all examined variables apart from high-intensity distance ($p = 0.081$). Irrespective of the training day, when compared to first-team players, U-18 players covered greater total and explosive distance, and performed a higher number of accelerations and decelerations. Conversely, first-team players covered greater sprint distance than U-18 players. Also, a significant ($p < 0.01$) main effect of the training day was detected for all examined variables. Post-hoc pairwise comparisons for the training day revealed that, irrespective of team (first-team / U-18), the total distance covered, high-intensity distance, sprint distance and explosive distance were greater on MD-3, followed by MD-4, MD-2 and MD-1. The above differences between days were significant ($p < 0.05$) for all examined metrics and for all pairwise comparisons between any pair of training days, with the exception of MD-2 vs. MD-1 comparison for sprint distance ($p = 0.259$). Conversely, the number of accelerations and decelerations was higher at MD-4, followed by MD-3, MD-2, and MD-1. For both accelerations and decelerations, the differences between all training days were statistically significant ($p < 0.05$), that is, MD-4 > MD-3 > MD-2 > MD-1. The team-by-training day interaction was significant ($p < 0.01$) for all examined outcome variables. To explore the source of the interaction, pairwise comparisons between teams at any given training day were examined as post-hoc analysis after the linear mixed-effect model analyses were conducted. Table 1 displays the estimated differences between teams for any given training day.

U-18 players covered greater total distance than first-team players at MD-4, MD-2, MD-1, with small (ES = 0.59) to large (ES = 1.47) differences. On the contrary, at MD-3, first-team players covered a greater total distance than U-18 players, with a moderate difference (ES = 0.70). For high-intensity distance, the differences between teams were not statistically significant at MD-4, MD-2, and MD-1, while first-team players covered greater high-intensity distance than U-18 players at MD-3, with a very large difference (ES = 2.23) between teams. The sprint distance covered was greater for the first-team compared to U-18 players at MD-4 with a moderate difference (ES = 1.00), and at MD-3 with a very large difference (ES = 2.84), while there were no significant differences between teams at MD-2 and MD-1. Explosive distance was greater for U-18 players than for first-team players at MD-2, with a moderate

difference (ES = 0.66), whereas no significant differences were detected at MD-4, MD-3, and MD-1. Finally, U-18 players performed a higher number of accelerations than first-team players at MD-3 and MD-2 (both moderate differences, ES = 0.91 and 0.61, respectively), and a higher number of decelerations at MD-4, with a small difference (ES = 0.56). On all other training days, no significant differences were observed between teams for the number of accelerations and decelerations (Table 1).

DISCUSSION

The aims of this study were to compare the TL among different training days and between elite senior (first-team) and youth (U-18 team) soccer players over two competitive seasons (2020-21 and 2021-2022) from an English Premiership club. Regardless of the team, the main results showed that the high-intensity distance, sprint distance and explosive distance were greater at MD-3, followed by MD-4, MD-2 and MD-1. Moreover, the number of accelerations and decelerations was higher at MD-4, followed by MD-3, MD-2, and MD-1. When comparing both teams, total distance was greater for U-18 players at MD-4, MD-2, MD-1, and greater for the first-team at MD-3. While, high-intensity and sprint distance were greater for the first-team at MD-3 (sprint distance also slightly greater at MD-4) and accelerations and decelerations were higher for the U-18 team.

To the best of the authors knowledge, this was the first study that analysed training data from two different age group teams from the same English Premiership club that contributes additional new findings for the specific context of English Premiership soccer. One of the strengths of the present study was that data from two consecutive seasons were used with the aim of data becoming more robust and not comparing data between seasons, where different players and coaches were used in both seasons, which was not the current scenario. The other major strength was the comparison of two teams, U-18 and first-team, which is very scarce in the literature [14, 15].

Nonetheless, considering the range values previously presented in the systematic review of young soccer players [22], the present data found that the U-18 team was within range for total distance of 3964–6500 m, greater for high-intensity distance (although with a different threshold) (12–250 m) and also greater for sprint distance (0–30 m) [22]. Regarding the number of accelerations and decelerations, the values seemed to be similar to those displayed by U-17 and U-19 Portuguese soccer players [45] with a slight tendency of higher values for the U-18 team of the present study. Moreover, considering the range values presented in the previous systematic review in professional soccer players, namely, total distance 2143–9540 m, distance > 18 km/h = 7–541 m, distance > 24 km/h = 1–190 m, acceleration number > 3 $m \cdot s^{-2}$ = 9–195, deceleration number > -3 $m \cdot s^{-2}$ = 10–157 [10], the findings of this study showed that the first-team values were within previous ranges.

Regarding the findings related to higher values at MD-3, followed by MD-4, MD-2 and MD-1 for total distance, this was similar to a previous study in U-18 English Premier league players that also found the second training day of the week produced higher values for running distance variables [46]. Similar findings in U-18 Spanish players for running, high-intensity and sprint distance revealed higher values at MD-3 and MD-2 when compared with the other training sessions, although only six training sessions from non-identical microcycle structures were reported [47]. Additionally, the present study found higher values at MD-4 for accelerometry-based variables. Still, no studies were found that analysed microcycles with only four training sessions in U-18 soccer players, although with three training sessions, it has been previously demonstrated that higher values for both accelerations and decelerations in the first training session of the week occur, while running distances were higher on the second training session of the week [45], which is similar to the findings of the present study. A study [13] in U-18 players with only five training sessions showed limited variation between MD-4, MD-3 and MD-2 which opposes the present study findings. Furthermore, other studies that included data from non-identical microcycle structures (which provided six training sessions) showed that accelerations and decelerations were higher at MD-4 compared with other training sessions in U-18 players [47].

In the professional first-team players analysed in the current study, the same pattern was observed, which was corroborated by the range values highlighted in the previous systematic review [11]. Indeed, previous studies with four training sessions showed different results. For instance, higher values at MD-3 (or the second session of the week) for running distances and accelerometry-based variables were also reported by English Premier League players [33] and for sprinting by Dutch Eredivisie players [32]. Nonetheless, higher values were shown at MD-4 (or the first session of the week), for running distances by Portuguese Premier League players [48] and for both running and accelerometry-based variables in Dutch Eredivisie players [32]. A possible justification for some differences between the results of the present study and the previous literature could be attributed to the different training competitions [46] and different coaching philosophies and training methods [49].

Regarding the comparison between the first and U-18 teams, it was observed that the first-team covered greater high-intensity and sprint distance especially at MD-3 compared with U-18 players, while the other training days were similar. This may be attributed to the use of absolute speed thresholds [50]. Even so, the present data suggests that first-team team players have greater sprint capabilities than youth players. Thus, future studies should test individual thresholds with English Premiership players. Additionally, at MD-4, MD-2 and MD-1, the U-18 team covered a greater total distance which may be associated with less competitive pressure compared to the first-team environment. A study conducted in the Chinese Super league observed that some positions such as central defenders and fullbacks covered more high-intensity and sprint running distance in the high possession teams, while wide midfielders and forwards covered more high-intensity and sprint running distance in the low possession teams [51]. Although the context of high/low ball possession was not considered

in the present research, it is possible that it could justify the present results. Thus, it is suggested to confirm such possibility in future investigations. Even so, there may be a practical application suggestion to develop physical capacities such as aerobic fitness, especially on MD-4 with on-pitch training, without the concern of an undulating, tapering strategy to recover players for the forthcoming match. Furthermore, the U-18 team performed more explosive distance, a greater number of accelerations and decelerations which may be attributed to the different training drills implemented and again a variation of a tapering strategy when compared with the first-team.

Despite the findings of this study, there are some limitations that should be listed: a) only one youth team and one professional soccer team players were used which consequently avoided the analysis of playing positions due to the small number in each team; b) no variable of internal load was used which could strengthen the findings of this study; c) generalisation of the results should be cautious as both teams analysed belonged to the same English Premiership club which may be different in other leagues and countries; d) any positional change across the two seasons, during the season or within weekly match-play that would alter the match demands for individual players was not considered; and e) other contextual factors such as formation change or change of manager and style of play that would also influence physical match demands was not measured.

Future studies should consider a study design that may include the analysis of starters and non-starters, with special regard to the first training session after the match, the analysis of playing positions, and the analysis of contextual variables such as the number of the matches in the week, match results, match location, and quality of opponents. For instance, a recent study on professional soccer players showed that match location, match outcome and level of the opponent slightly affected the weekly external TL while playing positions showed several differences [52]. Furthermore, when considering the number of matches, Clemente et al. [48] showed that acute load and training strain presented higher for players that started two or three matches in the same week. Finally, the inclusion of simultaneous match and TL data would provide greater insights and allow further analysis (e.g. training/match ratios [53]) into youth and first-teams.

CONCLUSIONS

In summary, we observed higher values in some of the selected training-related variables at MD-3 in two teams from the same English Premiership soccer club during the second training session of the week, while there were also higher values of different metrics (accelerations and decelerations) in the first training session of the week (MD-4). Specifically, U-18 players covered a higher total distance in the majority of training sessions (MD-4, MD-2, MD-1). Moreover, they also performed a higher number of accelerations and decelerations in all training sessions when compared with the first-team. Nonetheless, first-team players covered greater values of high-intensity and sprint distances at MD-3 (sprint distance also slightly greater at MD-4) than U-18 players. To our knowledge, the main strength of this study is the comparison between young and adult soccer players in the context of the same club over an extended period (two full consecutive seasons).

Practical applications

The current study provides information regarding the microcycle periodisation, and the type of exercises used in the training sessions. In addition, it provides average values that can be applied by other teams and coaches from similar contexts. Moreover, it shows that to train both youth and first-team players, TL may vary in terms of intensity and that different types or exercise choices and contextual competition may be of additional importance when preparing the microcyle plan. This study showed that U-18 soccer players are prepared to cope with first-team TL demands in terms of total distance, accelerations, and decelerations. Nonetheless, considering high-intensity, sprint and explosive distances, it would be better to increase such values before progressing to the first-team, although from a statistical point of view, such differences were almost non-existent.

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Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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REFERENCES

1. Bangsbo J. Physiological demands of football. Sports Sci Exch. 2014; 27:1–6.
2. Di Salvo V, Baron R, González-Haro C, Gormasz C, Pigozzi F, Bachl N. Sprinting analysis of elite soccer players during European Champions League and UEFA Cup matches. J Sports Sci. 2010; 28(14):1489–94. doi: 10.1080/02640414.2010.521166. PMID: 21049314.
3. Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The Evolution of Physical and Technical Performance Parameters in the English Premier League. International Journal of Sports Med. 2014; 35(13):1095–1100. doi: 10.1055/s-0034-1375695.
4. Nassis GP, Massey A, Jacobsen P, Brito J, Randers MB, Castagna C, Mohr M, Krustrup P. Elite football of 2030 will not be the same as that of 2020: Preparing players, coaches, and support staff for the evolution. Scan J Med Sci Sports. 2020; 30(6):962–964. https://doi.org/10.1111/sms.13681.
5. Varley MC, Fairweather IH, Aughey RJ. Validity and reliability of GPS for measuring instantaneous velocity during

acceleration, deceleration, and constant motion. J Sport Sci. 2012; 30:121–127. https://doi.org/10.1080/02640414.2011.627941.
6. Malone JJ, Di Michele R, Morgans R, Burgess D, Morton JP, Drust B. Seasonal training-load quantification in elite English Premier League soccer players. Int J Sports Physiol Perform. 2015; 10:489–497.
7. Impellizzeri FM, Rampinini E, Marcora SM. Physiological assessment of aerobic training in soccer. J Sports Sci. 2005; 23:583–592. doi:10.1080/02640410400021278.
8. Bourdon PC, Cardinale M, Murray A, Gastin P, Kellmann M, Varley MC, Gabbett TJ, Coutts AJ, Burgess DJ, Gregson W. Monitoring athlete training loads: Consensus statement. Int J Sports Physiol Perform. 2017; 12:161–170.
9. Vanrenterghem J, Nedergaard NJ, Robinson MA, Drust B. Training Load Monitoring in Team Sports: A Novel Framework Separating Physiological and Biomechanical Load-Adaptation Pathways. Sports Med. 2017; 47(11):2135–2142. https://doi.org/10.1007/s40279-017-0714-2.
10. Miguel M, Oliveira R, Loureiro N, García-Rubio J, Ibáñez SJ. Load measures in training/match monitoring in soccer: A systematic review. Int J Environ Res Public Health. 2021; 18:2721.
11. Oliveira R, Martins A, Moreno-Villanueva A, Brito JP, Nalha M, Rico-González M, Clemente FM. Reference values for external and internal training intensity monitoring in professional male soccer players: A systematic review. Int J Sports Sci Coaching. 2022; 17,6:1506–1530. https://doi.org/10.1177/17479541211072966.
12. Oliveira R, Brito JP, Moreno-Villanueva A, Nalha M, Rico-González M, Clemente FM. Reference Values for External and Internal Training Intensity Monitoring in Young Male Soccer Players: A Systematic Review. Healthcare. 2021; 9:1567. https://doi.org/10.3390/healthcare9111567.
13. Maughan PC, Niall G, MacFarlane NG, Swinton PA. Quantification of training and match-play load across a season in professional youth football players. International Journal of Sports Science & Coaching. 2021; 16:5,1169–1177.
14. Houtmeyers KC, Jaspers A, Brink MS, Vanrenterghem J, Varley MC, Helsen WF. External load differences between elite youth and professional football players: ready for take-off? Sci Med in Football. 2021; 5(1):1–5. https://doi.org/10.1080/24733938.2020.1789201.
15. Coppalle S, Ravé G, Moran J, Salhi I, Abderrahman AB, Zouita S, Granacher U, Zouhal H. Internal and External Training Load in Under-19 versus Professional Soccer Players during the In-Season Period. Int J Environ Res Public Health. 2021; 18,558. https://doi.org/10.3390/ijerph18020558.
16. Morgans R, Bezuglov E, Orme P, Burns K, Rhodes D, Babraj J, Di Michele R, Oliveira R. The Physical Demands of Match-Play in Academy and Senior Soccer Players from the Scottish Premiership. Sports. 2022; 10:150. https://doi.org/10.3390/ sports10100150.
17. Vigh-Larsen JF, Dalgas U, Andersen TB. Position-Specific Acceleration and Deceleration Profiles in Elite Youth and Senior Soccer Players. J Stren Cond Res. 2018; 32(4):1114–1122. https://doi.org/10.1519/JSC.0000000000001918.
18. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sports Sci. 2003; 21:519–528.
19. Drust B, Atkinson G, Reilly T. Future perspectives in the evaluation of the physiological demands of soccer. Sports Med. 2007; 37(9):783–805. doi: 10.2165/00007256-200737090-00003.
20. Buchheit M, Mendez-Villanueva A, Simpson BM, Bourdon PC. Match running performance and fitness in youth soccer. Int J Sports Med. 2010; 31:818–825. https://doi.org/10.1055/s-0030-1262838.
21. Vieira LHP, Carling C, Barbieri FA, Aquino R, Santiago PRP. Match running performance in young soccer players: A systematic review. Sports Med. 2019; 49:289–318. https://doi.org/10.1007/s40279-018-01048-8.
22. Oliveira R, Brito JP, Moreno-Villanueva A, Nalha M, Rico-González M, Clemente FM. Reference Values for External and Internal Training Intensity Monitoring in Young Male Soccer Players: A Systematic Review. Healthcare 2021; 9:1567. https://doi.org/10.3390/healthcare911156.
23. Aalbers B, Van Haaren J, editors. Distinguishing between roles of football players in play-by-play match event data. International Workshop on Machine Learning and Data Mining for Sports Analytics; 2019: Springer.
24. Trewin J, Meylan C, Varley MC, Cronin J. The influence of situational and environmental factors on match-running in soccer: a systematic review. Sci Med Footb. 2017; 1(2):183–194.
25. Ju W, Doran D, Hawkins R, Evans M, Laws A, Bradley PS. Contextualised high-intensity running profiles of elite football players with reference to general and specialised tactical roles. Biol Sport. 2023; 40(1):291–301.
26. Ingebrigtsen J, Dalen T, Hjelde GH, Drust B, Wisløff U. Acceleration and sprint profiles of a professional elite football team in match play. Eur J Sport Sci. 2015; 15:101–110.
27. Bradley PS, Sheldon W, Wooster B, Olsen P, Boanas P, Krustrup P. High-intensity running in English FA Premier League soccer matches. J Sports Sci. 2009; 27:159–168.
28. Winter EM, Maughan RJ. Requirements of ethics approval. J Sports Sci. 2009; 27:85.
29. Malone JJ, Di Michele R, Morgans R, Burgess D, Morton JP, Drust B. Seasonal training-load quantification in elite English Premier League soccer players. Int J Sports Physiol Perform. 2015; 10:489–497.
30. Oliveira R, Brito JP, Martins A, Mendes B, Marinho DA, Ferraz R. In-season internal and external training load quantification of an elite European soccer team. PLoS ONE. 2019; 14(4): e0209393. https://doi.org/10.1371/journal.pone.0209393.
31. Owen AL, Djaoui L, Newton M, Malone S, Mendes BA. A contemporary multi-modal mechanical approach to training monitoring in elite professional soccer. Sci Med Football 2017; 1:216–221.
32. Stevens TG, de Ruiter CJ, Twisk JW, Savelsbergh GJ, Beek PJ. Quantification of in-season training load relative to match load in professional Dutch Eredivisie football players. Sci Med Football. 2017; 1:117–125.
33. Akenhead R, Harley JA, Tweddle SP. Examining the external training load of an English Premier League football team with special reference to acceleration. J Stren Cond Res. 2016; 30:2424–2432.
34. Beato M, Coratella G, Stiff A, Iacono AD. The Validity and Between-Unit Variability of GNSS Units (STATSports Apex 10 and 18 Hz) for Measuring Distance and Peak Speed in Team Sports. Front Physiol. 2018; 9:1288.
35. Maddison R, Ni Mhurchu C. Global positioning system: a new opportunity in physical activity measurement. Int J Behav Nutr Phys Act. 2009; 6:73. PubMed doi:10.1186/1479-5868-6-73.
36. Beato M, Bartolini D, Ghia G, Zamparo P. Accuracy of a 10 Hz GPS unit in measuring shuttle velocity performed at different speeds and distances (5–20 M). J Hum Kinet. 2016; 54:15–22.
37. Buchheit M, Simpson B, Mendez-Villanueva A. Repeated high-speed activities during youth soccer games in relation to changes in maximal sprinting and aerobic speeds. Int J Sports Med. 2013; 34:40–48.
38. Castellano J, Casamichana D, Calleja-Gonza´lez J, San Roma´n J, Ostojic SM. Reliability and accuracy of 10 Hz GPS devices for short-distance exercise. J Sports Sci Med. 2011; 10:233.

39. Beato M, de Keijzer KL. The inter-unit and inter-model reliability of GNSS STATSports Apex and Viper units in measuring peak speed over 5, 10, 15, 20 and 30 meters. Biol Sport. 2019; 36:317–321.
40. Malone JJ, Lovell R, Varley MC, Coutts AJ. Unpacking the Black Box: Applications and Considerations for Using GPS Devices in Sport. Int J Sports Physiol Perf. 2017; 12:1–26.
41. Heidi T, Andre N, Delaney J, Serpiello F, Duthie G. Inter-unit reliability and effect of data processing methods of global positioning systems. Int J Sports Physiol Perform. 2018; [accessed 2018 Sep 28]: [24 p.]. https://journals.humankinetics.com/doi/abs/10.1123/ijspp.2018-0273.
42. Townshend AD, Worringham CJ, Stewart IB. Assessment of speed and position during human locomotion using nondifferential GPS. Med Sci Sports Exerc. 2008; 40(1):124–132.
43. Tierney PJ, Young A, Clarke ND, Duncan MJ. Match play demands of 11 versus 11 professional football using Global Positioning System tracking: Variations across common playing formations. Hum Mov Sci. 2016; 49:1–8.
44. R Core Team. R: A Language and Environment for Statistical Computing; Version 1.4.1717; R Foundation for Statistical Computing: Vienna, Austria, 2022.
45. Teixeira JE, Forte P, Ferraz R, Leal M, Ribeiro J, Silva AJ, Barbosa TM, Monteiro AM. Quantifying sub-elite youth football weekly training load and recovery variation. Appl Sci. 2021; 11:4871.
46. Hannon MP, Coleman NM, Parker LJF, McKeown J, Unnithan VB, Close GL, Drust B, Morton JP. Seasonal training and match load and micro-cycle periodization in male Premier League academy soccer players. J Sports Sci. 2021; 39:1838–1849.
47. de Dios-Álvarez V, Alkain P, Castellano J, Rey E. Accumulative Weekly External and Internal Load Relative to Match Load in Elite Male Youth Soccer Players. Ped Ex Sci. 2021; 1–6. https://doi.org/10.1123/pes.2021-0048.
48. Oliveira R, Brito J, Martins A. In-season training load quantification of one-, two- and three-game week schedules in a top European professional soccer team. Physiol Behav. 2019; 201:146–156.
49. Anderson L, Orme P, Di Michele R, Close GL, Milsom J, Morgans R, Drust B, Morton JP. Quantification of Seasonal-Long Physical Load in Soccer Players with Different Starting Status from the English Premier League: Implications for Maintaining Squad Physical Fitness. Int J Sports Physiol Perform. 2016; 11:1038–1046. doi.org/10.1123/ijspp.2015-0672.
50. Rago V, Brito J, Figueiredo P, Krustrup P, Rebelo A. Relationship between External Load and Perceptual Responses to Training in Professional Football: Effects of Quantification Method. Sports. 2019; 7(3):68. https://doi.org/10.3390/sports7030068.
51. Liu T, Yang L, Chen H, García-de-Alcaraz A. Impact of Possession and Player Position on Physical and Technical-Tactical Performance Indicators in the Chinese Football Super League. Front. Psychol. 2021; 12:722200. doi: 10.3389/fpsyg.2021.722200.
52. Oliva-Lozano JM, Rago V, Fortes V, Muyor JM. Impact of match-related contextual variables on weekly training load in a professional soccer team: a full season study. Biol Sport. 2022; 39(1):125–134.
53. Clemente FM, Silva R, Arslan E. The effects of congested fixture periods on distance-based workload indices: A full-season study in professional soccer players. Biol Sport. 2021; 38(1):37–44.

Effects of soy milk ingestion immediately after resistance training on muscular-related biomarkers in older men: a randomized controlled trial

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ABSTRACT: We evaluated the effects of soy milk ingestion on changes in body composition, strength, power, and muscular-related biomarkers following 12 weeks of resistance training in older men. Thirty healthy older men (age = 65.63 ± 3.16 years; body mass = 62.63 ± 3.86 kg) were randomly assigned to one of two groups: soy milk + resistance training (SR) or placebo + resistance training (PR). Participants in the SR group received 240 ml of vanilla-flavoured non-dairy soy milk immediately after every training session and at the same time on non-training days. Differences in muscle mass, upper limb body strength (UBS), lower limb aerobic power (LAP), activin A, and GDF15 were significantly greater in the SR group vs. the PR group ($P < 0.05$). Both intervention groups experienced a significant ($p < 0.05$) reduction in body mass (PR = -3.9 kg; SR = -3.2 kg), body fat % (PR = -0.8%; SR = -1.2%), activin A (PR = -5.1 pg/ml; SR = -12.8 pg/ml), GDF15 (PR = -8.1 pg/ml; SR = -14.7 pg/ml), TGFβ1 (PR = -0.43 pg/ml; SR = -0.41 pg/ml), and increase in muscle mass (PR = 0.81 kg; SR = 2.5 kg), UBS (PR = 3.4 kg; SR = 6.7 kg), lower limb body strength (PR = 2.8 kg; SR = 5.2 kg), upper limb aerobic power (PR = 34.3 W; SR = 38.6 W), LAP (PR = 23.2 W; SR = 45.2 W), BDNF (PR = 8.3 ng/ml; SR = 12.7 ng/ml), and irisin (PR = 1.5 ng/ml; SR = 2.9 ng/ml) compared to baseline. The ingestion of soy milk during 12 weeks of resistance training augmented lean mass, strength, and power, and altered serum concentrations of skeletal muscle regulatory markers in older men.

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INTRODUCTION

Aging is the age-related decline of biological functions [1]. Aging is a natural process associated with modifications in biological systems such as a decline in muscle mass and muscle strength [2]. Skeletal muscle accounts for approximately 40% of total body mass, and it plays an indispensable role in locomotion and metabolism [3, 4]. Between the ages of 20 and 80, humans lose approximately 20–30% of their skeletal muscle mass. Skeletal muscle undergoes a gradual loss of fat-free mass, size, and function in the aging process called sarcopenia [2]. Several possible mechanisms for age-related muscle atrophy have been described; however, the precise contribution of each is not well known. Age-related muscle loss is a result of reductions in the size and number of muscle fibres, possibly due to a multifactorial process that involves physical activity, nutritional intake, oxidative stress, and hormones or signalling molecules [5]. It has been suggested that elevations in circulating concentrations of cell-signalling molecules increase the likelihood of receptor interaction and thus enhance the probability of a physiological effect within skeletal muscle [6].

Muscle mass is determined by the balance between muscle protein synthesis (MPS) and muscle protein breakdown (MPB) [5]. The main anabolic pathways that lead to protein synthesis in muscle include serine/threonine kinase, protein kinase B, mammalian target of rapamycin (mTOR), hormones such as insulin-like growth factor and insulin and branched-chain amino acids (e.g. leucine, valine, isoleucine) [7]. Muscle protein breakdown includes activation of the ubiquitin-proteasome pathway by changing transforming growth factor-beta (TGF-β) and myostatin [7].

Tumour growth factor-β1, a member of the TGF-β family, is a multifunctional cytokine involved in the regulation of muscle repair via satellite cell activation, connective tissue formation, and regulation of the immune response intensity [8, 9]. Growth and differentiation factor-15 (GDF15) has both environment/situation mediated and direct effects on skeletal muscles, resulting in reduced muscle mass,

and therefore it is potentially involved in sarcopenia [8, 10]. Baseline GDF-15 predicts declining physical activity in the elderly [11]. Irisin is a novel myokine that has been shown to induce browning of white adipocytes. Irisin improves myogenesis and induces hypertrophy of skeletal muscle since it is secreted from muscles in response to exercise [12, 13]. Brain-derived neurotrophic factor (BDNF) as a protein is produced in the skeletal muscle and increased by muscle contraction to enhance fat oxidation, which can regulate glucose and fat metabolism [14]. Lower concentrations of BDNF and irisin, and higher concentrations of activin A, growth and differentiation factor-15 (GDF15), and tumour growth factor β1 (TGFβ1) have been reported during aging [15–18].

Resistance training improves musculoskeletal strength, muscle mass, bone mass, and connective tissue thickness [19]. Previous research has shown that strength training increases power and strength, muscle size, and plasma-metabolism biomarkers in the elderly [2, 15, 20–22]. Resistance training is a potent stimulus to increase skeletal muscle mass and results in an anabolic response [23]. The muscle protein accretion process depends on a robust synergistic action between protein intake and overload [23]. It is suggested that post-exercise protein ingestion increases plasma amino acids, which results in the activation of signalling molecules, leading to an increase of MPS and muscle hypertrophy, particularly leucine, thus activating the key anabolic signalling mechanism of the mechanistic target of rapamycin (mTOR) [23–25]. The balance between MPS and MPB is dependent on protein consumption and the accompanying hyperaminoacidaemia, which stimulates a marked rise in MPS and mild suppression of MPB [26]. Recently, it was suggested that soy milk (a plant-based non-dairy beverage) can be considered to be a nutritionally adequate and complete protein, which is enriched in fatty acids, phosphatidylcholine, and isoflavones, particularly genistein [27]. Soy milk is a good source of protein, calcium, and potassium [28]. Also, it has been reported that soy milk contains essential amino acids such as leucine, lysine, phenylalanine, and isoleucine [29, 30]. Based on the authors' knowledge, the present study is the first one to evaluate the effects of soy milk consumption and resistance training on serum concentrations of activin, GDF15, TGFβ1, BDNF, and irisin in older men. However, there have been limited studies with contradictory findings that have been conducted to examine the effects of soy milk consumption and resistance training on body composition, strength, and power. Therefore, we conducted the present study to assess the effects of soy milk ingestion on changes in body composition, strength, power, and muscular-related biomarkers (activin A, GDF15, TGFβ1, BDNF, and irisin) following 12 weeks of resistance training in older men.

MATERIALS AND METHODS

Participants

Thirty healthy elderly men (age 65.63 ± 3.16 years; body weight = 62.97 ± 4.18 kg) volunteered for this study (Figure 1). Age 60–80 and physical independence were inclusion criteria. Exclusion criteria were: current or previous significant cardiovascular histories; neurological, respiratory, muscular, metabolic, inflammatory, bone, joint, and movement disorders; consumption of dietary supplements; alcohol consumption or smoking for at least 1 year prior to study entry; allergy/sensitivity to soy milk and a history of regular physical activity in at least the last year. All of these criteria were assessed by the physician using the Physical Activity Readiness Questionnaire (PAR-Q) and the Health/Medical History Questionnaire. Written informed consent was obtained from all participants. All experiments were performed in accordance with the Declaration of Helsinki. This study has been approved by the Sport Sciences Research Institute of Iran (IR.SSRC.REC.1398.062) and registered in the Iranian Clinical Trials Registry (IRCT20190731044398N3).

Study design

This study was a randomized, double-blind, parallel prospective clinical trial (Figure 2). Prior to baseline measurements, all participants were familiarized with all tests and procedures. The participants were then randomized to two groups: soy milk + resistance training (SR; n = 15) or placebo + resistance training (PR; n = 15). The allocation was stratified using a digital tool available at www.randomizer.org. Measurements were collected at the beginning and end of the 12 weeks of intervention. All measurements were recorded at the same time and under the same environmental conditions. Participants were asked not to change their current lifestyle and eating habits during the study period.

Interventions

Supplementation protocol

Participants in the SR group received 240 ml of vanilla-flavoured dairy-free soy milk immediately after each training session and simultaneously on non-training days for 12 weeks. Also, participants in the PR group received 240 ml of placebo (a placebo with artificially sweetened water) at the same time as the SR group. Soy milk and placebo were in opaque (masked) beverage containers and were similar in taste and smell, texture and appearance [31]. The timing and dose of soy milk were chosen according to the previous studies conducted by other scientists [30, 32]. Soy milk (dairy-, lactose-, and casein-free; absolutely no carrageenan, gluten, egg, or peanut) was supplied from Saina Ghaza Part Company, Iran and registered with the health ministry (No:56/16554). The energy and macronutrient composition of this milk per 240 mL are as follows: energy, 99.6 kcal; protein, 6.75 g; carbohydrate, 9.15 g; fat, 4 g; calcium, 100 mg; sodium, 98 mg; cholesterol, 0 mg; iron, 1.1 mg; vitamin D 2.5 mcg; vitamin A, 150 mcg; vitamin B12, 1.5 mcg; potassium, 300 mg; riboflavin 0.4 mg. It should be noted that researchers monitored the soy milk supplementation. After the training sessions, soy milk was served to the participants by the researcher, who witnessed its consumption. On non-training days, supplementation was verified by phone or SMS. To assess compliance with supplementation on non-training days, participants provided empty nutrient boxes to study staff.

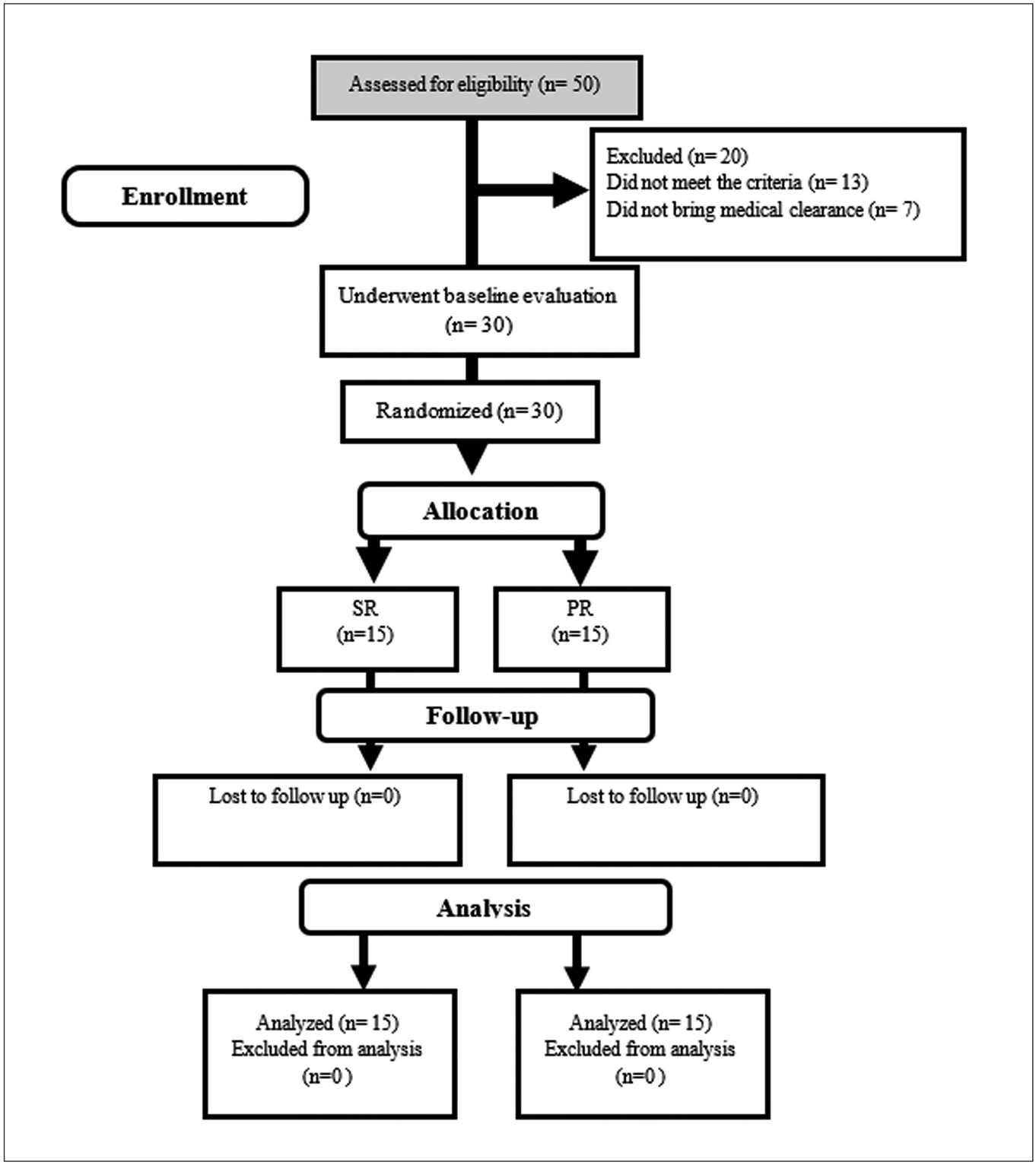


FIG. 1. Participants' flow diagram.

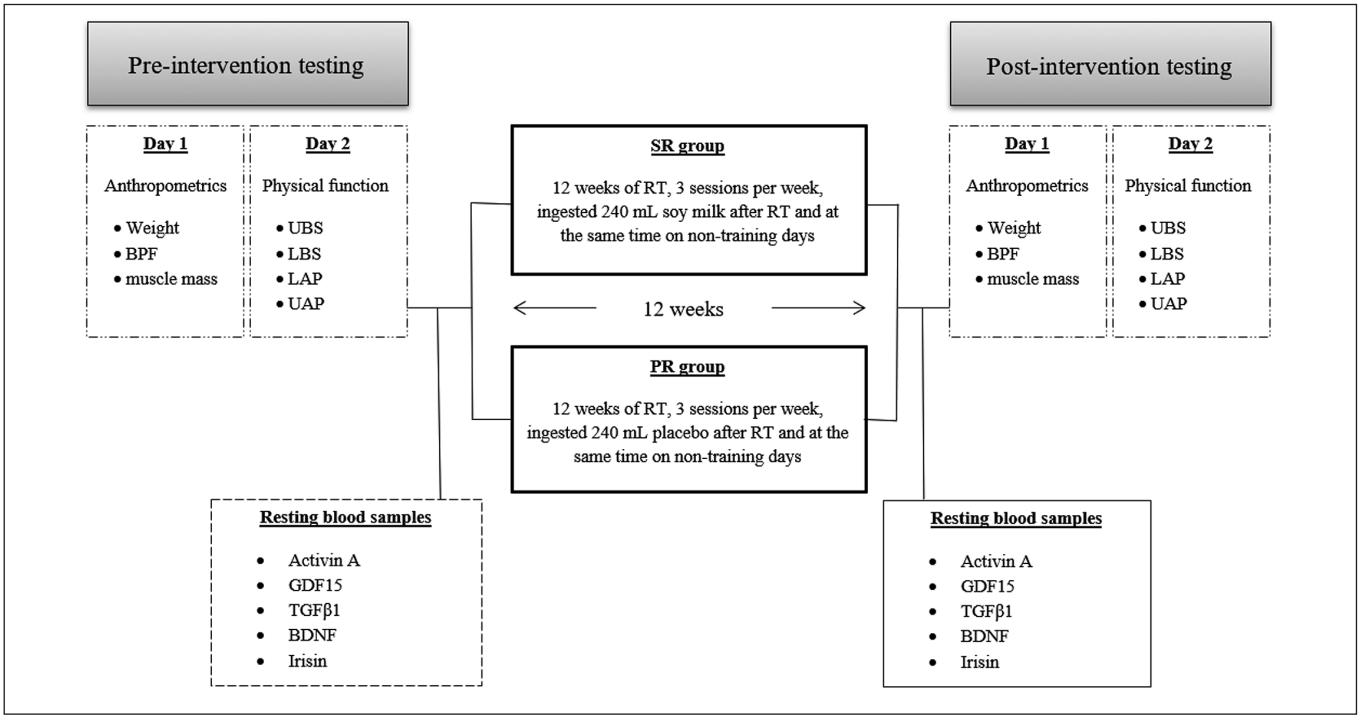


FIG. 2. Diagram of the study design.
Abbreviations; SR: soy milk + resistance training; PR: placebo + resistance training; BMI: Body Mass Index; BFP: Body Fat Percent; UBS: Upper body Strength; LBS: Lower body Strength; LAP: Lower Anaerobic Power; UAP: Upper Anaerobic Power.

TABLE 1. Resistance training program

SR and PR Groups	
Sessions per week	3
Warm-up	10 min treadmill running/ low density
Resistance training	**Exercise:** Leg Press, Chest Press, Seated Row, Leg Extension, Lat Pulldown, Tricep Dips **Intensity:** 60% 1RM **Volume:** 1 min per exercise, 30 sec recovery per exercise **Repetition:** Repeat × **4** sets
Cool-down	10 min

Abbreviation: SR: soy milk + resistance training; PR: placebo + resistance training.

Exercise training programme

In order to familiarize themselves with the training procedures, the members of the two groups were familiarized with the correct form of lifting and correct breathing techniques. Participants in these groups performed sessions of the resistance training programme on three non-consecutive days per week for 12 weeks. The training programme consisted of three stages: a 10-minute warm-up, 40-minute resistance training and a 10-minute cool-down (Table 1 shows the details of the training programme). The resistance training (four sets/six exercises/15 tempo-controlled repetitions/30-second rest between each exercise) included leg presses, chest presses, rows, leg stretches, pull-ups, and triceps push-ups. Participants began training at ~60% of one repetition maximum (1RM) at the beginning of the intervention; if they could comfortably do the exercise for about 60 seconds, we added about 5% weight gain for the next training session. 1RM was determined as described by Calvani et al. [33]. The periodized protocols were adapted from previous studies [34]. All training sessions were supervised by qualified personal trainers.

Measurements

Body composition assessments

Upon arrival at the laboratory, participants were asked to urinate completely within 30 minutes of the test. Body weight (BM) was measured using a digital scale (SECA, Germany) with an accuracy of 0.1 kg. The height of the participant was measured with a stadiometer (SECA, Germany) with an accuracy of 0.1 cm. Also, body fat percentage (BFP), body mass index (BMI), and muscle mass were assessed using a multi-frequency bioelectrical impedance device (BIA; Jawon Medical X Contact-356, South Korea), as previously described [35]. The test-retest reliability of the bioelectrical impedance method is high (R = 0.95 to 0.99) [36].

Physical performance tests

Lower limb anaerobic power (LAP) and upper limb anaerobic power (UAP) were evaluated by the Wingate anaerobic (Monark 831E and 894 Ea, Varberg, Sweden) test as previously described [36]. A medical doctor supervised the Wingate testing to monitor signs of cardiovascular discomfort. VO_{2max} of each participant was measured by the modified Bruce protocol as described by Bamman et al. to determine fitness level [37]. Also, the upper limb body strength (UBS) and lower limb body strength (LBS) of participants were evaluated by one-repetition maximum (1RM) on the chest press and leg press machines, respectively, as previously described [34].

Blood biochemistry

Fasting blood samples (~10 mL) were collected from the antecubital vein using standard procedures approximately 48 h before and after the last training session. Following the completion of blood sampling, the samples were centrifuged at 3000 rpm for 10 minutes, and serum was stored at -80°C until further analysis. Serum activin A (kit: Cusabio Co, sensitivity: 3.9 pg/ml), GDF15 (kit: Cusabio Co, sensitivity: 1.95 pg/ml), TGFβ1 (kit: Cusabio Co, sensitivity: 0.747 ng/ml), BDNF (kit: Abcam Co, sensitivity: 2.4 pg/ml), and irisin (kit: Cusabio Co, sensitivity: 0.78 ng/ml) concentrations were measured using commercial human ELISA kits. The intra- and inter-assay coefficients for all factors were < 8% and < 10%, respectively.

Nutrient intake and dietary analysis

Participants were asked to maintain their habitual diet during the study. To minimize dietary variability, participants submitted 3-day (2 weekdays and 1 weekend) food records at baseline and 12 weeks of the intervention. Each item of food was individually entered into Diet Analysis Plus version 10 (Cengage, Boston, MA, USA), and total energy consumption and the amount of energy derived from proteins, fats, and carbohydrates were evaluated [38].

Statistical analysis

Estimation of an appropriate sample size was conducted using the G*Power analysis software. Our rationale for sample size was based on previous studies [30, 34]. The analysis revealed that a sample size of at least 26 participants (n = 13 per group) was needed to provide power (1- β) of 0.80 (α = 0.05). The normality of data distribution was evaluated by the Shapiro–Wilk test. Analysis of variance (ANOVA) was applied to examine the intra- and inter-group differences. In the case of significant differences, a Fisher LSD post hoc test was used. Nutrition data were analysed using repeated measures ANOVA analysis. Statistical significance was set at $P \leq 0.05$. All statistical procedures were analysed using statistical package for social sciences IBM SPSS Statistics 22 (IBM Software Group, Chicago, IL, USA) and were expressed as mean ± SD. All the figures were prepared in GraphPad Prism (version 8.0.2).

RESULTS

Dietary intake monitoring and compliance with exercise training and supplementation interventions

Overall adherence to both exercise training and supplementation was 100% across PR and SR. There were no reports of an adverse event from either nutritional intervention or the resistance training

TABLE 2. Demographic data of participants

Variable	PR group (n = 15)	SR group (n = 15)
Age (year)	66.33 ± 0.86	64.40 ± 0.87
Height (cm)	167.93 ± 0.92	168 ± 0.97
Weight (kg)	64.85 ± 0.96	61.09 ± 0.98

Abbreviation: Values are presented as Mean ± SD; SR: soy milk + resistance training; PR: placebo + resistance training.

TABLE 3. Energy and macronutrients at the before and at the end of week 12

Variables	Group	Baseline	12 weeks	P-value
Energy (kcal/day)	PR	1773.33 ± 49.77	1792.80 ± 56.85	0.262
	SR	1762.00 ± 50.11	1789.60 ± 53.01	0.095
Protein (g/day)	PR	80.40 ± 7.47	77.80 ± 4.72	0.184
	SR	77.13 ± 4.76	77.86 ± 5.52	0.593
Carbohydrate (g/day)	PR	242.93 ± 6.95	246.80 ± 6.85	0.129
	SR	244.26 ± 9.16	247.73 ± 6.00	0.095
Fat (g/day)	PR	53.33 ± 2.76	53.60 ± 3.71	0.830
	SR	52.93 ± 3.19	54.13 ± 3.73	0.440

Abbreviation: SR: soy milk + resistance training; PR: placebo + resistance training. Values are Mean ± SD.

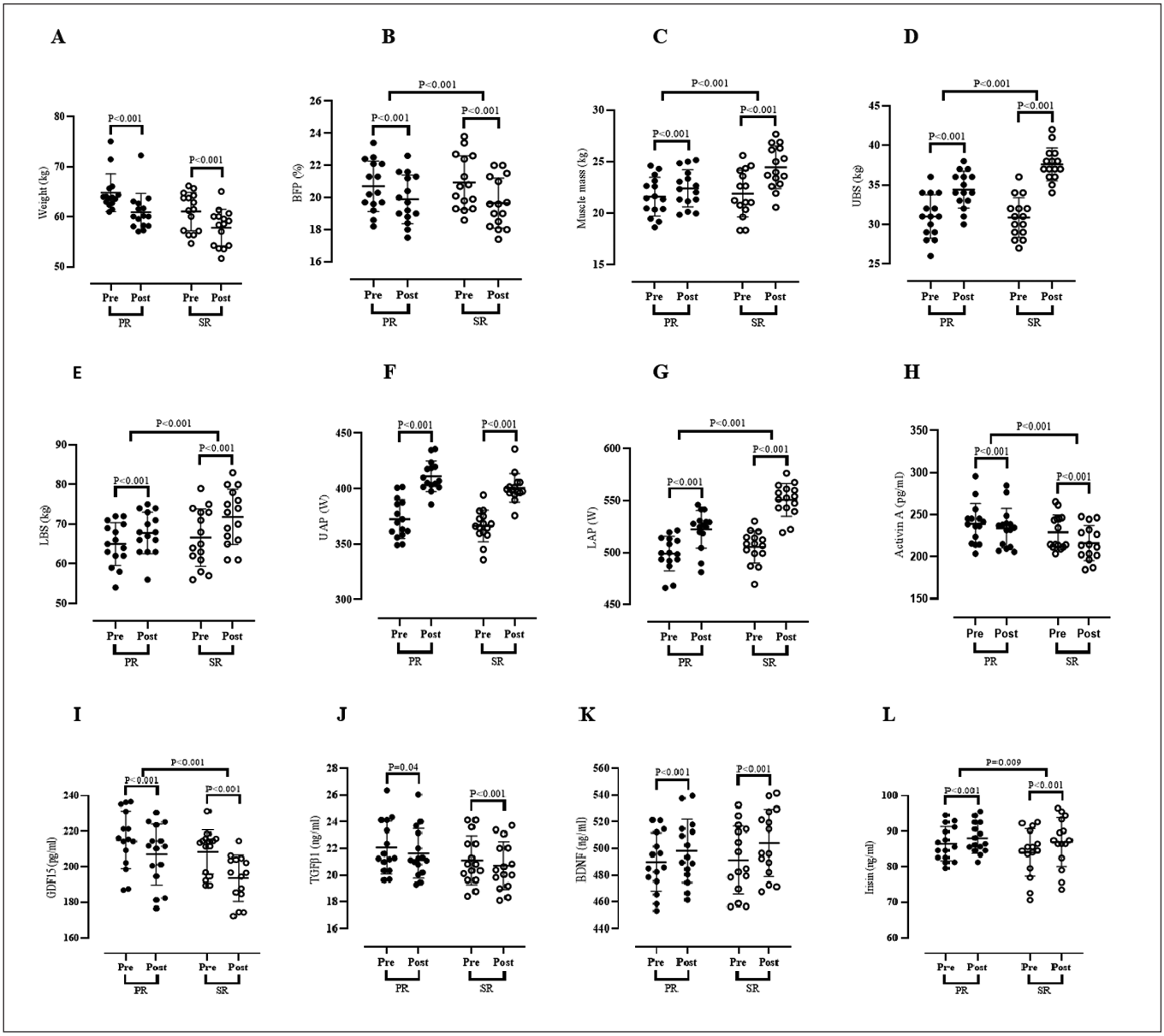


FIG. 3. Changes in blood markers, physical performance and body compositions parameters in response to 12 weeks of soy milk ingestion immediately after resistance training. Weight, (A); BFP, Body Fat Percentage, (B); Muscle Mass, (C); UBS, Upper Body Strength (D); LBS, Lower Body Strength, (E); UAP, Upper Anaerobic Power, (F), LAP, Lower Anaerobic Power, (G), Activin A, (H); GDF15 (I); TGFβ1 (J); BDNF (K); and irisin (L) from pre-training to post-training in the PR (placebo + resistance training) and SR (soy milk + resistance training) groups. Error bars represent standard error of the mean.

programme. The mean demographic characteristics of the two groups are summarized in Table 2. Nutrient analysis of the dietary records of PR and SR groups before and after the intervention period by using repeated measures ANOVA analysis is presented in Table 3. There were no significant differences in total energy intake or protein, fat, and carbohydrate intakes between the study groups (P > 0.05).

Body composition

Figure 3 presents values for body composition. Results of the present study indicated a significant decrease in weight [PR = -3.91 kg (95% confidence interval (CI), 5.55 to 2.27) (*P < 0.001*) and SR = -3.23 kg (95% CI 3.78 to 2.67) (*P < 0.001*) (Figure A)] and BFP [PR = -0.82% (95% CI, 0.94 to 0.69) (*P < 0.001*) and SR = -1.27% (95% CI 1.41 to 1.13) (*P < 0.001*) (Figure B)] over time. Also, a significant enhancement was experienced for muscle mass [PR = 0.81% (95% CI, -0.65 to -0.97) (*P < 0.001*) and SR = -2.56% (95% CI -2.22 to -2.89) (*P < 0.001*) (Figure C)] over time. ANOVA did not show that soy milk had a significant effect on body weight values ($F_{(1, 28)} = 0.710$, $p = 0.407$, $\eta^2 = 0.025$) in interaction with the resistance training programme (Figure A). Only a similar effect of the resistance training programme was confirmed for both groups ($F_{(1, 28)} = 78.387$, $p < 0.001$, $\eta^2 = 0.736$). A significant effect of using soy milk was observed in interaction with the resistance training programme for BFP ($F_{(1, 28)} = 27.431$, $p < 0.001$,

η^2 = 0.495) and muscle mass ($F_{(1, 28)}$ = 99.631, p < 0.001, η^2 = 0.781) (Figure B and C; respectively). Fisher's LSD post-hoc test did not confirm that, either before or after 12 weeks of resistance training, the BFP values were statistically different between PR and SR groups (p > 0.05). Fisher's LSD post-hoc test showed statistically significantly higher muscle mass values in the SR group compared to the PR group after the completion of the resistance training programme (p < 0.001).

Physical fitness assessments

Figure 3 presents values for physical fitness assessments. Findings of the present study showed significantly increased UBS [PR = 3.40 kg (95% CI, -2.81 to -3.98) (*P < 0.001*) and SR = 6.73 kg (95% CI -6.20 to -7.26) (*P < 0.001*) (Figure D)], LBS [PR = 2.80 kg (95% CI, -1.79 to -3.80) (*P < 0.001*) and SR = 5.26 kg (95% CI – 4.31 to – 6.21) (*P < 0.001*) (Figure E)], UAP [PR = 34.34 W (95% CI, -26.74 to – 41.93) (*P < 0.001*) and SR = 38.62 W (95% CI – 33.76 to – 43.47) (*P < 0.001*) (Figure F)], and LAP [PR = 23.28 W (95% CI, -19.86 to – 26.71) (*P < 0.001*) and SR = 45.28 W (95% CI – 39.50 to – 51.06) (*P < 0.001*) (Figure G)] over time. ANOVA showed that soy milk had a significant impact on UBS ($F_{(1, 28)}$ = 41.97, p < 0.001, η^2 = 0.744), LBS ($F_{(1, 28)}$ = 14.631, p < 0.001, η^2 = 0.343) and LAP ($F_{(1, 28)}$ = 49.34, p < 0.001, η^2 = 0.638) in interaction with the resistance training programme (Figure D, E, and G; respectively). For UAP only a similar effect of resistance training programme for both PR and SR groups was found ($F_{(1, 28)}$ = 301.43, p < 0.001, η^2 = 0.915) (Figure F). Fisher's LSD post-hoc test showed statistically significantly higher UBS and LAP values in the SR group compared to the PR group after the completion of the resistance training programme (p < 0.0001). Fisher's LSD post-hoc test did not confirm that, either before or after the 12 weeks of the resistance training programme, the LBS values differed significantly between PR and SR groups (p > 0.05).

Blood markers

Figure 3 presents values for serum concentrations of muscular-related biomarkers. There were significant reductions in serum concentrations of activin A [PR = -5.14 pg/ml (95% CI, 7.76 to 2.52) (*P < 0.001*) and SR = -12.89 pg/ml (95% CI, 16.70 to 9.08) (*P < 0.001*) (Figure H)], GDF15 [PR = -8.15 pg/ml (95% CI, 10.84 to 5.45) (*P < 0.001*) and SR = -14.79 pg/ml (95% CI, 17.43 to 12.15) (*P < 0.001*) (Figure I)], and TGFβ1 [PR = -0.43 pg/ml (95% CI, 0.85 to 0.02) (*P = 0.04*) and SR = -0.41 pg/ml (95% CI, 0.48 to 0.33) (*P < 0.001*) (Figure J)], and significantly increased serum concentrations of BDNF [PR = 8.37 ng/ml (95% CI, -5.63 to -11.11) (*P < 0.001*) and SR = 12.77 ng/ml (95% CI, -8.72 to -16.81) (*P < 0.001*) (Figure K)], and Irisin [PR = 1.56 ng/ml (95% CI, -0.81 to -2.30) (*P < 0.001*) and SR = 2.94 ng/ml (95% CI, -2.34 to – 3.53) (*P < 0.001*) (Figure L)] over time. ANOVA showed that the usage of soy milk had a significant influence on activin A ($F_{(1,28)}$ = 12.910, p < 0.001, η^2 = 0.316), GDF15 ($F_{(1,28)}$ = 14.232, p < 0.001, η^2 = 0.337) and irisin ($F_{(1, 28)}$ = 9.639, p = 0.004, η^2 = 0.256) in interaction with the resistance training programme (Figure H, I, and L; respectively). Fisher's LSD post-hoc test showed significantly higher values of activin A (p = 0.036) and GDF15 (p = 0.019) in the SR group compared to the PR group after completion of the resistance training programme. Fisher's LSD post-hoc test did not confirm that neither before or after the 12 weeks of the resistance training programme the irisin levels differed significantly between the PR and SR groups (p > 0.05). For BDNF ($F_{(1,28)}$ = 86.23, p < 0.001, η^2 = 0.757) and TGFβ1 ($F_{(1,28)}$ = 18.671, p < 0.001, η^2 = 0.400) only a similar effect of the resistance training programme was observed for both PR and SR groups (Figure J).

DISCUSSION

This was the first randomized controlled clinical trial to examine the effects of soy milk ingestion during a resistance training programme in older men. The main findings of our study were that in both SR and PR groups, significantly increased muscle mass and strength, and serum concentrations of BDNF and irisin, and decreased BFP, serum concentrations of activin A, GDF15, and TGFβ1 were observed. The results showed that soy milk ingestion (post-exercise) during 12 weeks of resistance training increased muscle mass, muscle performance (strength and power), and serum concentrations of irisin compared to a placebo; however, the same was not observed in serum concentrations of BDNF. Also, it was found that soy milk ingestion (post-exercise) during 12 weeks of resistance training decreased serum concentrations of activin A and GDF15, compared to a placebo; however, the same was not observed in serum concentrations of TGFβ1 and BFP. There were no adverse events reported from either nutritional intervention or the resistance training programme.

The significant gain in muscle mass and muscular strength from soy milk ingestion compared to placebo in older men was in agreement with the findings of the previous research. For instance, Chiang et al. reported that soy milk (200 mL) during 12 weeks of mild resistance training significantly increased muscle mass and handgrip strength in very old nursing home residents with sarcopenia [39]. Orsatti et al. found that adding soy to milk combined with 16 weeks of resistance training resulted in a more significant gain in muscle mass and strength [40]. Nabuco et al. observed that 12 weeks of whey protein (1·4 g/kg per day) along with resistance training led to a significant gain in muscle mass and strength and functional capacity in older women [3]. In addition, it was demonstrated that taking protein about 1·6 g/kg per day led to a significant gain in muscle mass and strength [41]. Resistance training stimulates rates of muscle protein synthesis (MPS), which are further improved by the presence of dietary proteins [42]. Based on a meta-analysis by Messina et al. [43], leucine, one of the three branched-chain amino acids, is able to stimulate the activation of MPS. In particular, leucine activates MPS through the mTOR complex 1 (mTORC1); therefore it prevents muscle atrophy during the aging process [43]. In the present study, it may be possible that an increase of MPS led to

significant enhancement of muscular accretion and muscular strength during the intervention. However, MPS was not evaluated in the present study, but one of the possible reasons for an increase in muscle mass is MPS. Improvement of muscle mass and muscular strength after soy milk ingestion and resistance training might be due to the mTORC1 signalling cascade, which integrates signals from mechanical stimuli, growth factors, and nutrients to stimulate MPS. Therefore, the combination of soy milk and resistance training had beneficial effects on elevating muscle mass and muscular strength.

Muscle protein balance is also influenced by various hormones and myokines, which have been suggested to alter the balance between anabolic and catabolic stimuli in muscle, leading to an increase or decrease in muscle mass. Among TGFβ isoforms, TGFβ1 is the most abundant and ubiquitously expressed isoform, which has a key role in various biological processes, including cell growth, muscle differentiation, apoptosis, tissue development, and inflammation [44]. TGFβ1 is a potent inhibitor of growth and differentiation in myoblasts and vascular smooth muscle cells; it also suppresses division and blocks fusion of satellite cells by suppressing myogenic factors [44]. In addition, activin A and GDF-15, other members of the TGF-β family, seem to have an inverse relationship with skeletal muscle growth and differentiation [45]. We found a significant reduction in serum concentrations of TGFβ1, activin A, and GDF15 in both groups. However, participants in the SR group experienced the most significant reduction in serum concentrations of activin A and GDF15 compared with the PR group. The mechanism of the effect of soy milk and resistance training on serum concentrations of activin A and GDF15 is still unclear. Elevated expression of activins promotes muscle wasting and cachexia, whereas blocking of activin type II receptors protects skeletal muscle from atrophy and leads to strong hypertrophy [45]. Chen et al. [46] reported that enhancement of circulating activin A not only promoted the reduction of muscle mass and body weight in a dose-dependent manner but also reduced muscle function, highlighting the therapeutic potential of activin A inhibitors [46]. Therefore, it may have been expected that a significant reduction in serum concentration of activin A and GDF15 in the SR group may be due to a significant gain of muscle mass. In this regard, Bagheri et al. reported a modest correlation between the changes in activin A and lean mass following post-exercise Icelandic yogurt consumption in healthy untrained older men [42]. Soy milk ingestion during resistance training can control protein synthesis by intracellular signalling pathways [47]. Protein consumption made a positive balance, which led to the transfer of amino acids into the cell [31]. Potential mechanisms for these changes are the synergy and interaction of soy milk and resistance training. Nevertheless, the superiority of the interaction of soy milk supplementation and resistance training elucidates the improvement of skeletal muscle regulatory markers by suppressing activin A and GDF15 concentrations in skeletal muscle.

According to the literature, skeletal muscle is increasingly classified as an endocrine organ that can release a variety of signalling molecules and regulate cytokines called myokines, such as irisin, which regulates several aging-related physiological and pathological processes [22]. Previous research showed a positive correlation between concentrations of irisin and muscle mass gains in humans [22]. A recent study by Chang et al. [48] reported that a low blood concentration of irisin was a sensitive molecular marker for muscle weakness and atrophy [48]. Huh et al. [49] reported a positive correlation between the decrease in serum irisin concentration and the loss of muscle mass associated with aging [49]. Kim et al. [50] stated that there was a positive correlation between the changes in circulating level of irisin and the change of muscle mass following resistance training in obese adults [50]. The present study used 12 weeks of resistance training with soy milk supplementation, which led to a significant rise in serum concentrations of irisin in the SR compared to the PR group. These differences may be due to irisin responsiveness to muscle mass gain [22], since it appears to be upregulated in response to an increase in muscle mass, which was observed in the soy milk ingestion group. Considering the benefits of soy milk ingestion after resistance training in improving muscle strength and function for the frail elderly, soy milk ingestion after resistance training could seem to be a beneficial intervention strategy to increase irisin concentrations in the aging population. A growing body of studies has demonstrated that lower serum concentrations of BDNF are correlated with the aging process [51, 52]. The change in concentrations of BDNF with increasing age and neuronal loss in older persons has been shown to be related to low peripheral BDNF levels [51]. Our study indicated that both SR and PR groups experienced similar and significant increases in serum concentrations of BDNF. These results are contradictory to the findings of Gomes et al., who noted that serum concentrations of BDNF were increased in elderly men after chronic exercise (12 weeks of aerobic training, consisting of a 50-min walk 3 times per week) [53]. Goekint et al. reported an insignificant increase in serum concentrations of BDNF after eight weeks of resistance training in untrained subjects [54]. To the best of our knowledge, the present study was the first one to evaluate the effect of soy milk ingestion during resistance training on circulating BDNF in elderly men. Our results suggest that resistance training interventions provide sufficient exercise stimulus to increase concentrations of BDNF in elderly men. The effect of using soy milk in interaction with the resistance training programme was not proven, although the trend of BDNF change in the SR group was greater than in the PR group (though not statistically significant).

The strengths of this study are triple. Firstly, the study design is a randomized, controlled clinical trial. Secondly, we proved the benefits of soy milk ingestion and resistance training, and their direct effects on muscular-related biomarkers as well as fitness and body composition markers in older men. Thirdly, valid and objective measures were utilized for the evaluation of muscular-related biomarkers, body composition, and physical fitness. This study also had some limitations. One of the limitations of this study was the lack of dietary intake monitoring, and therefore dietary intake was not carefully controlled. However, given the uncertain effect of soy milk on

the results of our study, further research is needed to develop more effective diets for this older population.

CONCLUSIONS

In conclusion, the strategic ingestion of soy milk (post-exercise) during 12 weeks of resistance training augmented lean mass, strength, and power, and altered serum concentrations of skeletal muscle regulatory markers (activin A, GDF15) in older men compared to placebo. Hence, older men may use soy milk ingestion after exercise to improve muscular performance.

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Conflict of interest

The authors declare no conflicts of interest.

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REFERENCES

1. Danan G, Matthew ED. Encyclopedia of Gerontology and Population Aging. Springer International Publishing. 2019:29–1.
2. Nabuco HCG, Tomeleri CM, Fernandes RR, Sugihara Junior P, Cavalcante EF, Cunha PM, Antunes M, Nunes JP, Venturini D, Barbosa DS, Burini RC, Silva AM, Sardinha LB, Cyrino ES. Effect of whey protein supplementation combined with resistance training on body composition, muscular strength, functional capacity, and plasma-metabolism biomarkers in older women with sarcopenic obesity: A randomized, double-blind, placebo-controlled trial. Clin Nutr ESPEN. 2019; 32:88–95.
3. Nabuco HCG, Tomeleri CM, Sugihara Junior P, Fernandes RR, Cavalcante EF, Antunes M, Ribeiro AS, Teixeira DC, Silva AM, Sardinha LB, Cyrino ES. Effects of Whey Protein Supplementation Pre- or Post-Resistance Training on Muscle Mass, Muscular Strength, and Functional Capacity in Pre-Conditioned Older Women: A Randomized Clinical Trial. Nutrients. 2018; 10(5):563.
4. Hooshmand-Moghadam B, Eskandari M, Golestani F, Rezae S, Mahmoudi N, Gaeini AA. The effect of 12-week resistance exercise training on serum levels of cellular aging process parameters in elderly men. Exp Gerontol. 2020; 141:111090.
5. Sakuma K, Yamaguchi A. Novel intriguing strategies attenuating to sarcopenia. J Aging Res. 2012; 2012:251217.
6. Patel VK, Demontis F. GDF11/myostatin and aging. Aging (Albany NY). 2014; 6(5):351–2.
7. Schiaffino S, Dyar KA, Ciciliot S, Blaauw B, Sandri M. Mechanisms regulating skeletal muscle growth and atrophy. FEBS J. 2013; 280(17):4294–314.
8. Xu X, Zheng L, Yuan Q, Zhen G, Crane JL, Zhou X, Cao X. Transforming growth factor-β in stem cells and tissue homeostasis. Bone Res. 2018; 6:2.
9. Ismaeel A, Kim JS, Kirk JS, Smith RS, Bohannon WT, Koutakis P. Role of Transforming Growth Factor-β in Skeletal Muscle Fibrosis: A Review. Int J Mol Sci. 2019; 20(10):2446.
10. Yatsuga S, Fujita Y, Ishii A, Fukumoto Y, Arahata H, Kakuma T, Kojima T, Ito M, Tanaka M, Saiki R, Koga Y. Growth differentiation factor 15 as a useful biomarker for mitochondrial disorders. Ann Neurol. 2015; 78(5):814–23.
11. Barma M, Khan F, Price RJG, Donnan PT, Messow CM, Ford I, McConnachie A, Struthers AD, McMurdo MET, Witham MD. Association between GDF-15 levels and changes in vascular and physical function in older patients with hypertension. Aging Clin Exp Res. 2017; 29(5):1055–1059.
12. Reza MM, Subramaniyam N, Sim CM, Ge X, Sathiakumar D, McFarlane C, Sharma M, Kambadur R. Irisin is a pro-myogenic factor that induces skeletal muscle hypertrophy and rescues denervation-induced atrophy. Nat Commun. 2017; 8(1):1104.
13. Chang JS, Kong ID. Irisin prevents dexamethasone-induced atrophy in C2C12 myotubes. Pflugers Arch. 2020; 472(4):495–502.
14. Zhang Z, Wang B, Fei A. BDNF contributes to the skeletal muscle anti-atrophic effect of exercise training through AMPK-PGC1α signaling in heart failure mice. Arch Med Sci. 2019; 15(1):214–222.
15. Planella-Farrugia C, Comas F, Sabater-Masdeu M, Moreno M, Moreno-Navarrete JM, Rovira O, Ricart W, Fernández-Real JM. Circulating Irisin and Myostatin as Markers of Muscle Strength and Physical Condition in Elderly Subjects. Front Physiol. 2019; 10:871.
16. Sheida V, Fathi M, Mir E. The effect of core stabilization exercise on the serum level of Activin A and back performance scale in elderly women with chronic low back pain: a randomized clinical trial. Medical Sciences. 2020; 30(11):867–875.
17. Fujita Y, Taniguchi Y, Shinkai S, Tanaka M, Ito M. Secreted growth differentiation factor 15 as a potential biomarker for mitochondrial dysfunctions in aging and age-related disorders. Geriatr Gerontol Int. 2016; 16 Suppl 1:17–29.
18. Baccarelli A, Morpurgo PS, Corsi A, Vaghi I, Fanelli M, Cremonesi G, Vaninetti S, Beck-Peccoz P, Spada A. Activin A serum levels and aging of the pituitary-gonadal axis: a cross-sectional study in middle-aged and elderly healthy subjects. Exp Gerontol. 2001; 36(8):1403–12.
19. Krieger JW. Single vs. multiple sets of resistance exercise for muscle hypertrophy: a meta-analysis. J Strength Cond Res. 2010; 24(4):1150–9.
20. Grgic J, Garofolini A, Orazem J, Sabol F, Schoenfeld BJ, Pedisic Z. Effects of Resistance Training on Muscle Size and Strength in Very Elderly Adults: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. Sports Med. 2020; 50(11):1983–1999.
21. Máderová D, Krumpolec P, Slobodová L, Schön M, Tirpáková V, Kovaničová Z, Klepochová R, Vajda M, Šutovský S, Cvečka J, Valkovič L, Turčáni P, Kršňák M, Sedliak M, Tsai CL, Ukropcová B, Ukropec J. Acute and regular exercise distinctly modulate serum, plasma and skeletal muscle BDNF in the elderly. Neuropeptides. 2019; 78:101961.
22. Kim HJ, So B, Choi M, Kang D, Song W. Resistance exercise training increases the expression of irisin concomitant with improvement of muscle function in aging mice and humans. Exp Gerontol. 2015; 70:11–7.
23. Guimarães-Ferreira L, Cholewa JM, Naimo MA, Zhi XI, Magagnin D, de Sá RB, Streck EL, Teixeira Tda S, Zanchi NE. Synergistic effects of resistance training and protein intake: practical aspects. Nutrition. 2014; 30(10):1097–103.

24. Moro T, Brightwell CR, Velarde B, Fry CS, Nakayama K, Sanbongi C, Volpi E, Rasmussen BB. Whey Protein Hydrolysate Increases Amino Acid Uptake, mTORC1 Signaling, and Protein Synthesis in Skeletal Muscle of Healthy Young Men in a Randomized Crossover Trial. J Nutr. 2019; 149(7):1149–1158.
25. McCroskery S, Thomas M, Maxwell L, Sharma M, Kambadur R. Myostatin negatively regulates satellite cell activation and self-renewal. J Cell Biol. 2003; 162(6):1135–47.
26. Phillips SM, Tang JE, Moore DR. The role of milk- and soy-based protein in support of muscle protein synthesis and muscle protein accretion in young and elderly persons. J Am Coll Nutr. 2009; 28(4):343–54.
27. Sethi S, Tyagi SK, Anurag RK. Plant-based milk alternatives an emerging segment of functional beverages: a review. J Food Sci Technol. 2016; 53(9):3408–3423.
28. Mohammad-Shahi M, Mowla K, Haidari F, Zarei M, Choghakhori R. Soy milk consumption, markers of inflammation and oxidative stress in women with rheumatoid arthritis: A randomised cross-over clinical trial. Nutrition & Dietetics. 2015; 73(2):139–145.
29. Keshavarz SA, Nourieh Z, Attar MJ, Azadbakht L. Effect of Soymilk Consumption on Waist Circumference and Cardiovascular Risks among Overweight and Obese Female Adults. Int J Prev Med. 2012; 3(11):798–805.
30. Liao YH, Chen CN, Hu CY, Tsai SC, Kuo YC. Soymilk ingestion immediately after therapeutic exercise enhances rehabilitation outcomes in chronic stroke patients: A randomized controlled trial. NeuroRehabilitation. 2019; 44(2):217–229.
31. Pourabbas M, Bagheri R, Hooshmand Moghadam B, Willoughby DS, Candow DG, Elliott BT, Forbes SC, Ashtary-Larky D, Eskandari M, Wong A, Dutheil F. Strategic Ingestion of High-Protein Dairy Milk during a Resistance Training Program Increases Lean Mass, Strength, and Power in Trained Young Males. Nutrients. 2021; 13(3):948.
32. Eslami O, Shidfar F, Maleki Z, Jazayeri S, Hosseini AF, Agah S, Ardiyani F. Effect of Soy Milk on Metabolic Status of Patients with Nonalcoholic Fatty Liver Disease: A Randomized Clinical Trial. J Am Coll Nutr. 2019; 38(1):51–58.
33. Calvani R, Marini F, Cesari M, Tosato M, Picca A, Anker SD, von Haehling S, Miller RR, Bernabei R, Landi F, Marzetti E; SPRINTT Consortium. Biomarkers for physical frailty and sarcopenia. Aging Clin Exp Res. 2017; 29(1):29–34.
34. Bagheri R, Moghadam BH, Church DD, Tinsley GM, Eskandari M, Moghadam BH, Motevalli MS, Baker JS, Robergs RA, Wong A. The effects of concurrent training order on body composition and serum concentrations of follistatin, myostatin and GDF11 in sarcopenic elderly men. Exp Gerontol. 2020; 133:110869.
35. Abreu EL, Cheng AL, Kelly PJ, Chertoff K, Brotto L, Griffith E, Kinder G, Uridge T, Zachow R, Brotto M. Skeletal muscle troponin as a novel biomarker to enhance assessment of the impact of strength training on fall prevention in the older adults. Nurs Res. 2014; 63(2):75–82.
36. Ahmad A, Alghamdi SS, Mahmood K, Afzal M. Fenugreek a multipurpose crop: Potentialities and improvements. Saudi J Biol Sci. 2016; 23(2):300–10.
37. Bamman MM, Hill VJ, Adams GR, Haddad F, Wetzstein CJ, Gower BA, Ahmed A, Hunter GR. Gender differences in resistance-training-induced myofiber hypertrophy among older adults. J Gerontol A Biol Sci Med Sci. 2003; 58(2):108–16.
38. Eskandari M, Hooshmand Moghadam B, Bagheri R, Ashtary-Larky D, Eskandari E, Nordvall M, Dutheil F, Wong A. Effects of Interval Jump Rope Exercise Combined with Dark Chocolate Supplementation on Inflammatory Adipokine, Cytokine Concentrations, and Body Composition in Obese Adolescent Boys. Nutrients. 2020; 12(10):3011.
39. Chiang FY, Chen JR, Lee WJ, Yang SC. Effects of Milk or Soy Milk Combined with Mild Resistance Exercise on the Muscle Mass and Muscle Strength in Very Old Nursing Home Residents with Sarcopenia. Foods. 2021; 10(11):2581.
40. Orsatti FL, Maestá N, de Oliveira EP, Nahas Neto J, Burini RC, Nunes PRP, Souza AP, Martins FM, Nahas EP. Adding Soy Protein to Milk Enhances the Effect of Resistance Training on Muscle Strength in Postmenopausal Women. J Diet Suppl. 2018; 15(2):140–152.
41. Hevia-Larraín V, Gualano B, Longobardi I, Gil S, Fernandes AL, Costa LAR, Pereira RMR, Artioli GG, Phillips SM, Roschel H. High-Protein Plant-Based Diet Versus a Protein-Matched Omnivorous Diet to Support Resistance Training Adaptations: A Comparison Between Habitual Vegans and Omnivores. Sports Med. 2021; 51(6):1317–1330.
42. Bagheri R, Hooshmand Moghadam B, Candow DG, Elliott BT, Wong A, Ashtary-Larky D, Forbes SC, Rashidlamir A. Effects of Icelandic yogurt consumption and resistance training in healthy untrained older males. Br J Nutr. 2022; 127(9):1334–1342.
43. Messina M, Lynch H, Dickinson JM, Reed KE. No Difference Between the Effects of Supplementing With Soy Protein Versus Animal Protein on Gains in Muscle Mass and Strength in Response to Resistance Exercise. Int J Sport Nutr Exerc Metab. 2018; 28(6):674–685.
44. Nikooie R, Jafari-Sardoie S, Sheibani V, Nejadvaziri Chatroudi A. Resistance training-induced muscle hypertrophy is mediated by TGF-1-Smad signaling pathway in male Wistar rats. J Cell Physiol. 2020; 235(7–8):5649–5665.
45. Oesen S, Halper B, Hofmann M, Jandrasits W, Franzke B, Strasser EM, Graf A, Tschan H, Bachl N, Quittan M, Wagner KH, Wessner B. Effects of elastic band resistance training and nutritional supplementation on physical performance of institutionalised elderly--A randomized controlled trial. Exp Gerontol. 2015; 72:99–108.
46. Chen JL, Walton KL, Winbanks CE, Murphy KT, Thomson RE, Makanji Y, Qian H, Lynch GS, Harrison CA, Gregorevic P. Elevated expression of activins promotes muscle wasting and cachexia. FASEB J. 2014; 28(4):1711–23.
47. Volpi E, Kobayashi H, Sheffield-Moore M, Mittendorfer B, Wolfe RR. Essential amino acids are primarily responsible for the amino acid stimulation of muscle protein anabolism in healthy elderly adults. Am J Clin Nutr. 2003; 78(2):250–8.
48. Chang JS, Kim TH, Nguyen TT, Park KS, Kim N, Kong ID. Circulating irisin levels as a predictive biomarker for sarcopenia: A cross-sectional community-based study. Geriatr Gerontol Int. 2017; 17(11):2266–2273.
49. Huh JY, Panagiotou G, Mougios V, Brinkoetter M, Vamvini MT, Schneider BE, Mantzoros CS. FNDC5 and irisin in humans: I. Predictors of circulating concentrations in serum and plasma and II. mRNA expression and circulating concentrations in response to weight loss and exercise. Metabolism. 2012; 61(12):1725–38.
50. Kim HJ, Lee HJ, So B, Son JS, Yoon D, Song W. Effect of aerobic training and resistance training on circulating irisin level and their association with change of body composition in overweight/obese adults: a pilot study. Physiol Res. 2016; 65(2):271–9.
51. Forti LN, Van Roie E, Njemini R, Coudyzer W, Beyer I, Delecluse C, Bautmans I. Dose-and gender-specific effects of resistance training on circulating levels of brain derived neurotrophic factor (BDNF) in community-dwelling older adults. Exp Gerontol. 2015; 70:144–9.
52. Walsh JJ, Scribbans TD, Bentley RF, Kellawan JM, Gurd B, Tschakovsky ME. Neurotrophic growth factor responses to lower body resistance training in older adults. Appl Physiol Nutr Metab. 2016; 41(3):315–23.

53. Gomes WF, Lacerda AC, Mendonça VA, Arrieiro AN, Fonseca SF, Amorim MR, Teixeira AL, Teixeira MM, Miranda AS, Coimbra CC, Brito-Melo GE. Effect of exercise on the plasma BDNF levels in elderly women with knee osteoarthritis. Rheumatol Int. 2014; 34(6):841–6.
54. Goekint M, De Pauw K, Roelands B, Njemini R, Bautmans I, Mets T, Meeusen R. Strength training does not influence serum brain-derived neurotrophic factor. Eur J Appl Physiol. 2010; 110(2):285–93.

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Worst-case scenario analysis of physical demands in elite men handball players by playing position through big data analytics

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ABSTRACT: The physical demands of intermittent sports require a preparation based, by definition, on high-intensity actions and variable recovery periods. Innovative local positioning systems make it possible to track players during matches and collect their distance, speed, and acceleration data. The purpose of this study was to describe the worst-case scenarios of high-performance handball players within 5-minute periods and per playing position. The sample was composed of 180 players (27 goalkeepers, 44 wings, 56 backs, 23 centre backs and 30 line players) belonging to the first eight highest ranked teams participating in the European Men's Handball Championship held in January 2022. They were followed during the 28 matches they played through a local positioning system worn on their upper bodies. Total and high-speed distance covered (m), pace (m/min), player load (a.u.) and high-intensity accelerations and decelerations (n) were recorded for the twelve 5-min periods of each match. Data on full-time player average and peak demands were included in the analysis according to each playing position. A systematic three-phase analysis process was designed: 1) information capture of match activities and context through sensor networks, the LPS system, and WebScraping techniques; 2) information processing based on big data analytics; 3) extraction of results based on a descriptive analytics approach. The descriptive cross-sectional study of worst-case scenarios revealed an ~17% increment in total distance covered and pace, with a distinct ~51% spike in high-intensity actions. Significant differences between playing positions were found, with effect sizes ranging from moderate to very large (0.7–5.1). Line players, in particular, showed a lower running pace peak (~10 m/min) and wings ran longer distances at high speed (> 4.4 m/s) than the rest of the field players (~76 m). The worst-case scenario assessment of handball player locomotion demands will help handball coaches and physical trainers to design tasks that replicate these crucial match moments, thus improving performance based on a position-specific approach.

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INTRODUCTION

Handball is a dynamic team sport presenting physical, physiological, technical, and tactical demands as well as cognitive challenges [1]. During competitions, the game is divided into different phases (offensive and defensive). Players (six players and one goalkeeper) attempt to create space to shoot effectively, while the defence tries to prevent them from doing so. Such play leads to demanding physical confrontations between players followed by variable recovery periods [2].

Quantifying workload in intermittent sports poses a challenge for sport scientists. Indeed, they have to quantify not only the physiological demands of the movements but especially their mechanical demands. Handball players must be able to sprint, cut, jump, shoot, block and push [3, 4] across variable short-duration and maximum-intensity combinations. In this regard, previous research has focused on describing the conditional demands of intermittent sports by combining internal load (heart rate data) and external load variables (mainly through video analysis) as a prerequisite to tailoring the training sessions to the players' actual demands. Notably, these studies have identified an effect of the contextual variables, such as playing position, on the physical demands of soccer [5], basketball [6] and handball [7–9], paving the way towards training individualisation in intermittent sports.

In recent decades, many companies have developed ultra-wideband systems to collect real-time data in outdoor sports. This has made it possible to better analyse players' physical demands during training and competition using Global Positioning System (GPS) technology [8, 10, 11]. This novel technology has been adapted to indoor sports using local positioning systems (LPS). In particular, it has been implemented in handball by the European Handball Federation (EHF),

Select and Kinexon, together with the Kinexon tracking system for handball players (Kinexon: München, Germany; Select Sport 1947: Glostrup, Denmark). Thanks to its recent validation [12, 13], it has been used in research on handball physical demands [4, 14–20] and other indoor team sports [21–24].

LPS studies have traditionally quantified average physical demands in different team sports during training and competition using variables such as distance run at different speeds (in m); time at different speeds (in s); and number (n) of high-intensity accelerations (HIA), decelerations (HID), and changes of direction [25, 26]. Of note, a number of companies recently developed a composite variable called "player load" in an attempt to capture and synthesise 3-axis accelerations, decelerations, impacts and changes of direction with a unique number, expressed in arbitrary units (a. u.). This number has been used to establish differences between playing positions [18]. Researchers have since stated, however, that due to the fluctuating nature of team sports, the average demands approach underestimates actual player workload during intermittent efforts. The reason advanced is that it does not sufficiently weight the effects of high-intensity actions concentrated in the most strenuous phases of an actual competition [27, 28]. As a result, worst case scenario (WCS) analysis in team sports has emerged. This novel approach aims to quantify the highest possible demands within brief time intervals, which are also known as the most demanding passages. WCS are defined as short time periods of maximum physical performance (distance covered at high running speed) throughout a match [29, 30]. The fixed duration method was the first attempt to quantify WCS [31] and consisted of dividing the match from start to end into fixed 5-minute periods. It aimed at reflecting more accurately the physiological and mechanical demands of intermittent sports [32, 33]. From this standpoint, identifying and quantifying the highest demands during a competition has become of great value to team sport coaches and physical trainers: the knowledge helps them to design training tasks that reproduce the most demanding contexts – not only average demands.

To date, team sport WCS analyses have been based on time windows ranging from 30 seconds to 10 minutes, relative demands being higher in shorter time windows [10, 23]. Only one study [23] has analysed WCS in handball however, and players from just one team were included in the study. A WCS analysis requires processing a large amount of information as well as heterogeneous data sources and formats. It is thus necessary to devise a system that homogenises and automates this process in order to obtain the information in a limited time and with adequate quality. As a result, we designed a modular and comprehensive system based on Big Data Analytics. It allowed the proposed methodology to be implemented with the objective of capturing, storing, processing, and analysing the information that was necessary for this study. Therefore, the main objective of the present study was to describe the WCS of maximal time-motion demands in elite male handball players during an official competition and to identify differences between playing positions.

MATERIALS AND METHODS

Experimental approach to the problem

A cross-sectional, observational study was implemented to describe time-motion WCSs in handball players and identify the differences between playing positions: goalkeepers (GK), wings (W), centre backs (CB), backs (B) and line players (LP). Results included the average values of 28 competitive official matches disputed in the European Men's Handball Championship, held in Hungary and Slovakia in January 2022. In order to obtain and analyse the WCSs, a comprehensive system based on a sensors network, LPS and big data analytics was designed following the methodology described in Figure 1.

Subjects

The data were obtained from the 180 players (27 GK, 44 W, 56 B, 23 CB and 30 LP) belonging to the top eight qualifiers of the European Handball Federation (EHF) Euro 2022. Anthropometric characteristics and the players' age are presented in Table 1. All

TABLE 1. Players' physical characteristics (mean ± standard deviation).

Playing Position	n	Height (cm)	Body Mass (kg)	BMI (kg/m^2)	Age (Years)
Centre back	23	190.8 ± 4.6	92.3 ± 6.8	25.3	28.8 ± 4.6
Left back	33	195.5 ± 4.3	97.1 ± 6.2	25.4	27.3 ± 4.3
Right back	23	192.7 ± 5.0	94.3 ± 5.5	25.4	28.2 ± 3.8
Line player	30	197.3 ± 4.9	105.1 ± 9.1	27.0	28.5 ± 4.5
Left wing	24	189.0 ± 4.9	88.2 ± 6.3	24.7	27.8 ± 3.2
Right wing	20	186.4 ± 4.4	83.6 ± 6.4	24.0	29.2 ± 5.4
Goalkeeper	27	195.0 ± 5.8	97.2 ± 8.7	25.6	30.4 ± 5.0
Total	180	192.9 ± 0.6	94.8 ± 9.5	25.5	28.5 ± 4.5

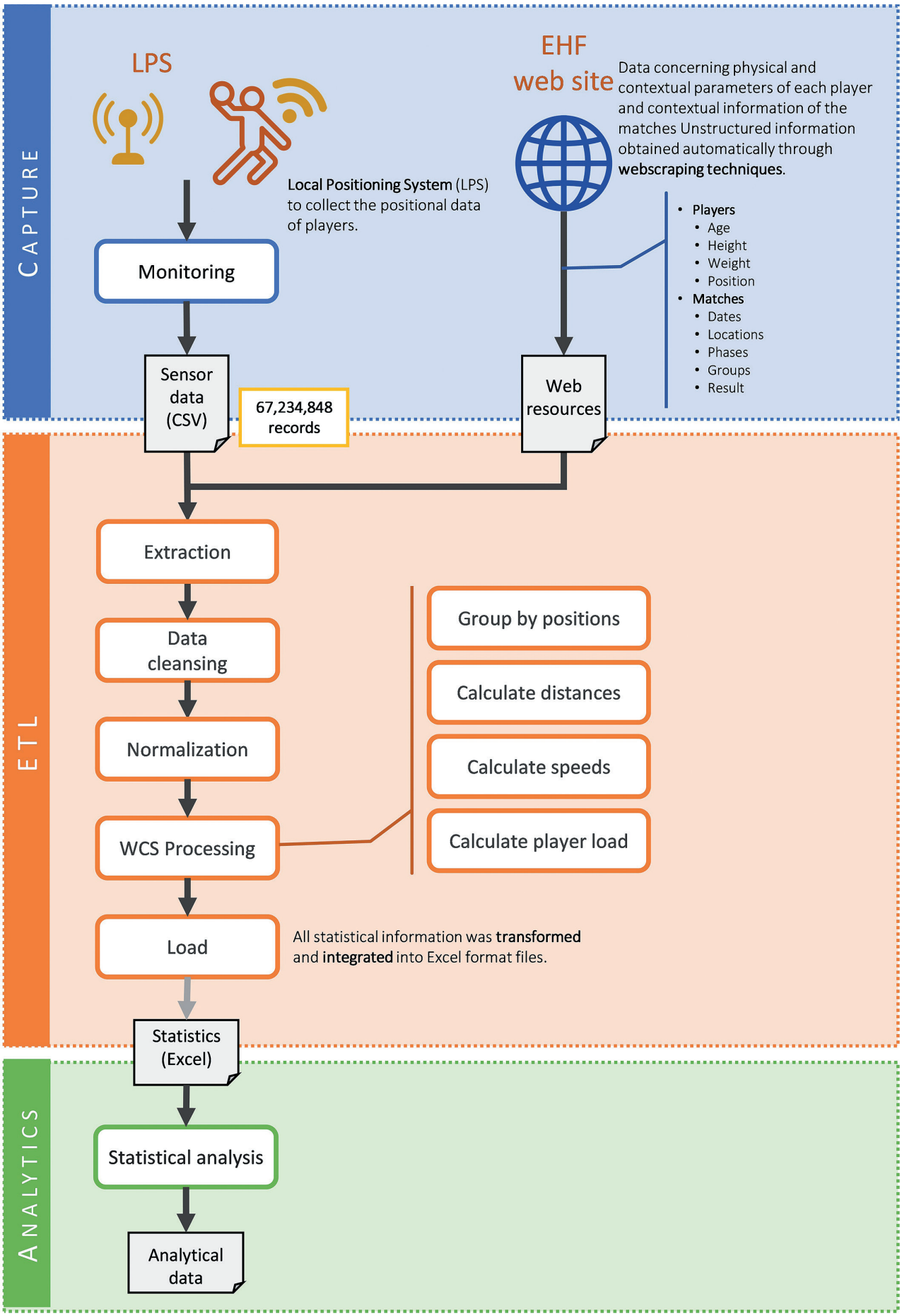


FIG. 1. Methodology of the comprehensive handball system proposed.

information (67,234,848 records) was collected from the official statistical data provided by the EHF and the routine monitoring of players during the competition (Figure 1, Capture layer). Ethics committee approval was therefore not required [34]. Nonetheless, the study followed the Declaration of Helsinki recommendations.

Competitive match monitoring (Figure 1, Capture layer)

Each player's 3D position data (x / y / z) were obtained in real time via a wearable inertial sensor (Kinexon SafeTag, Kinexon Precision Technologies, Munich, Germany) that was included in a top worn under the playing shirt, and that fit between the shoulder blades to avoid any inconvenience to the players. This tiny device (49 × 33 × 8 mm) weighs only 14 g and provides 9-axis inertial data (accelerometer, gyroscope, magnetometer) capable of recording accelerations/decelerations, rotation, and orientation angles (roll, pitch, yaw) with an update rate up to 60 Hz. The device has notably already been used for time-motion analysis in indoor team sports [20, 21, 35]. Indeed, it presents adequate between-device reliability (coefficient of variation around 5%) and a high level of agreement when compared to well-known systems such as GPS [12, 36].

The Kinexon system operates by means of triangulations between 9 antennae located around the handball court and connected to a server, and ten reference antennae acting as anchors. Setting, calibration and verification of the LPS system in all championship facilities followed the procedure described in the study by Manchado et al. [35].

The rest of the data necessary to perform the WCS analysis were collected from the EHF Website using WebScraping techniques.

Data processing (Figure 1, ETL layer)

Total distance covered (m), high-speed running (HSR) (≥ 4.4 m/s) (m), running pace (m/min), player load (arbitrary units), HIA (> 2 m/s^{-1}) (n) and HID (> -2 m/s^{-1}) (n) were individually recorded for the twelve 5-min periods of each match, following official EHF timekeeping. The pace was calculated as the ratio between distance covered and playing time, and player load was expressed as the accumulated square root of the sum of the squared instantaneous rates of acceleration change in each one of the three planes [24, 37, 38].

The collected data were cleaned up and normalised before proceeding to the WCS processing phase. Thereafter, the 5-min period with the peak values for each player was selected for every variable.

Finally, in order to perform the subsequent data analysis, we conducted the loading process and all the information necessary for the study was transformed into Excel format files using an input format compatible with the statistical analysis tool.

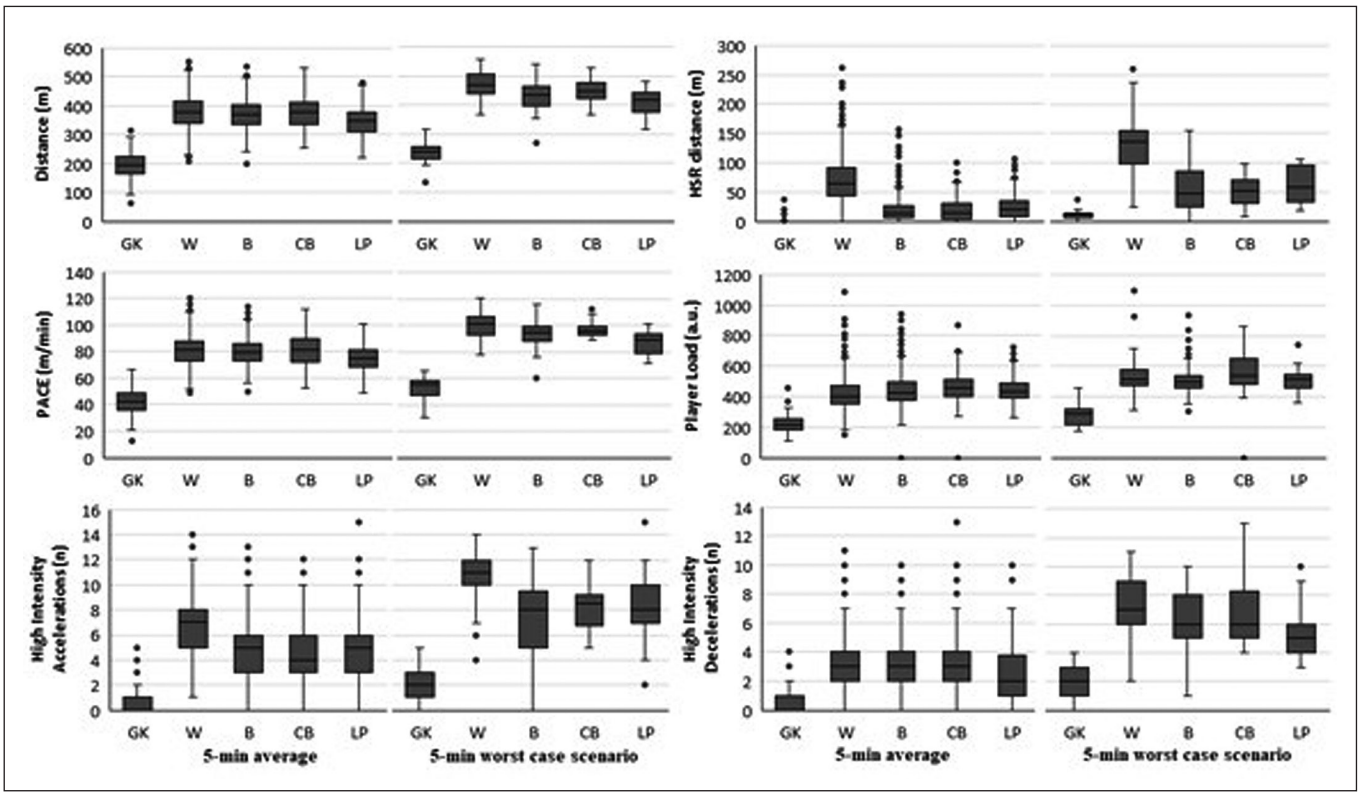


FIG. 2. Performance analysis of 5-min time spans in average (left columns) and worst-case scenarios (right columns) according to the different playing positions, shown for full-time players.

TABLE 2. Worst-case scenario analysis of 5-minute time spans during the 2022 European men's handball championship. Effect size and statistically significant differences between playing positions in time-motion variables.

Variables	Wing (W)	Mean Difference	ES	Centre back (CB)	Mean Difference	ES	Back (B)	Mean Difference	ES	Line Player (LP)	Mean Difference	ES	Goalkeeper
Total distance (m)	469 ± 49	CB: 21 ± 13 B: 34 ± 19* LP: 55 ± 11* GK: 233 ± 12*	0.5 0.7 1.2 4.9	447 ± 49	B: 12 ± 13 LP: 34 ± 14 GK: 212 ± 14*	0.3 0.8 5.1	435 ± 48	LP: 22 ± 11 GK: 199 ± 11*	0.5 4.3	413 ± 45	GK: 178 ± 13*	4.0	235 ± 42
HSR distance (m)	133 ± 47	CB: 82 ± 10* B: 76 ± 8* LP: 71 ± 9* GK: 122 ± 9*	1.9 1.7 1.7 3.2	51 ± 26	B: -6 ± 10 LP: -11 ± 11 GK: 40 ± 11*	0.2 0.4 2.2	57 ± 41	LP: -5 ± 9 GK: 46 ± 9*	0.1 1.3	62 ± 29	GK: 51 ± 10*	2.3	11 ± 8
Pace (m/min)	100 ± 10	CB: 2 ± 2 B: 5 ± 2 LP: 12 ± 2** GK: 47 ± 2**	0.3 0.7 1.2 4.9	97 ± 9	B: -2 ± 3 LP: 10 ± 3* GK: 212 ± 14*	0.3 1.3 5.1	94 ± 10	LP: 7 ± 2* GK: 42 ± 2*	0.7 4.1	87 ± 8	GK: 35 ± 3*	4.0	52 ± 9
Player Load (a. u)	546 ± 139	CB: 9 ± 34 B: 26 ± 26 LP: 30 ± 30 GK: 264 ± 31*	0.1 0.2 0.2 2.2	537 ± 177	B: 17 ± 38 LP: 21 ± 37 GK: 255 ± 30*	0.1 0.2 2.0	520 ± 119	LP: -4 ± 39 GK: 238 ± 39*	.04 2.2	516 ± 91	GK: 234 ± 34*	2.8	282 ± 73
HIA (n)	10.6 ± 2.1	CB: 2.4 ± 0.6* B: 3.0 ± 0.5* LP: 2.2 ± 0.6* GK: 8.4 ± 0.4*	1.2 1.2 0.9 4.4	8.2 ± 2.0	B: 0.6 ± 0.6 LP: -0.2 ± 0.7 GK: 5.9 ± 0.5*	0.2 0.1 3.5	7.6 ± 2.7	LP: -0.8 ± 0.6 GK: 5.3 ± 0.5*	0.3 2.3	8.4 ± 2.6	GK: 6.1 ± 0.6*	2.9	2.2 ± 1.4
HID (n)	6.8 ± 2.2	CB: .004 ± 0.6 B: 0.8 ± 0.4 LP: 1.4 ± 0.5* GK: 4.7 ± 0.5*	0.0 0.3 0.7 2.4	6.8 ± 2.4	B: 0.8 ± 0.6 LP: 1.4 ± 0.6 GK: 4.7 ± 0.6*	0.4 0.7 2.6	6.0 ± 2.1	LP: 0.6 ± 0.5 GK: 3.9 ± 0.4*	0.3 2.1	5.4 ± 1.9	GK: 3.2 ± 0.4*	2.0	2.2 ± 1.1

ES: effect size; HSR: High Speed Running (> 4.4 m/s); HIA: High Intensity Accelerations (> $2m \cdot s^{-1}$); HID: High Intensity decelerations (> $2m \cdot s^{-1}$); Player Load (a. u.): sum of the squared rates of change in acceleration (also known as jerk) in each of the three vectors expressed in arbitrary units.

*Significant differences ($p < 0.05$); moderate = 0.6 to 1.19, large = 1.2 to 1.99, very large = 2.0 to 3.99, and nearly perfect = 4.0

Firmware and software versions employed in this study corresponded to the latest update of the aforementioned company (2019).

Statistical analysis (Figure 1, Analytics layer)

Descriptive statistics are presented as means and standard deviations (SD) for all workload variables. Mean and peak demands were averaged for each fixed 5-min timespan and playing position. Playing time was recorded only when the players were on court and only full-time players (≥ 240 s for each 300 s time window) were included in the analyses.

The Kolmogorov-Smirnov test was conducted to confirm data distribution normality and Levene's test for equality of variances. A separate one-way analysis of variance (ANOVA) was used to identify differences between playing positions, regarding both average and peak demands for the fixed 5-min time spans. Finally, Gabriel or Games-Howell post-hoc analyses were also conducted when appropriate to determine significant differences between playing positions. Effect sizes for all pairwise comparisons were also calculated using Cohen's d, with 95% confidence intervals. Cohen's d was interpreted as follows: trivial = 0 to 0.19, small = 0.2 to 0.59, moderate = 0.6 to 1.19, large = 1.2 to 1.99, very large = 2.0 to 3.99, and nearly perfect = 4.0 [39].

RESULTS

Table 2 shows the WCS of the examined variables according to the different handball playing positions in fixed 5-min time spans. The one-way ANOVA showed significant differences between goalkeepers and all other positions ($p < 0.001$), with effect sizes ranging from very large to nearly perfect (2.0–5.1). After post-hoc testing, differences between line players and all other positions were found for

TABLE 3. Performance variables of elite men handball players in fixed 5-min time spans: Position-specific Comparison between average and peak values.

Position Variables	**5-min Average**	**5-min Worst Case Scenario**	**Difference (%)**
Goalkeeper			
Total distance (m)	194 ± 39	235 ± 42	17
HSR distance (m)	1 ± 4	11 ± 8	91
Pace (m/min)	42.5 ± 9	52.3 ± 9	19
Player Load (a. u)	217 ± 50	282 ± 73	23
HIA (n)	0.8 ± 1.0	2.2 ± 1.4	65
HID (n)	0.6 ± 0.8	2.2 ± 1.1	72
Wing			
Total distance (m)	378 ± 56	469 ± 49	19
HSR distance (m)	70 ± 38	133 ± 47	47
Pace (m/min)	81 ± 11	100 ± 10	19
Player Load (a. u)	419 ± 118	546 ± 139	23
HIA (n)	6.7 ± 2.3	10.6 ± 2.1	37
HID (n)	3.3 ± 1.9	6.8 ± 2.2	52
Back			
Total distance (m)	369 ± 50	435 ± 48	15
HSR distance (m)	20 ± 23	57 ± 41	65
Pace (m/min)	80 ± 10	94 ± 10	15
Player Load (a. u)	448 ± 114	520 ± 119	14
HIA (n)	4.7 ± 2.2	7.6 ± 2.7	38
HID (n)	3.1 ± 1.9	6.0 ± 2.1	49
Centre back			
Total distance (m)	374 ± 54	447 ± 39	16
HSR distance (m)	19 ± 20	51 ± 26	63
Pace (m/min)	81 ± 11	97 ± 9	17
Player Load (a. u)	456 ± 108	537 ± 177	15
HIA (n)	4.5 ± 2.5	8.2 ± 2.0	45
HID (n)	3.2 ± 2.2	6.8 ± 2.2	53
Line player			
Total distance (m)	346 ± 49	413 ± 45	16
HSR distance (m)	24 ± 23	62 ± 29	61
Pace (m/min)	75 ± 9	87 ± 8	14
Player Load (a. u)	442 ± 79	516 ± 91	14
HIA (n)	4.9 ± 2.4	8.4 ± 2.6	42
HID (n)	2.5 ± 1.8	5.4 ± 1.9	54

HSR: High Speed Running (> 4.4 m/s); HIA: High Intensity Accelerations (> $2m \cdot s^{-1}$); HID: High Intensity decelerations (> $2m \cdot s^{-1}$); Player Load (a. u.): sum of the squared rates of change in acceleration (also known as jerk) in each of the three vectors expressed in arbitrary units.

peak running pace (effect sizes between 0.7 and 4.0). For their part, wing players presented longer distances covered at HSR (> 4.4 m/s) than the rest, except the centre backs (effect sizes between 1.7 and 3.2). Moreover, no differences were found between playing positions in terms of player load, excluding goalkeepers. The position-specific performance analyses in fixed 5-min windows, of both average and peak demands, are shown in Figure 2. Additionally, Table 3 reports the differences (in %) between average and peak demands for the aforementioned 5-min fixed time spans.

DISCUSSION

The aim of the current study was to profile the position-specific worst-case scenarios of locomotor demands in elite male handball players across fixed, 5-min time spans, and to identify differences between playing positions. The main findings were twofold: i) significant differences between playing positions were found in WCS locomotor demands with effect sizes ranging from moderate to very large (0.7–5.1) – wings performing longer distances at HSR (~55%) and line players showing the lowest pace among field players (~11%); and ii), 5-min WCS were revealed to be ~17% higher than the average demands in terms of total distance covered and pace, with a particular increase in high-intensity actions (~51%).

Worst-case scenario differences between playing positions

Regarding WCS analyses, only two recent studies [23, 40] have described time-motion variables in top-level handball players. As in the current study, Fleureau [40] found that wing players endured the highest peak locomotor intensity (i.e., running pace) during matches (wings = 102 ± 7; backs = 95 ± 9; line players = 89 m/min). These results confirm our findings (100 ± 10; 95 ± 10; 87 ± 8 m/min, respectively), as line players also presented the lowest locomotion demands among field players – though their study revealed slightly lower effect sizes overall.

Nevertheless, HSR distance was significantly higher than in our study. It was not possible, however, to assess differences because of the thresholds defined in this study to classify HSR (> 4 m/s vs > 4.4 m/s). In addition, the present study analysed fixed 5-min intervals, while Fleureau's study applied rolling averages to identify the WCS. Previous comparisons between these methods have shown that the rolling average approach identified 10% to 25% higher peak demands when using 5-min time windows [41, 42]. Therefore, peak demand may have been underestimated in the present study.

It is also worth mentioning that Fleureau [40] assessed only 11 players from one top French professional league team, whereas the current study monitored 180 players from 8 different national teams during 29 competitive matches, providing further robustness to the results.

On the other hand, the study by Garcia [23] compared overall locomotion demands of different team sports from the same club. In the case of handball, a generic field player showed values similar to those of the present study for the total distance run (< 6% of

difference) but larger differences when comparing high-intensity actions (~50%). Again, the thresholds defined to classify HSR differed slightly from those used in the Kinexon system, which prevented us from assessing any agreement regarding high-intensity actions between both studies.

Average vs peak demands

Average values have traditionally been used to profile the physical demands of intermittent sports. It has recently been suggested, however, that this latter approach may overlook the most demanding match-play phases, underestimating the physiological and mechanical effects of repeated high-intensity actions – which are so characteristic of these sports [28, 43]. Nevertheless, the evidence regarding WCS in handball remains scarce. We thus decided to include a descriptive analysis of the average demands in fixed 5-min periods to be able to compare our results with previous evidence, as well as to outline the percentage of change between the average values and the WCS.

Our results identified differences of ~17% in total distance covered and pace, and ~50% in high-intensity actions when comparing average and peak values during 5-min time spans. In this regard, previous research [40] suggested reductions of ~15% and ~37%, respectively, when compared 5- to 15-min periods.

Regarding average demands, a range of previous studies [4, 14–18, 20, 25, 26, 44] have quantified the position-specific handball physical requirements in different contexts (amateur/professional, male/female), with controversial results. Despite the fact that they described lower average running paces and total distances covered in their whole match analyses [4, 9, 18], peak values in Karcher's and Luteberget's studies resembled ours. Moreover, Karcher and Buchheit's study [4, 18] also identified wing players as having the longest distances and high-speed actions (ES = 1.1) and pivots as having the least (ES = 1.7). Of note, these studies described a wider range of high-intensity actions (e.g., contacts, duels, jumps) using a notation system that hinders a comparison with LPS data [4].

Comparable results were found by Manchado [35] regarding average running pace and HSR distance according to playing position. Centre and left backs, however, were found to be the most demanding positions overall. In this regard, the works of Kniubaite [17] and Font [16] introduced the player load as an accurate metric to control external load during competition, describing centre backs as having the highest workload among field players. Conversely, our results confirmed no differences between playing positions, whether during average or peak demands. A possible explanation could be found in the studies of Povoas [9] and Karcher [4]: the characteristic actions of line players and backs include a greater number of duels, impacts and changes of direction than in the case of wingers. They may thus present similar or greater values in overall external load than the latter, but with lower locomotor demands.

Despite the reported findings, the current study presented some limitations. First, only full-time players were included in the analysis, preventing us from knowing the time-motion characteristics of attacking or defensive specialists. Additionally, the use of fixed time spans may lead to underestimating the most demanding phases during games compared to rolling averages. In this sense, a study profiling the different locomotor demands of attack and defence phases based on shorter time periods would allow the current knowledge gap to be filled. Moreover, a single, unified criterion is needed to determine locomotion categories in LPS analysis, as this lack of common criterion is currently preventing comparisons between studies. In this regard, future research should focus on handball characteristics based on a holistic perspective and include collisions, fights and impacts as well as peak locomotor activities in the game analysis, thus mirroring similar rugby studies [45, 46].

Despite these limitations, the present study on handball locomotion worst-case scenarios provides meaningful information making it possible to customise training drills to each player position and to better prepare players for peak demands during competitions.

CONCLUSIONS

The position-specific description of handball locomotor peak demands showed that wing players cover longer total and HSR, whereas line players cover the shortest distances among all playing positions. These results have direct implications for the design of position-specific conditioning drills (e.g., short or long intervals, repeated sprints, etc.): practitioners should consider including more duels and impacts, and less running distance for line players, together with supplementary repeated sprint work for wingers. In addition, the traditional average method was found to underestimate worst-case demands over 5-min fixed periods by up to 51%. Therefore, when designing training sessions and rehabilitation protocols, coaches must be aware of the possible worst-case scenario, as the average-based approach may fail to prepare players for what they will actually experience during elite handball competitions. The performance of the present study required the design of an integral and modular system based on a sensors network, LPS, and big data analytics.

Conflict of interest

The authors declared no conflict of interests.

REFERENCES

1. Wagner H, Finkenzeller T, Würth S, Von Duvillard SP. Individual and Team Performance in Team-Handball: A Review. J Sport Sci Med [Internet]. 2014 [cited 2016 Feb 24]; 13(4):808–16. Available from: http://www.jssm.org
2. Fasold F, Redlich D. Foul or no foul? Effects of permitted fouls on the defence performance in team handball. J Hum Kinet. 2018; 63(1):53–9.
3. Gorostiaga EM, Granados C, Ibáñez J, Izquierdo M. Differences in physical fitness and throwing velocity among elite and amateur male handball players. Int J Sports Med. 2005 Mar; 26(3):225–32.
4. Karcher C, Buchheit M. On-court demands of elite handball, with special reference to playing positions. Sport Med. 2014; 44(6):797–814.
5. Di Salvo V, Baron R, Tschan H, Calderon Montero FJ, Bachl N, Pigozzi F. Performance characteristics according to playing position in elite soccer. Int J Sports Med. 2007 Mar; 28(3):222–7.
6. Pino-Ortega J, Rojas-Valverde D, Gómez-Carmona CD, Bastida-Castillo A, Hernández-Belmonte A, García-Rubio J, et al. Impact of contextual factors on external load during a congested-fixture tournament in elite U'18 basketball players. Front Psychol. 2019; 1100.
7. Michalsik LB, Aagaard P. Physical demands in elite team handball: Comparisons between male and female players. J Sports Med Phys Fitness. 2015; 55(9):878–91.
8. Ortega-Becerra M, Belloso-Vergara A, Pareja-Blanco F. Physical and physiological demands during handball matches in male adolescent players. J Hum Kinet. 2020; 72(1):253–63.
9. Póvoas SCA, Ascensão AAMR, Magalhães J, Seabra AF, Krustrup P, Soares JMC, et al. Physiological demands of elite team handball with special reference to playing position. J Strength Cond Res. 2014; 28(2):430–42.
10. Harper DJ, Carling C, Kiely J. High-intensity acceleration and deceleration demands in elite team sports competitive match play: a systematic review and meta-analysis of observational studies. Sport Med. 2019; 49(12):1923–47.
11. Taylor JB, Wright AA, Dischiavi SL, Townsend MA, Marmon AR. Activity demands during multi-directional team sports: a systematic review. Sport Med. 2017; 47(12):2533–51.
12. Hoppe MW, Baumgart C, Polglaze T, Freiwald J. Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. PLoS One. 2018; 13(2):e0192708.
13. Serpiello FR, Hopkins WG, Barnes S, Tavrou J, Duthie GM, Aughey RJ, et al. Validity of an ultra-wideband local positioning system to measure locomotion in indoor sports. J Sports Sci. 2018; 36(15):1727–33.
14. Cardinale M, Whiteley R, Hosny AA, Popovic N. Activity profiles and positional differences of handball players during the World Championships in Qatar 2015. Int J Sports Physiol Perform. 2017; 12(7):908–15.
15. Fleureau A, Lacome M, Buchheit M, Couturier A, Rabita G. Validity of an ultra-wideband local positioning system to assess specific movements in handball. Biol Sport. 2020; 37(4):351–7.
16. Font R, Karcher C, Reche X, Carmona G, Tremps V, Irurtia A. Monitoring external load in elite male handball players depending on playing positions. Biol Sport. 2021; 38(3):475–81.
17. Kniubaite A, Skarbalius A, Clemente FM, Conte D. Quantification of external and internal match loads in elite female team handball. Biol Sport. 2019; 36(4):311–6.
18. Luteberget LS, Trollerud HP, Spencer M. Physical demands of game-based training drills in women's team handball. J Sports Sci. 2018; 36(5):592–8.
19. Manchado C, Tortosa-Martínez J, Vila H, Ferragut C, Platen P. Performance Factors in Women's Team Handball: Physical and Physiological Aspects—A Review. J Strength Cond Res [Internet]. 2013; 27(6). Available from: https://journals.lww.com/nsca-jscr/Fulltext/2013/06000/Performance_Factors_in_Women_s_Team_Handball_.31.aspx
20. Manchado C, Tortosa Martínez J, Pueo B, Cortell Tormo JM, Vila H, Ferragut C, et al. High-performance handball player's time-motion analysis by playing positions. Int J Environ Res Public Health. 2020; 17(18):6768.
21. Link D, Weber M, Linke D, Lames M. Can positioning systems replace timing gates for measuring sprint time in ice hockey? Front Physiol. 2019; 9:1882.
22. Bastida-Castillo A, Gómez-Carmona CD, De la Cruz-Sánchez E, Reche-Royo X, Ibáñez SJ, Pino Ortega J. Accuracy and inter-unit reliability of ultra-wide-band tracking system in indoor exercise. Appl Sci. 2019; 9(5):939.
23. García F, Fernández D, Illa J, Reche X, Font R, Guitart M, et al. Comparing the most demanding scenarios of official matches across five different professional team sports in the same club. Apunt Sport Med. 2022; 57(215):100390.
24. Vazquez-Guerrero J, Fernández-Valdés B, Jones B, Moras G, Reche X, Sampaio J. Changes in physical demands between game quarters of U18 elite official basketball games. PLoS One. 2019; 14(9):e0221818.
25. González-Haro PJ, Gómez-Carmona CD, Bastida-Castillo A, Rojas-Valverde D, Gómez-López M, Pino-Ortega J. Analysis of playing position and match statusrelated differences in external load demands on amateur handball: A case study. Rev Bras Cineantropometria Desempenho Hum. 2020; 22.
26. Póvoas SCA, Castagna C, Resende C, Coelho EF, Silva P, Santos R, et al. Physical and physiological demands of recreational team handball for adult untrained men. Biomed Res Int. 2017; (6204603):1–10.
27. Gabbett TJ, Kennelly S, Sheehan J, Hawkins R, Milsom J, King E, et al. If overuse injury is a 'training load error', should undertraining be viewed the same way? Vol. 50, British Journal of Sports Medicine. 2016.
28. Varley MC, Elias GP, Aughey RJ. Current match-analysis techniques' underestimation of intense periods of high-velocity running. Int J Sports Physiol Perform. 2012; 7(2).
29. Delaney JA, Duthie GM, Thornton HR, Scott TJ, Gay D, Dascombe BJ. Acceleration-based running intensities of professional rugby league match play. Int J Sports Physiol Perform. 2016; 11(6):802–9.
30. Reardon C, Tobin DP, Tierney P, Delahunt E. The worst case scenario: Locomotor and collision demands of the longest periods of gameplay in professional rugby union. PLoS Med [Internet]. 2017 [cited 2023 Mar 9]; 12(5):e0177072. Available from: https://doi.org/10.1371/journal.pone.0177072
31. Bradley PS, Sheldon W, Wooster B, Olsen P, Boanas P, Krustrup P. High-intensity running in English FA Premier League soccer matches. J Sports Sci. 2009 Jan 15; 27(2):159–68.
32. Oliva-Lozano JM, Martín-Fuentes I, Fortes V, Muyor JM. Differences in worst-case scenarios calculated by fixed length and rolling average methods in professional soccer match-play. Biol Sport. 2021; 38(3):325.
33. Rico-González M, Oliveira R, Vieira LHP, Pino-Ortega J, Clemente F. Players' performance during worst-case scenarios in professional soccer matches: a systematic review. Biol Sport. 2022; 39(3):695–713.
34. Winter EM, Maughan RJ. Requirements for ethics approvals. J Sports Sci. 2009; 27(10):985.
35. Manchado C, Pueo B, Chirosa-Rios LJ, Tortosa-Martínez J. Time–Motion Analysis by Playing Positions of Male Handball Players during the European Championship 2020. Int J Environ Res Public Health. 2021; 18(6):2787.

36. Alt PS, Baumgart C, Ueberschär O, Freiwald J, Hoppe MW. Validity of a local positioning system during outdoor and indoor conditions for team sports. Sensors. 2020; 20(20):5733.
37. García F, Vázquez-Guerrero J, Castellano J, Casals M, Schelling X. Differences in physical demands between game quarters and playing positions on professional basketball players during official competition. J Sports Sci Med. 2020; 19(2):256.
38. Fox JL, Stanton R, Scanlan AT. A comparison of training and competition demands in semiprofessional male basketball players. Res Q Exerc Sport. 2018; 89(1):103–11.
39. Fritz CO, Morris PE, Richler JJ. Effect size estimates: current use, calculations, and interpretation. J Exp Psychol Gen. 2012; 141(1):2.
40. Fleureau A, Rabita G, Leduc C, Buchheit M, Lacome M. Peak Locomotor Intensity in Elite Handball Players: A First Insight Into Player Position Differences and Training Practices. J Strength Cond Res. 2022; 10–1519.
41. Sheppy E, Hills SP, Russell M, Chambers R, Cunningham DJ, Shearer D, et al. Assessing the whole-match and worst-case scenario locomotor demands of international women's rugby union match-play. J Sci Med Sport. 2020; 23(6):609–14.
42. Cunningham DJ, Shearer DA, Carter N, Drawer S, Pollard B, Bennett M, et al. Assessing worst case scenarios in movement demands derived from global positioning systems during international rugby union matches: Rolling averages versus fixed length epochs. PLoS One. 2018; 13(4):e0195197.
43. Gabbett TJ, Hulin BT, Blanch P, Whiteley R. High training workloads alone do not cause sports injuries: How you get there is the real issue. Br J Sports Med. 2016; 50(8):444–5.
44. Manchado C, Pers J, Navarro F, Han A, Sung E, Platen P. Time-motion analysis in women's team handball: importance of aerobic performance. J Hum Sport Exerc. 2013; 8(2):376–90.
45. Weaving D, Sawczuk T, Williams S, Scott T, Till K, Beggs C, et al. The peak duration-specific locomotor demands and concurrent collision frequencies of European Super League rugby. J Sports Sci. 2019; 37(3):322–30.
46. Johnston RD, Weaving D, Hulin BT, Till K, Jones B, Duthie G. Peak movement and collision demands of professional rugby league competition. J Sports Sci. 2019; 37(18):2144–51.

Effect of training load on sleep parameters and biochemical fatigue markers in elite swimmers

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ABSTRACT: The effect of strenuous exercise on sleep patterns in swimmers is equivocal. Therefore, the purpose of the study was to describe possible changes in sleep parameters among elite swimmers subjected to different training loads (TL). Methods: Eighteen elite swimmers (8 females) were monitored across two high-volume preparatory 1–wk periods (P1, P2) and a lower-volume tapering 1–wk period (P3) before a major competition. Internal (the session rating of perceived exertion [sRPE]) and external TL (training duration and volume) were measured, along with several sleep indices (e.g., bedtime, get-up time, sleep time, wake after sleep onset [WASO]). Serum measurements of urea, creatine kinase (CK), testosterone and cortisol were taken before and after training sessions at the beginning (Mondays) and end (Fridays) of each micro cycle. Athlete TL decreased significantly in a stepwise manner from P1 to P2 and from P2 to P3. Of all sleep parameters, only significant differences in bedtime and get-up time emerged (P3 > P1 and/or P2). Sleep duration (~6.3 h) or quality (WASO: 41–45 min) were also unaffected by TL. CK levels declined from P1 to P3 (d = -0.8), and from P2 to P3 (d = -0.6). Positive exercise-induced changes in CK were also seen in each training period. The other biomarkers did not show the same temporal or acute patterns. Irrespective of the TL, the monitored swimmers experienced insufficient and fragmented sleep across this study. Neither sleep quality nor quantity were affected by different magnitudes of TL. Among the biochemical markers of fatigue, baseline plasma CK activity best reflected the physiological response to TL.

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INTRODUCTION

Sleep is considered a principal component of training and competition recovery, and essential for optimizing athletic performance [1]. Given the importance of sleep to athletic performance and recovery, it is surprising that poor sleep is still prevalent among elite athletes [2]. Many factors can affect the sleeping patterns (e.g., travel, unfamiliar environment, pre-competition anxiety, the use of electronic devices, altitude) of athletic populations [2–5], including intensified training periods [2, 3]. For instance, a 3-wk overload training program promoted overreaching in triathletes and this, in turn, promoted a decline in sleep quantity and quality [6]. Similarly, a short period of intensified training affected sleep efficiency among male cyclists [7]. Others have, however, found no association between TL variation and sleep [8, 9]. These discrepancies could be explained by the interdependence of sleep-exercise interactions, such that sleep might drive, and be driven by, shifts in TL.

Other difficulties arise in terms of identifying the sleep component that best reflects TL. Taylor et al., [10] examined sleep changes in female swimmers during three phases of a competitive season. Most indicators of sleep quantity (e.g., total sleep time) and quality (e.g., sleep latency) did not differ across the season, but time spent in deep sleep was higher during the onset and peak training (vs. tapering) period. A more recent study profiled competitive swimmers across four training phases [9]. They found only trivial to small differences in sleep quantity between phases, whilst other parameters (e.g., sleep latency) showed only small to moderate differences. Substantial between-individual variation in sleep responses also emerged. Hence, a broad assessment of sleep, ideally combining subjective and objective measures, is needed to explicate more complex sleep-TL interactions. Adding to these difficulties, it is not clear whether sleep disturbances are a consequence of physical or psychological overload, thereby contributing to an overreaching or overtraining state [11], or simply a manifestation of the aforementioned syndromes.

Training load is generally classified into two components; internal and external [12]. Internal TL (e.g., heart rate response to training), reflects the psychophysiological response to exercise, whilst external TL (e.g., total distance covered), refers to the physical work

completed. Both external TL [9, 13] and internal TL measures have been used in sleep research on athletes [14, 15], but few have combined these approaches to capture the nuances of sports training [16]. Others expanded their assessment to include salivary testosterone (T) and cortisol (C) measures [17, 18], but linkages to sleep were equivocal due to individual and context specificity, with both measures more strongly affected by psychological stress rather than fatigue [17, 18]. As such, implementing a panel of blood biomarkers could help decode the impact of training-related fatigue mechanisms on sleep patterns or vice versa.

Though none of the currently available blood biomarkers are regarded as the definitive fatigue indicator, some are considered promising and used in science and practice to monitor fatigue and the recovery process (e.g., creatine kinase [CK], urea [URE], T, C) [19, 20]. Serum CK activity, for example, reflects metabolic and/or mechanical damage of the muscle fibres resulting from repeated and intense contractions [21]. Increased serum URE is a marker of enhanced protein breakdown (in the absence of excessive protein intake) and stimulated gluconeogenesis that results from increased training loads [19, 20]. Both CK and URE may also provide information pertaining to increased muscular and/or metabolic strain [19, 20]. Cortisol is an important signal for stress and metabolic regulation, sometimes promoting catabolic processes, and synchronization of peripheral clocks with the circadian cycle [22]. Testosterone often works antagonistically to cortisol, promoting protein synthesis and reducing protein breakdown; thus, increased C and/or decreased T levels might indicate high physiological strain [20].

The purpose of this study was to describe possible changes in actigraphy-based and subjective sleep parameters among professional swimmers subjected to different TLs, assessed using a combination of external and internal TL measures. Specifically, the swimmers were monitored across three training micro-cycles that differed in prescribed load: two preparatory periods (P1, P2) with a relatively high TL and a pre-competition tapering period (P3) with a relatively low TL. We investigated the interplay between TL and sleep, and also whether any adaptive shifts would manifest as biochemical (URE, CK, T, C) changes, both baseline activity and acute exercise-induced reactivity. We broadly hypothesized that a higher TL in P1 and P2 would lead to a deterioration in sleep quality and/or quantity, along with changes in biochemical fatigue markers (e.g., increase in baseline and exercise changes in CK and C, lowering of baseline T), with restoration of these outcomes in P3 following a lower TL.

MATERIALS AND METHODS

Participants

Eighteen elite swimmers from one swimming team, subjected to one training plan, were recruited through convenience sampling. This cohort comprised of eight females (mean ± *SD*; height = 171.5 ± 4.5 cm, body mass = 64.7 ± 7.9 kg, training experience = 8 ± 2 years) and 10 males (mean ± *SD*; height = 184.5 ± 3.7 cm, body mass = 78.0 ± 3.6 kg, training experience = 13 ± 3 years) with a mean (± SD) age of 21 ± 4 years (range 16–28 years).These athletes competed at the highest national and/or international level with mean FINA points of 763 ± 110 (range 633 to 940 points). Inclusion criteria were age ≥ 16 years and swimming performance level of ≥ 600 World Aquatics points (formerly: Fédération Internationale de Natation, FINA points). Exclusion criteria were diagnosed sleeping disorder, tobacco use, use of sleep medications, travel across different time zones before the study commenced. All athletes were healthy and injury-free throughout the monitoring period. The participants were informed of the study aims, potential risks, procedures and benefits, after which they provided written informed consent. For participants under the consenting age of 18 years, informed consent was provided by their parents or legal guardians. This study received ethical approval (KEBN-19-43-OS) from the Ethics Committee of the Institute of Sport—National Research Institute, Poland, in agreement with the Helsinki Declaration.

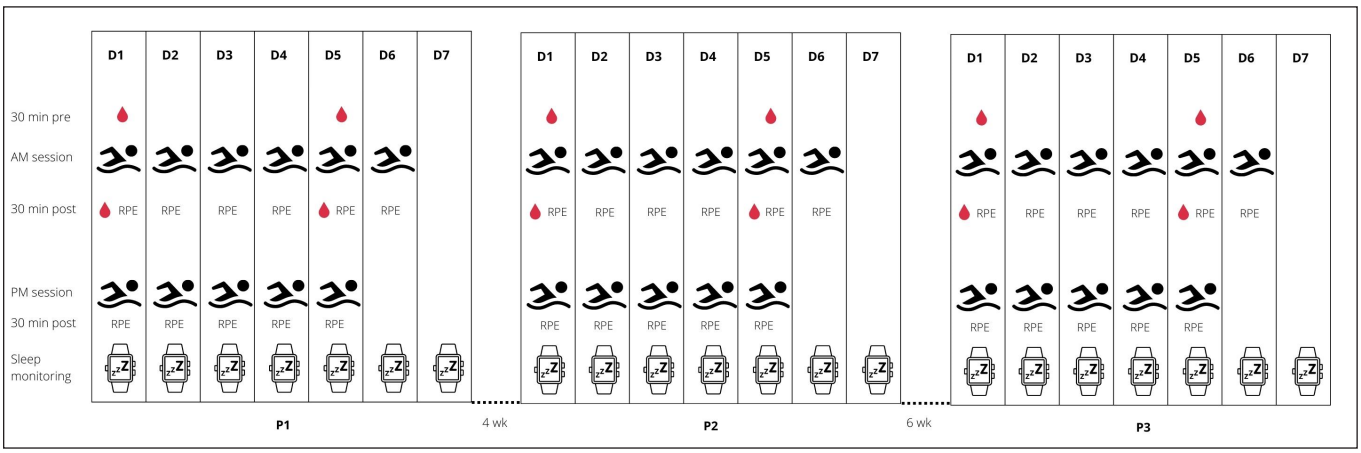


FIG. 1. Schematic representation of the study design, including time points of training sessions, blood sampling, and the session rating of perceived exertion (sRPE) collection.

Study design

A single group within-subject design was used to address the study aim. The participants were monitored for weekly internal and external TL, sleep patterns, and biochemical changes across a 1-week block during three training periods (P1, P2, P3), as they prepared for the Polish National Swimming Championships. Four weeks of training separated P1 (aerobic endurance capacity; session duration = 113 ± 13 min, session volume = 6.4 ± 1.4 km) and P2 (aerobic endurance capacity; session duration = 111 ± 19 min, session volume = 5.3 ± 1.4 km), with six weeks separating P2 and P3 (tapering; session duration = 66 ± 9 min, session volume = 3.2 ± 0.4 km). P3 ended some three days before the championship event, where success was crucial to obtain a qualifying time standard for other international events (e.g., 18th FINA World Championships, European Junior Swimming Championships). A traditional linear periodization plan (low-intensity and high-volume training across the first periods of the macrocycle, with progressive increases in training intensity and concurrent decreases in training volumes of the consecutive periods) was developed by the head trainer to ensure peak performance. To achieve this goal, an incremental decrease in training volume (in km) was prescribed from P1 to P2 to P3. Training frequency did not change within each micro cycle. This entailed 6 training days a week, comprising of 6 morning (starting 6:00 am in P1 and P2, 6:45 am in P3) and 5 afternoon (starting 4:00–6:00 pm) sessions. Figure 1 shows an overview of the study design as well as the collected parameters.

Training load

Internal TL was measured using the session rating of perceived exertion (sRPE) method; a common approach in sport [23, 24] that offers a valid and easily accessible method for monitoring TL in competitive swimmers [23]. Each athlete provided a RPE (on a 0 to 10 scale) within 30 minutes of completing a swim-based training session. This score was multiplied by other metrics to derive two TL measures, as a function of: 1/training intensity and session duration expressed in min (sRPEh); 2/ training intensity and session distance expressed in km (sRPEkm). This dual approach was taken to account for a greater effect of training volume on perceived exertion than training duration in endurance sports like swimming [24]. The participants were familiarized with the RPE scale prior to study commencement. For P1, P2 and P3, weekly TL was calculated as the sum of all swim-based sessions completed during that micro cycle. Training load did not include non-specific training (i.e., gym sessions). Athlete training intensity was determined by a pre-study assessment of blood lactate concentration. Training intensity zones were classified as zone 1 (< 1 mmol/l; skills), zone 2 (1–3 mmol/l; aerobic capacity), zone 3 (3–5 mmol/l; aerobic capacity – threshold), zone 4 (> 5 mmol/l; anaerobic capacity), zone 5 (sprint) [25]. The division of training intensity into five different zones was adopted arbitrarily by the coaching staff.

Sleep assessment

Sleep was assessed using a wearable sensor (ActiGraph GT3X-BT, USA) and daily sleep diary. The sensor was worn continuously (on the non-dominant hand) across each training period, except during swimming sessions or taking a bath. Raw actigraphy data were sampled at 30 Hz and converted to 60-second epoch files for analysis with dedicated software (ActiGraph v6.13.4, USA). Sleep and non-sleep periods were scored with the Cole-Kripke Algorithm [26], which has been shown to be more accurate not only in adults but also in children [27]. The sleep diary (e.g., quality of sleep, time in bed) was completed within one hour of getting out of bed. Diary information was also used to identify, and adjust, any mis-specified sleeping events from sensing data. The following sleep measures were obtained: 1/bedtime (hrs) – time when the subject went to bed; 2/ get-up time (hrs) – time when the subject got out of bed; 3/ sleep latency (min) – the number of minutes between the in bedtime and the sleep onset time for a specific sleep period; 4/sleep efficiency (%) – the percentage of time in bed that was spent asleep; 5/total sleep time (TST) (min) – the total number of minutes scored as "asleep." at night; 6/wake after sleep onset (WASO) (min) – the total number of minutes the subject was marked awake after sleep onset occurred; 7/fragmentation index or FI (%) – the percentage of one minute periods of sleep vs. all periods of sleep in the sleep period; 8/self-reported sleep latency (min) – participant's self-rating of the period of time between bedtime and sleep onset time; 9/subjective sleep score (1-5) – subjects' self-rating of sleep quality (1 = very poor sleep quality to 5 = very good sleep quality). For exploration purposes, we also collected information on other factors likely to affect sleep, including: caffeine and alcohol intake, medication usage, health, appetite, willingness to train, pain, napping, and stress levels.

Assessment of blood biochemistry

Our selection of blood parameters was based on several factors: 1/ whether they offer physiological insight into the mechanisms underlying exercise-induced fatigue; 2/ scientific evidence of their utility in relation to muscle fatigue or damage and sleep; 3/ previous use by team coaches and trainers to fine-tune training prescription [20, 28, 29]. These parameters were measured in capillary blood, as it offers several advantages over venipuncture techniques (eg., quick, simple and less invasive), leading to better athlete compliance.

Capillary blood samples were collected (within 45 minutes after waking) 30 minutes before (6:00 am ± 30 min) and 30 minutes after training sessions (8:00 am ± 30 min) at the beginning (Mondays) and the end (Fridays) of each micro cycle. Blood collection was adjusted to the training schedule, as well as the routine of monitoring fatigue indicators adopted by the coaches. Fingertip blood samples (660 μl) were placed into Na-heparinized tubes, centrifuged at 2000 g for 10 minutes, then cooled prior to analysis. The samples were tested within three hours of collection. Plasma CK activity (U/l) and URE concentrations (mmol/l) were determined by spectrophotometry (Cobas Integra

400 Roche analyzer, Switzerland) with kit reagents from the manufacturer. Samples for assayed for T and C concentrations (nmol/l) using enzyme-linked immunosorbent kits (DRG, Germany). Inter-assay variability was less than 7% for CK, 4% for URE, 10% for T, and 7% for C. All assays were conducted by a certified technician in an accredited laboratory (number AB946) at the Institute of Sport – National Research Institute.

Statistical analyses

Data were analysed in the R programming environment (version 3.5.1) (R Core Team, 2013) using the lmerTest package (version 3.1-0) [30]. The lmerTest package extends the 'lmerMod' class of the lme4 to provide p values for linear mixed-effect models. Given the longitudinal study design and missingness in our dataset (sleep and biochemical measures ~7%, TL ~4%), a linear mixed-effect model was deemed appropriate. Fitting was performed with a restricted maximum likelihood approach using Satterthwaite's approximation to estimate denominator degrees of freedom and obtain p values. Significance was set at an alpha level of $p < 0.05$.

To evaluate the impact of TL on sleep and biochemical fatigue, we examined each set of variables using a one-way (training period [3 levels]) repeated measures analysis of variance. The same approach was used to test the biochemical outcomes, both baseline values and exercise-induced responses (pre to post changes). The day effect (Monday and Friday) was aggregated within this model to better capture any phasic response rather than day-to-day variability. Each model was specified with a random intercept and included gender as a covariate. Where appropriate, post-hoc assessments were performed using Tukey post-hoc contrasts. Post-hoc trends ($p < 0.1$) are highlighted if the effect size is medium or large, as they may reflect changes of practical significance for elite athletes. Prior to analysis, all variables were natural log-transformed to normalize data distribution and reduce non-uniformity bias. Log-transformed data are presented as back-transformed values in the original units or as a percentage change. Cohen's d was calculated as an effect size statistic, with mean differences reported as a small (0.2 to < 0.5), medium (0.5 to < 0.8), or large (0.8+) effect. Significance was set at an alpha level of $p < 0.05$.

RESULTS

Athlete training intensity varied, based on five different "zones" of physical effort. The division of training intensity into five different zones was adopted arbitrarily by the coaching staff. The percentage of training volume spent in each zone is depicted in Figure 2.

TL parameters

Our analyses yielded a significant ($p < 0.001$) effect of training period on all TL parameters (see Table 1). Post-hoc contrasts revealed that training duration (week) was shorter ($p < 0.001$) in P3 than both P1 ($d = 4.3$) and P2 ($d = 4.1$). Weekly training volume was highest in P1, before decreasing in P2 ($d = -2.2$, $p < 0.001$). A further reduction was observed in P3 that differed ($p < 0.001$)

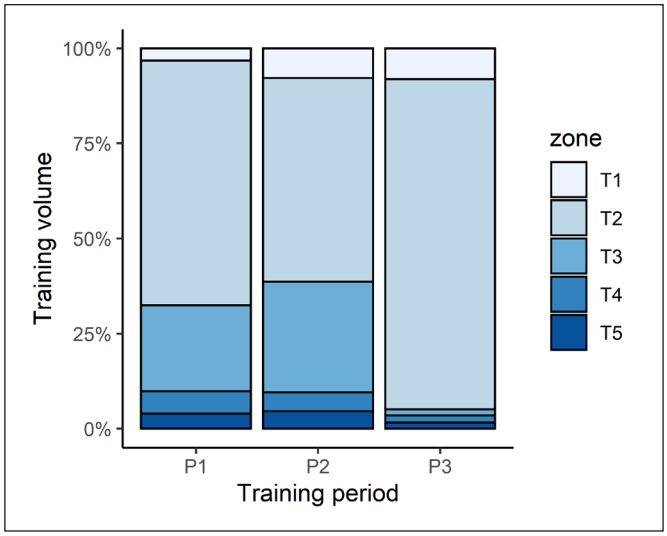


FIG. 2. Percentage of training volume performed at a given intensity zone.

TABLE 1. Weekly training load in each training phase. Data are presented as estimated marginal means with a 95% CI.

Variables	Period 1 (P1)		Period 2 (P2)		Period 3 (P3)	
	Mean	95% CI	Mean	95% CI	Mean	95% CI
Training time (min)	1176	1086, 1261	1108	1022, 1188	620[AB]	572, 665
Training volume (km)	66.7	63.4, 70.8	54.6[A]	51.9, 57.4	28.2[AB]	26.8, 29.7
sRPEh (a.u.)	5219	4537, 5943	4770	4188, 5378	1604[AB]	1408, 1808
sRPEkm (a.u.)	299	260, 344	226[A]	198, 257	76.7[AB]	67.4, 87.5

[A]Significant from P1, [B]Significant from P2, all $p < 0.05$; a.u. – arbitrary units; sRPEh – session rating of perceived exertion as a function of training intensity and session duration expressed in minutes; sRPEkm – session rating of perceived exertion as a function training intensity and session distance expressed in km.

TABLE 2. Sleep quality and quantity measures in each training period. Data are presented as estimated marginal means with a 95%CI.

Variables	Period 1 (P1)		Period 2 (P2)		Period 3 (P3)	
	Mean	95% CI	Mean	95% CI	Mean	95% CI
Bedtime (hrs)	22:24	22:06, 22:42	22:24	22:06, 22:42	22:36 [AB]	22:18, 22:54
Get-up time (hrs)	5:48	5:36, 6:00	5:30	5:24, 5:42	5:54[B]	5:42, 6:00
Total sleep time (min)	388	369, 403	376	358, 395	376	358, 395
Sleep efficiency (%)	88	87, 91	88	86, 90	88	86, 91
Sleep latency (min)	5	3, 6	4	3, 6	4	3, 5
SF sleep latency (min)	12	7, 17	11	8, 16	12	8, 16
Fragmentation index (%)	10	8, 12	11	9, 13	11	9, 14
WASO (min)	41	33, 51	45	36, 56	41	33, 51
SF sleep score (1-5 score)	3.6	3.3, 3.9	3.7	3.4, 4.0	3.7	3.4, 4.0

[A]Significant from P1, [B]Significant from P2, all $p < 0.05$; SF- self reported; WASO – wake after sleep onset

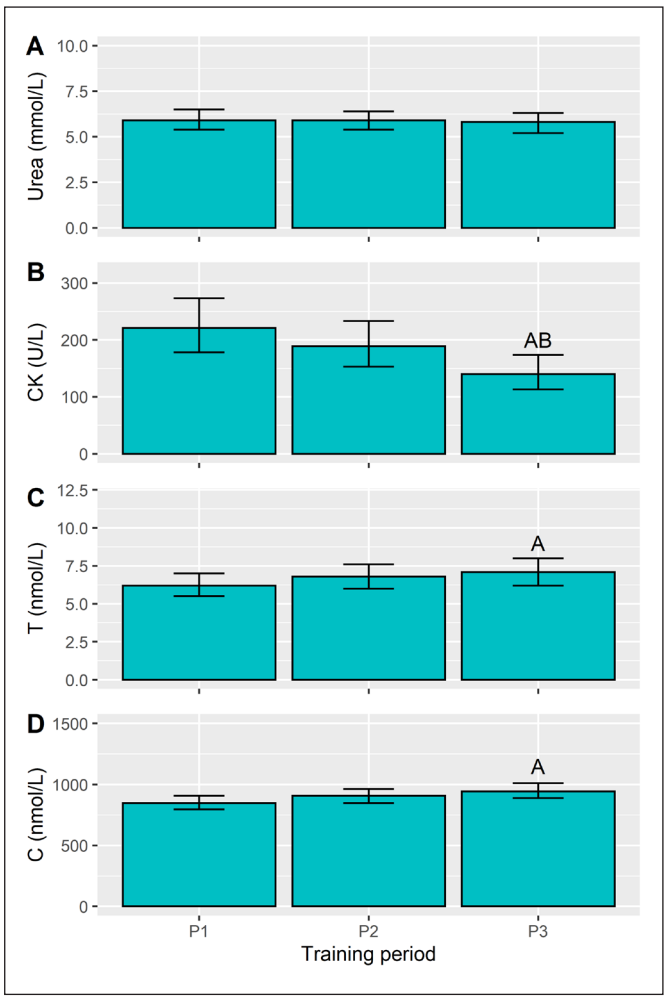


FIG. 3. Pre-session urea, creatine kinase (CK), testosterone (T), and cortisol (C) concentration in each training period. Data are presented as estimated marginal means with a 95% CI. ASignificant from P1, BSignificant from P2, all $p<0.05$.

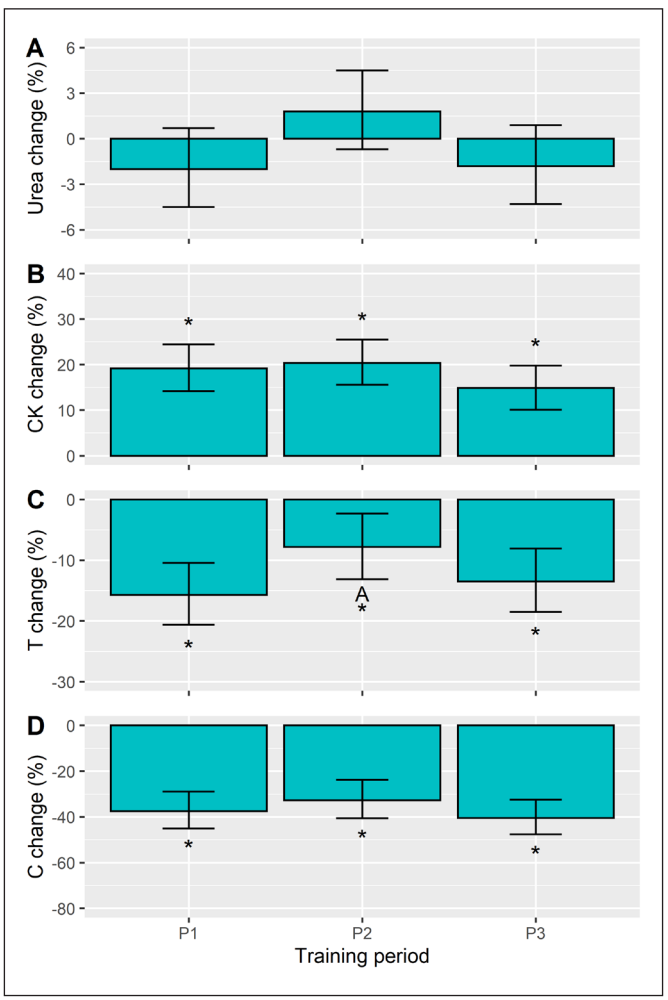


FIG. 4. Acute within-session changes (%) in urea, creatine kinase (CK), testosterone (T), and cortisol (C) in each training period. The Monday and Friday sessions were pooled for the analysis. Data are presented as estimated marginal means with a 95% CI. *Significant from baseline, A Significant from P1, B Significant from P2, all $p<0.05$.

from P1 (d = -9.5) and P2 values (d = -7.7). Weekly TL (sRPEmin) was also significantly ($p < 0.001$) lower in P3 than that seen in P1 (d = -4.5) and P2 (d = 4.4). Similar patterns (all $p \leq 0.01$) emerged for weekly TL (sRPEkm); being higher in P1 than P2 (d = 1.0) and P3 (d = 4.9), whilst P2 results also exceeded that of P3 (d = 4.1).

Sleep parameters

The sleep parameters are shown in Table 2. Of all the measured sleep (quantity or quality) variables, only a significant training effect on bedtime ($p = 0.013$) and get-up time ($p = 0.014$) emerged. Contrast testing revealed a later bedtime in P3 compared with P1 (d = 0.9, $p = 0.050$) and P2 (d = 1.1, $p = 0.017$), and a later get-up time in P3 than P2 (d = 1.1, $p = 0.021$).

Biochemical parameters

Training period did not affect ($p = 0.682$) pre-session URE concentration (Figure 3A). Pre-session CK ($p = 0.001$), C ($p = 0.010$) and T ($p = 0.031$) did, however, vary with respect to training phase. CK levels declined from P1 to P3 (Figure 3B) with a large effect (d = -0.8, $p = 0.001$), with a similar difference from P2 to P3 (d = -0.6, $p = 0.036$). Plasma T concentration rose from P1 to P3 (Figure 3C), a moderate effect (d = 0.7, $p = 0.008$), but neither differed from P2. A similar pattern emerged for C (Figure 3D), with a higher concentration in P3 than P1 (d = 0.6, $p = 0.024$), whereas P2 results were similar (non-significant) to both P1 and P3.

The within-session biochemical responses (%) were interpreted as being significant from baseline, if the 95% CI did not cross zero. We found no significant URE changes (Figure 4A), whereas positive CK changes were seen in each training period (Figure 4B). Conversely, a declining T (Figure 4C) and C (Figure 4D) response was observed in each period. When comparing these responses, a period effect on URE responsivity ($p = 0.033$) emerged, but the post-hoc comparisons did not reach statistical significance. The CK and C changes were unaffected by training phase ($p \geq 0.127$). For T, the training effect was significant ($p = 0.038$) and follow-up tests identified a smaller (negative) change in P2 versus P1 (d = 0.6, $p = 0.037$).

DISCUSSION

This study is the first to examine the interplay between TL, sleep and biochemical fatigue in elite swimmers across different training phases preceding a major competition. The swimmers experienced insufficient and fragmented sleep, regardless of the physical demands associated with different training periods. Only bedtime and get-up time differed (P3 > P1 and/or P2) in this study, but these differences resulted from the later start time of morning training across P3 (6:45) vs P1 (6:00) and P2 (6:00). Nevertheless, the magnitude of this difference was not large enough to be meaningful in real life; therefore, our hypothesis that higher levels of TL would affect sleep quantity and quality was not supported. Baseline plasma CK activity best reflected changes in TL, decreasing in a stepwise manner, although the anticipated rebound in P3 did not occur.

The impact of training load on sleep patterns in swimmers is equivocal [9, 10, 14, 15, 31]. As expected, all TL indices decreased incrementally over time with respect to P1, but with little corresponding change in athlete's sleep quantity or quality. Only bedtime and get-up time differed in this work (P3 > P1 and/or P2), likely reflecting training schedule rather than reduced TL and shorter workouts prescribed during athlete tapering for the championship event. However, the results are not practically significant. Firstly, even though in P3 participants got out of bed later than in P1 and/or P2 they went to bed later as well. Secondly, changes in bedtime and get-up time did not translate to an increase in total sleep duration. A similar pattern was seen in swimmers during a 14–day altitude training camp at 1500 m [4]. In the monitored athletes, gradually increasing training loads (sRPE) did not jeopardize their sleeping patterns. Our findings also concur with with Walsh et al., [9] who reasoned that a threshold effect might be operating. That is, training differences in sleep parameters are more likely to occur when a much higher TL, and one that induces excessive overload, is prescribed. Still, there is no consensus as to whether impaired sleep is a cause or a consequence of heavy training loads [11, 32]. Sleep disturbances are common in sport, particularly among athletes experiencing training maladaptation that elicit overreaching or overtraining [6, 31]. Recently, Vachon et al. [32] reported that poor sleep quality prior to intensive training predisposed athletes to the development of functional overreaching. Throughout this study, all swimmers showed systematic improvements in performance, which indicates the prescribed TLs were not excessive, but entirely appropriate to promote positive adaptations. Moreover, based on the assessed fatigue biomarkers, it might be assumed that our subjects were not in an overreached or overtrained state.

Our major finding is that, irrespective of the training period and TLs, the swimmers slept less (~6.3 h) than the recommended 8–10 h or 7–9 h of sleep per night for healthy adolescents and adults, respectively [33, 34]. Supporting our results, many studies have reported disruptions in the sleep patterns of swimmers depending on their training schedule [9, 35–38]. For instance, the amount of sleep achieved by Australian swimmers during nights preceding training days (5.4 h) was substantially lower than prior to rest days (7.1 h) [35]. This reduction in sleep was linked to early morning training sessions (i.e., 6:00 am) and a failure to compensate with an earlier bedtime. Others have attributed low sleep quantity (i.e., 6.6 h) among swimmers to early-morning starts (i.e., 6:30 am) [36]. Correspondingly, a longer total sleep time (7.7–7.9 h) was found among swimmers who begun their first sessions at a later time of day (7:30–8:30 am) [9]. However, Vitale et. al. [15], who monitored sleep in swimmers 4 nights before and 14 nights during a 14-day training camp, frequently observed reduced sleep times (< 7 h) during this study, even though the athletes started training at 8:30 am. Thus, our observation of insufficient sleep quantity most

likely stems from the early-morning workouts, scheduled around 6:00–6:45 am, which is typical of elite swimmers. The justification for this is to fit around schooling or work activities, and to provide maximum time for recovery between the sessions, since there is no performance rationale for early-morning starts. Interestingly, morning exercise might cause phase advances regardless of the chronotype [39]. People with late chronotypes, as often seen in young adults, are particularly susceptible to circadian disruption caused by misalignment of the internal rhythms with early-morning duties [39]. Further research is needed to confirm if swimmers with late chronotypes may benefit from phase advances induced by exercise in the morning. Although, participating in this study, being elites with several years of training experience, were training routinely in the early morning, so their sleep patterns were likely adjusted to the early morning start. Nonetheless, the negative impact of early-morning training sessions on sleep quantity is well recognized, as is the consequences of sleep restriction (e.g., fatigue, excessive daytime sleepiness, decreased exercise and cognitive performance, decreased mood) [2, 34].

Regardless of TL, the subjects did not meet recommendations for WASO (i.e., ≥ 41 min) [40], indicating restless or fragmented sleep. In the current study, swimmers spent less time awake after sleep was initiated (WASO: 41–45 min) than adolescent Icelandic swimmers (WASO : 64.8 ± 24.8 min) [38], but more than adult open-water swimmers (WASO: 22–27 min) monitored across altitude camp [15] or Dutch elite athletes (WASO: 33.3 ± 17.0 min) [8] from various sports disciplines during seven consecutive days of regular training. Impaired sleep continuity has been attributed to increased TLs [41], muscle soreness and general fatigue in athletes [14]. These data indicate that the swimmers obtained an insufficient amount of fragmented sleep, indicating an urgent need for sleep optimizing strategies focused on sleep extension and promoting continuous sleep. Hence, key swimming stakeholders should consider different strategies to maximize sleep, especially at the individual level. For instance, when feasible, delaying morning training sessions to allow longer sleep duration should be considered. Sleep hygiene education may encourage earlier bedtimes and reduce causes of excessive nighttime awakenings. Moreover, napping should be encouraged, particularly if extending nocturnal sleep is not possible.

To our knowledge, no previous research has investigated the impact of training on sleep in swimmers combining workload with blood fatigue biomarkers. Baseline plasma CK activity best reflected changes in TL, but with no corresponding change in athlete's sleep pattern. Considering the entire preparation period, the most visible shifts in the biochemical parameters were identified for biochemical parameters prior to training sessions. This included a decline in CK levels, coupled with a gradual rise in T and C concentrations, as the athletes transitioned from high-volume training to low-volume, pre-event tapering. There are conflicting reports concerning fatigue biomarkers and TL in swimmers. In swimmers starting from second week of preseason training, CK levels have been shown to decrease across subsequent weeks of training [42] and tapering period [43–45]. Similar to our findings, T level decreased when swimming training intensified and increased during periods of decreased TL (i.e., post –taper) [44]. Even though the C increase across the taper period was unexpected, it was in line with previous findings as well [43]. On the contrary, some [46] have demonstrated weekly changes in URE but not CK, T or C levels in adolescent swimmers and triathletes, whilst others found no CK and endocrinological differences to periods of intense swimming training and taper [47].

Serum CK level is considered an indirect marker of muscle tissue damage [21]. Although swimming is a non-contact sport, where concentric muscle actions predominate over eccentric actions, increased TL and highly repetitive motions may enhance metabolic and/or mechanical disruption of muscle cells, leading to a rise in baseline serum CK changes [21], as we demonstrated herein. Also noteworthy is that the CK response to acute exercise was consistently elevated (by 15–20%) above baseline. Two possibilities could explain this finding: (1) exercise intensity was sufficiently high to induce changes in skeletal muscle membrane permeability, resulting in increased CK release independent of mechanically-induced damage; (2) swimming is a repetitive movement that places high demands on joint articulations and thus, leading to muscular strain that also promotes greater CK efflux [48].

The hormones T and C contribute to athletic performance and training adaption through several mechanisms [49]. One example being the anabolic to catabolic balance in muscle tissue regeneration and TL tolerance [50]. The observed rise in pre-training T level, when TL was the lowest, could represent greater pituitary activation following the more intense training period, leading to a downstream increase in T when tapering [50]. The corresponding increase in C might reflect a need to partition metabolic resources in preparation for the impending National Swimming Championships, where success was pivotal to obtain a qualifying time standard for 18th FINA World Championships and/or European Junior Swimming Championships [51]. In addition, it cannot be ruled out that higher C level might reflect an emotional response (eg. activation of the sympathetic nervous system and hypothalamic-pituitary-adrenal axis) in anticipation to a crucial sporting event [51]. We also observed a decline (by -8 to -40%) in T and C reactivity to exercise that arguably reflects normal circadian variation in steroid hormones [52], but no patterns emerged with regards to TL. Serum urea concentration (baseline and reactive) did not differentiate between high and low TLs, perhaps due to individual variability and other metabolic factors (e.g., availability of carbohydrates).

Finally, a number of important study limitations need to be considered. Although the biochemical parameters are recognized as surrogate markers of TL, their use as definitive biomarkers of fatigue should be done so with caution, namely due to high inter-subject variability and individual response patterns [46]. Furthermore, changes of plasma volume, that could affect post-training biochemistry, were not assessed. Another limitation is the lack of a chronotype assessment, which would allow for a better understanding of the

impact of TL on sleep, since submaximal RPE and fatigue score are likely to be influenced by chronotype [53]. In addition, the sample size was small, due to recruitment restrictions when undertaking research on elite athletes, but this was offset somewhat by the repeated measures design and intensive monitoring procedures. Inferences of any TL effect are also limited by the number of assessment occasions, especially when the swimmers were already experiencing a high volume of training at study inception. Additionally, data were pooled across both sexes to increase our sample size. Recruiting a larger number of male and female swimmers would allow a more detailed examination of gender-related differences in the studied variables. Future studies should look to increase sample size, but where restrictions on recruitment are a limiting factor, it is advisable to adopt a repeated measures design to increase study power and subsequent inferences. Moreover, the phase assessment of TL did not include non-specific training (i.e., gym sessions), although the "dry-land" training presumably had no significant effect on the monitored parameters.

CONCLUSIONS

In conclusion, the profiling of elite swimmers revealed insufficient and fragmented sleep, regardless of the physical demands associated with different training periods. In fact, neither sleep quality nor quantity were affected by different magnitudes of TL. Even though swimming is a sport with a predominant share of concentric muscle actions, baseline plasma (pre-training) CK activity best reflected the physiological response to TL among the monitored biochemical fatigue markers.

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Conflict of interest

The authors decalre no conflict of interest.

REFERENCES

1. Vitale KC, Owens R, Hopkins SR, Malhotra A. Sleep Hygiene for Optimizing Recovery in Athletes: Review and Recommendations. Int J Sports Med. 2019; 40(8):535–43. doi:10.1055/a-0905-3103.
2. Gupta L, Morgan K, Gilchrist S. Does Elite Sport Degrade Sleep Quality? A Systematic Review. Sports Med. 2017; 47(7):1317–33. doi:10.1007/s40279-016-0650-6.
3. Nedelec M, Aloulou A, Duforez F, Meyer T, Dupont G. The Variability of Sleep Among Elite Athletes. Sport Med - open. 2018; 4(1):34. doi:10.1186/s40798-018-0151-2.
4. Vitale JA, Galbiati A, De Giacomi G, Tornese D, Levendowski D, Ferini-Strambi L, Banfi G. Sleep Architecture in Response to a Late Evening Competition in Team-Sport Athletes. Int J Sports Physiol Perform. 2022; 17(4):569–75. doi:10.1123/ijspp.2021-0292.
5. Vitale JA, Banfi G, Galbiati A, Ferini-Strambi L, La Torre A. Effect of a Night Game on Actigraphy-Based Sleep Quality and Perceived Recovery in Top-Level Volleyball Athletes. Int J Sports Physiol Perform. 2019; 14(2):265–9. doi:10.1123/ijspp.2018-0194.
6. Hausswirth C, Louis J, Aubry A, Bonnet G, Duffield R, Le Meur Y. Evidence of disturbed sleep and increased illness in overreached endurance athletes. Med Sci Sports Exerc. 2014; 46(5):1036-45. doi:10.1249/MSS.0000000000000177.
7. Killer SC, Svendsen IS, Jeukendrup AE, Gleeson M. Evidence of disturbed sleep and mood state in well-trained athletes during short-term intensified training with and without a high carbohydrate nutritional intervention. J Sports Sci. 2017; 35(14):1402–10. doi:10.1016/j.jsams.2017.07.003.
8. Knufinke M, Nieuwenhuys A, Geurts SAE, Most EIS, Maase K, Moen MH, Coenen AML, Kompier MAJ. Train hard, sleep well? Perceived training load, sleep quantity and sleep stage distribution in elite level athletes. J Sci Med Sport. 2018; 21(4):427–32. doi:10.1016/j.jsams.2017.07.003.
9. Walsh JA, Sanders D, Hamilton DL, Walshe I. Sleep Profiles of Elite Swimmers During Different Training Phases. J Strength Cond Res. 2019; 33(3):811–8. doi:10.1519/JSC.0000000000002866.
10. Taylor SR, Rogers GG, Driver HS. Effects of training volume on sleep, psychological, and selected physiological profiles of elite female swimmers. Med Sci Sports Exerc. 1997; 29(5):688–93. doi:10.1097/00005768-199705000-00016.
11. Lastella M, Vincent GE, Duffield R, Roach GD, Halson SL, Heales LJ, Sargent C. Can Sleep Be Used as an Indicator of Overreaching and Overtraining in Athletes? Front Physiol. 2018; 9:436. doi:10.3389/fphys.2018.00436.
12. Impellizzeri FM, Marcora SM, Coutts AJ. Internal and External Training Load: 15 Years On. Int J Sports Physiol Perform. 2019; 14(2):270–3. doi:10.1123/ijspp.2018-0935.
13. Lalor BJ, Halson SL, Tran J, Kemp JG, Cormack SJ. A Complex Relationship: Sleep, External Training Load, and Well-Being in Elite Australian Footballers. Int J Sports Physiol Perform. 2020; 15(6):777-787. doi:10.1123/ijspp.2019-0061.
14. Aloulou A, Duforez F, Léger D, De Larochelambert Q, Nedelec M. The Relationships Between Training Load, Type of Sport, and Sleep Among High-Level Adolescent Athletes. Int J Sports Physiol Perform. 2021; 16(6):890–9. doi:10.1123/ijspp.2020-0463.
15. Vitale JA, Ieno C, Baldassarre R, Bonifazi M, Vitali F, La Torre A, Piacentini MF. The Impact of a 14-Day Altitude Training Camp on Olympic-Level Open-Water Swimmers' Sleep. Int J Environ Res Public Health. 2022; 19(7):4253. doi:10.3390/ijerph19074253.
16. Thornton H, Delaney J, Duthie G, Dascombe B. Effects of Pre-Season Training on the Sleep Characteristics of Professional Rugby League Players. Int J Sports Physiol Perform. 2018; 13(2):176-182. doi:10.1123/ijspp.2017-0119.
17. O'Donnell S, Bird S, Jacobson G, Driller M. Sleep and stress hormone responses to training and competition in elite female athletes. Eur J Sport Sci. 2018; 18(5):611–8. doi:10.1080/17461391.2018.1439535.
18. Serpell BG, Horgan BG, Colomer CME, Field B, Halson SL, Cook CJ. Sleep and Salivary Testosterone and Cortisol During a Short Preseason Camp: A Study in Professional Rugby Union. Int J Sports Physiol Perform. 2019; 14(6):796–804. doi:10.1123/ijspp.2018-0600.
19. Hecksteden A, Skorski S, Schwindling S, Hammes D, Pfeiffer M, Kellmann M, Ferrauti A, Meyer T. Blood-Borne Markers of Fatigue in Competitive Athletes - Results from Simulated Training Camps. PLoS One. 2016; 11(2):e0148810. doi:10.1371/journal.pone.0148810.
20. Urhausen A, Kindermann W. Diagnosis of overtraining: what tools do we have? Sports Med. 2002; 32(2):95–102. doi:10.2165/00007256-200232020-00002.

21. Baird MF, Graham SM, Baker JS, Bickerstaff GF. Creatine-kinase- and exercise-related muscle damage implications for muscle performance and recovery. J Nutr Metab. 2012; 2012:960363. doi:10.1155/2012/960363.
22. O'Byrne NA, Yuen F, Butt WZ, Liu PY. Sleep and Circadian Regulation of Cortisol: A Short Review. Curr Opin Endocr Metab Res. 2021; 18:178-186. doi:10.1016/j.coemr.2021.03.011.
23. Wallace LK, Slattery KM, Coutts AJ. The ecological validity and application of the session-RPE method for quantifying training loads in swimming. J Strength Cond Res. 2009; 23(1):33–8. doi:10.1519/JSC.0b013e3181874512.
24. Collette R, Kellmann M, Ferrauti A, Meyer T, Pfeiffer M. Relation Between Training Load and Recovery-Stress State in High-Performance Swimming. Front Physiol. 2018; 9:845. doi:10.3389/fphys.2018.00845.
25. Sozański H. Kierunki optymalizacji obciążeń treningowych. Wydaw. AWF [Akademii Wychowania Fizycznego]; 1992.
26. Cole RJ, Kripke DF, Gruen W, Mullaney DJ, Gillin JC. Automatic sleep/wake identification from wrist activity. Sleep. 1992; 15(5):461–9. doi:10.1093/sleep/15.5.461.
27. Quante M, Kaplan ER, Cailler M, Rueschman M, Wang R, Weng J, Taveras EM, Redline S. Actigraphy-based sleep estimation in adolescents and adults: a comparison with polysomnography using two scoring algorithms. Nat Sci Sleep. 2018; 10:13–20. doi:10.2147/NSS.S151085.
28. Urhausen A, Gabriel H, Kindermann W. Blood hormones as markers of training stress and overtraining. Sports Med. 1995; 20(4):251–76. doi:10.2165/00007256-199520040-00004.
29. Buyse L, Decroix L, Timmermans N, Barbé K, Verrelst R, Meeusen R. Improving the Diagnosis of Nonfunctional Overreaching and Overtraining Syndrome. Med Sci Sports Exerc. 2019; 51(12):2524-2530. doi:10.1249/MSS.0000000000002084.
30. Kuznetsova A, Brockhoff PB, Christensen RHB. lmerTest Package: Tests in Linear Mixed Effects Models. J Stat Softw. 2017; 82(13). doi:10.18637/jss.v082.i13.
31. Wall SP, Mattacola CG, Swanik CB, Levenstein S. Sleep Efficiency and Overreaching in Swimmers. J Sport Rehabil. 2003; 12(1):1–12. doi:10.1123/jsr.12.1.1.
32. Vachon A, Berryman N, Mujika I, Paquet J-B, Sauvet F, Bosquet L. Impact of tapering and proactive recovery on young elite rugby union players' repeated high intensity effort ability. Biol Sport. 2022; 39(3):735–43. doi:10.5114/biolsport.2022.109453.
33. Hirshkowitz M, Whiton K, Albert SM, Alessi C, Bruni O, DonCarlos L, Hazen N, Herman J, Adams Hillard PJ, Katz ES, Kheirandish-Gozal L, Neubauer DN, O'Donnell AE, Ohayon M, Peever J, Rawding R, Sachdeva RC, Setters B, Vitiello M V, Ware JC. National Sleep Foundation's updated sleep duration recommendations: final report. Sleep Heal. 2015; 1(4):233–43. doi:10.1016/j.sleh.2015.10.004.
34. Paruthi S, Brooks LJ, D'Ambrosio C, Hall WA, Kotagal S, Lloyd RM, Malow BA, Maski K, Nichols C, Quan SF, Rosen CL, Troester MM, Wise MS. Consensus Statement of the American Academy of Sleep Medicine on the Recommended Amount of Sleep for Healthy Children: Methodology and Discussion. Clin Sleep Med. 2016; 12(11):1549-1561. doi:10.5664/jcsm.6288.
35. Sargent C, Halson S, Roach GD. Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. Eur J Sport Sci. 2014; 14 Suppl 1:S310-5. doi:10.1080/17461391.2012.696711.
36. Surda P, Putala M, Siarnik P, Walker A, De Rome K, Amin N, Sangha MS, Fokkens W. Sleep in elite swimmers: prevalence of sleepiness, obstructive sleep apnoea and poor sleep quality. BMJ open Sport Exerc Med. 2019; 5(1):e000673. doi:10.1136/bmjsem-2019-000673.
37. Steenekamp T, Zaslona J, Gander P, Rowlands D, Leigh Signal T. Sleep/wake behaviour of competitive adolescent athletes in New Zealand: insight into the impact of early morning training. Sleep Med. 2021; 77:88–95. doi:10.1016/j.sleep.2020.11.023.
38. Gudmundsdottir SL. Training Schedule and Sleep in Adolescent Swimmers. Pediatr Exerc Sci. 2020; 32(1):16-22. doi:10.1123/pes.2019-0067.
39. Thomas JM, Kern PA, Bush HM, McQuerry KJ, Black WS, Clasey JL, Pendergast JS. Circadian rhythm phase shifts caused by timed exercise vary with chronotype. JCI insight. 2020; 5(3):e134270. doi:10.1172/jci.insight.134270.
40. Ohayon M, Wickwire EM, Hirshkowitz M, Albert SM, Avidan A, Daly FJ, Dauvilliers Y, Ferri R, Fung C, Gozal D, Hazen N, Krystal A, Lichstein K, Mallampalli M, Plazzi G, Rawding R, Scheer FA, Somers V, Vitiello M V. National Sleep Foundation's sleep quality recommendations: first report. Sleep Heal. 2017; 3(1):6–19. doi:10.1016/j.sleh.2016.11.006.
41. de Blasiis K, Joncheray H, Elefteriou J, Lesenne C, Nedelec M. Sleep-Wake Behavior in Elite Athletes: A Mixed-Method Approach. Front Psychol. 2021; 12:658427. doi:10.3389/fpsyg.2021.658427.
42. Rusnak M, VanderMeulen M, Byrd B, Byrd G, Rusnak R, Martin J, Hew-Butler T. Muscle Damage, Soreness, and Stress During Preseason Training in Collegiate Swimmers. Clin J Sport Med. 2021; 31(3):237-243. doi:10.1097/JSM.0000000000000736.
43. Costill DL, Thomas R, Robergs RA, Pascoe D, Lambert C, Barr S, Fink WJ. Adaptations to swimming training: influence of training volume. Med Sci Sports Exerc. 1991; 23(3):371-7.
44. Flynn MG, Pizza FX, Boone JBJ, Andres FF, Michaud TA, Rodriguez-Zayas JR. Indices of training stress during competitive running and swimming seasons. Int J Sports Med. 1994; 15(1):21-6. doi:10.1055/s-2007-1021014.
45. Li Y, Zhu Y, Zhang J, Zhang X, Zeng Y. Biochemical changes and endocrine responses in pre-competition training in elite swimmers. Biol Sport. 2012; 29(1):71–5. doi:10.5604/20831862.984263.
46. Julian R, Meyer T, Fullagar HHK, Skorski S, Pfeiffer M, Kellmann M, Ferrauti A, Hecksteden A. Individual Patterns in Blood-Borne Indicators of Fatigue-Trait or Chance. J Strength Cond Res. 2017; 31(3):608-619.
47. Mujika I, Chatard JC, Padilla S, Guezennec CY, Geyssant A. Hormonal responses to training and its tapering off in competitive swimmers: relationships with performance. Eur J Appl Physiol Occup Physiol. 1996; 74(4):361-6. doi:10.1007/BF02226933.
48. Brancaccio P, Maffulli N, Limongelli FM. Creatine kinase monitoring in sport medicine. Br Med Bull. 2007; 81–82(1):209–30. doi:10.1093/bmb/ldm014.
49. Crewther BT, Cook C, Cardinale M, Weatherby RP, Lowe T. Two Emerging Concepts for Elite Athletes. Sport Med. 2011; 41(2):103–23. doi:10.2165/11539170-000000000-00000.
50. Mujika I, Padilla S, Pyne D, Busso T. Physiological changes associated with the pre-event taper in athletes. Sports Med. 2004; 34(13):891–927. doi:10.2165/00007256-200434130-00003.
51. van Paridon KN, Timmis MA, Nevison CM, Bristow M. The anticipatory stress response to sport competition; a systematic review with meta-analysis of cortisol reactivity. B BMJ Open Sport Exerc Med. 2017; 3(1):e000261. doi:10.1136/bmjsem-2017-000261.
52. Guignard MM, Pesquies PC, Serrurier BD, Merino DB, Reinberg AE. Circadian rhythms in plasma levels of cortisol, dehydroepiandrosterone, delta 4-androstenedione, testosterone and dihydrotestosterone of healthy young men. Acta Endocrinol (Copenh). 1980; 94(4):536-45. doi:10.1530/acta.0.0940536.
53. Vitale JA, Weydahl A. Chronotype, Physical Activity, and Sport Performance: A Systematic Review. Sport Med. 2017; 47(9):1859–68. doi:10.1007/s40279-017-0741-z.

A comparison of activity demands between trial matches and in-season matches across multiple teams and seasons in semi-professional, male rugby league players

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ABSTRACT: Trial matches are frequently used for team preparation in rugby league competitions, making it essential to understand the demands experienced to assess their specificity to actual competition. Consequently, this study aimed to compare the activity demands between pre-season trial matches and early in-season rugby league matches. Following a repeated-measures observational design, 39 semi-professional, male rugby league players from two clubs were monitored using microsensors during two trial matches and the first two in-season matches across two consecutive seasons. Total distance, average speed, peak speed, absolute and relative high-speed running (HSR; > 18 km·h^{-1}) and low-speed running (LSR; < 18 km·h^{-1}) distance, as well as absolute and relative impacts, accelerations (total and high-intensity > 3 m·s^{-2}), and decelerations (total and high-intensity < -3 m·s^{-2}) were measured. Linear mixed models and Cohen's *d* effect sizes were used to compare variables between match types. Playing duration was greater for in-season matches ($p < 0.001$, $d = 0.64$). Likewise, higher ($p < 0.001$, $d = 0.45$–0.70) activity volumes were evident during in-season matches indicated via total distance, HSR distance, LSR distance, total accelerations, high-intensity accelerations, total decelerations, and high-intensity decelerations. Regarding activity intensities, a higher average speed ($p = 0.008$, $d = 0.31$) and relative LSR distance ($p = 0.005$, $d = 0.31$) only were encountered during in-season matches. Despite players completing less volume, the average activity intensities and impact demands were mostly similar between trial and early in-season matches. These findings indicate trial matches might impose suitable activity stimuli to assist players in preparing for early in-season activity intensities.

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INTRODUCTION

Rugby league is one of the most popular team sports in Australia, with over 171,000 adults (> 15 years of age) and 133,000 children (< 14 years of age) participating in rugby league in 2020 [1]. Furthermore, over 5.7 million Australians aged > 14 years viewed televised matches of the 2020 National Rugby League (NRL) season [2]. The NRL represents the highest standard of male professional rugby league competition in Australia and New Zealand, and currently comprises 17 registered teams [3]. In turn, NRL teams have affiliations with semi-professional teams competing within state-wide competitions including the Queensland Cup, which are positioned directly beneath the NRL in the male player pathway [3]. Accordingly, many semi-professional, male rugby league players aim to develop their physical, technical, and mental attributes with ambition to transition to professional competition [4]. In this regard, semi-professional rugby league competitions not only offer a competitive, marketable product involving high-level players, but also play an important role in aiding the development of players to compete at professional levels [3]. To assist in player preparation and development it is important that semi-professional rugby league teams adopt strategies to ensure players are adequately prepared for match demands.

The monitoring of player demands using microsensors containing accelerometers and global positioning system (GPS) components,

is increasingly adopted as routine practice within semi-professional rugby league teams [3]. This uptake of monitoring technology has enabled comparisons in match demands between semi-professional and professional rugby league players [5–7] and between successful and less successful semi-professional teams [8, 9]. Furthermore, player-worn microsensors permit a better understanding of the demands imposed on players during different training tasks and throughout match-play [10]. In this way, rugby league coaching staff can ensure their players are being exposed to appropriate demands during training to best prepare them for the rigours of competition.

The annual season in rugby league can be broadly split into pre-season, in-season, and off-season phases [11]. From a physiological perspective, the pre-season is a crucial phase whereby relevant fitness attributes can be developed through progressive overload of training stimuli to sufficiently enable players to cope with the demands of the upcoming in-season matches [11, 12]. In this regard, professional and semi-professional rugby league teams often participate in trial matches late in the pre-season, which are unofficial matches that do not determine official team standings. Coaching staff can use trial matches for various purposes including to evaluate new or development players, assess existing players in alternative positions, and rehearse set-plays alongside different player combinations. Nevertheless, given trial matches provide the most specific competitive context for rugby league teams during the pre-season, it is important to understand how the activity demands imposed during trial matches compare to in-season matches to ensure the observations made by coaching staff hold strong translation to official competition. For instance, if trial matches impose lower activity demands than in-season matches, the new players, player combinations, and set-plays that were rated positively by coaching staff during the trial matches may be less successful in competitive scenarios performed at higher intensities and/or for longer durations.

To date, only one study has compared the activity demands of trial matches to in-season matches in rugby league, examining a sample of professional male players [13]. Gabbett [13] reported professional, male rugby league players (n = 16) competing in the NRL had lower average speeds (d = 1.03–2.06), covered less distance at high (> 18 km·h^{-1}; d = 0.26–0.98) and low speeds (< 18 km·h^{-1}; d = 0.93–2.09), and had fewer repeated high-intensity efforts per minute (d = 0.90–2.99; all $p < 0.05$) in trial matches compared to in-season matches. These data show trial matches may not replicate key volumes or intensities of in-season matches in professional, male rugby league players, suggesting coaches may have difficulties in assessing whether players will be able to cope with the demands and team strategies will be successful during official competition based on observations made in trial matches. However, these findings cannot be simply extrapolated to semi-professional rugby league given the varied match demands reported between professional and semi-professional Australian rugby league competitions [5, 6, 13]. In this way, further research is needed to understand the demands of trial matches at the semi-professional level, which may have implications for player preparation processes. The purpose of this study was to compare the activity demands between trial matches and early in-season matches in semi-professional, male rugby league players.

MATERIALS AND METHODS

Experimental design

A repeated-measures observational study design was adopted whereby 60 semi-professional, male, rugby league players from two teams competing in the Queensland Cup were monitored during matches using microsensors throughout the 2021 and 2022 seasons. Each team participated in two trial matches in each season, towards the end of the pre-season phase. As a result, we monitored all available trial matches for these two teams across this two-year period. The first two matches of the in-season (i.e., round 1 and round 2) were also monitored for each team in each season to represent early in-season matches. Only the first two matches of the in-season phase were monitored to provide an equivalent comparison to trial matches while avoiding any temporal fluctuations in match demands that may occur with season progression [14]. A schematic timeline showing when the matches took place alongside the field- and gym-based training sessions leading into each match for each team are shown in Figure 1. The two teams participating in this study played each other in the first trial match in each season. Details of the matches monitored for both teams are shown in Table 1. Among the sample of games monitored, similar opponent rankings (mean opponent rank based on end of season ladder position for the respective year: trial matches = 10; in-season matches = 9), match times (mean start time [hh:mm]: trial matches = 18:10; in-season matches = 16:50), results (wins/losses/draws: trial matches = 4/4/0; in-season matches = 3/4/1), and identical distribution of match locations (home = 8; away = 8) were evident. All matches were 80 min in duration (plus stoppage time) in accordance with competition regulations.

Subjects

Monitored players were included in final analyses if they participated in at least three of the four monitored matches in at least one of the seasons, and registered at least 10 min of playing time in each match they played in. Therefore, a final sample of 39 players (age: 23.7 ± 1.9 years; height: 182.3 ± 5.4 cm; body mass: 96.4 ± 9.1 kg) were included in this study with 21 players excluded due to insufficient data being provided. This sample consisted of 20 forwards, 10 backs, and nine adjustables [15]. All players provided written informed consent after being made aware of the procedures, benefits, and risks associated with participation. Ethical approval was obtained from an Institutional Ethics Committee for use of the collected data across both teams (numbers: 0000023344 and 0000023985) in accordance with the standards of the Declaration of Helsinki.

Procedures

All players were monitored during matches using Catapult PlayerTek™ GPS devices (PlayerTek™ Pod; Catapult Sports; Melbourne, Australia;

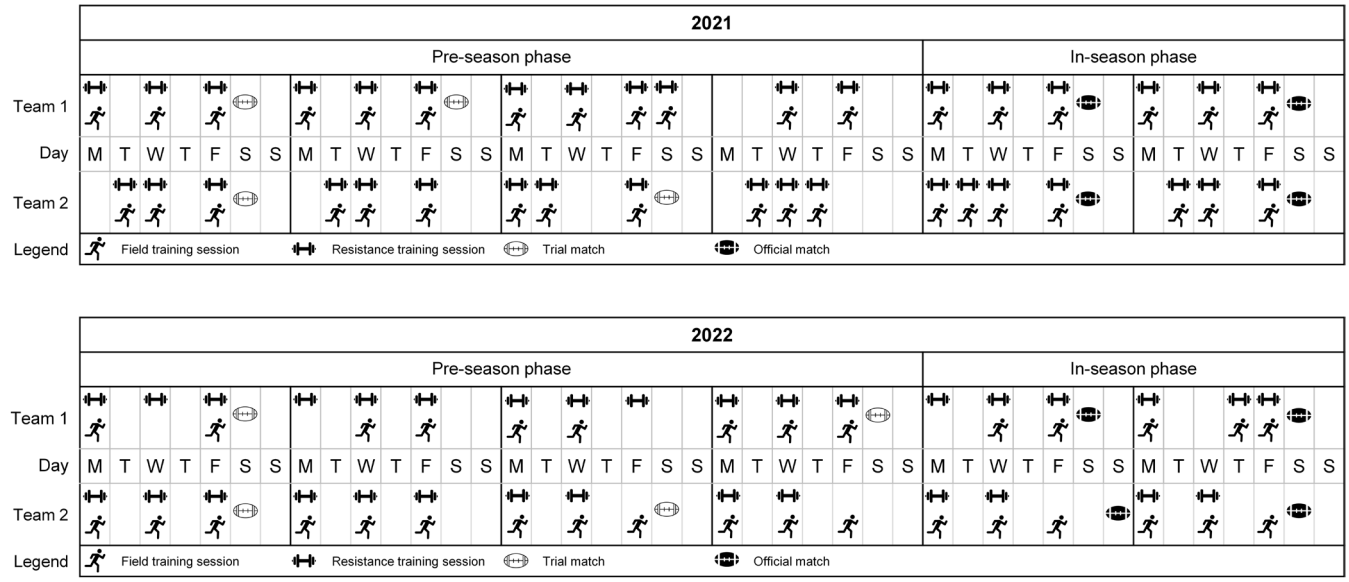


FIG. 1. Schematic overview of training and match schedules for both participating semi-professional, male rugby league teams in the 2021 and 2022 seasons.

specifications: 10-Hz sampling rate, 42 g mass, 84 mm × 42 mm × 21 mm dimensions), which were fitted in manufacturer-produced neoprene vests under playing jerseys ~15 min prior to pre-match warm-up. Data in Gaelic football players (n = 10) [16] support the validity (mean difference: distance vs. manual measurement of distance = < 0.01%, $p > 0.05$; peak speed vs. speed measured with a radar gun = 0.03%, $p > 0.05$) and retest reliability (coefficient of variation = 1.1% for total distance to 11.7% for very high-speed running distance at > 22 km·h^{-1}) of PlayerTek™ devices. All collected data were downloaded from devices following each match and processed using proprietary software (PlayerTek™ Cloud; Catapult Sports; Melbourne, Australia). Match files for each player were trimmed to include only time when on the field and exclude any time when interchanged out of matches and half-time breaks. Trimming of all match data files was performed using documented times and visual inspection of data traces in the proprietary software. Outcome variables taken from each match included total distance (m), average speed (m·min^{-1}), as well as absolute (m) and relative (m·min^{-1}) distance (i.e., average speed) performing low-speed running (LSR; < 18 km·h^{-1}) and high-speed running (HSR; > 18 km·h^{-1}) as commonly reported in the rugby league literature [15]. Furthermore, on-field duration (min), peak speed (m·s^{-1}), absolute impacts (count; > 5 g), relative

TABLE 1. Details for the trial and in-season matches monitored.

Detail	2021 season				2022 season			
	Trial matches		*In-season matches*		*Trial matches*		*In-season matches*	
	1	*2*	*1*	*2*	*1*	*2*	*1*	*2*
Team 1								
Opponent rank*	12	8	4	9	11	12	14	12
Match location	Away	Home	Away	Home	Home	Away	Away	Home
Match time of day (hh:mm)	18:00	19:15	15:00	19:15	18:00	18:00	15:00	16:00
Match outcome	Loss	Win	Loss	Draw	Win	Win	Win	Win
Team 2								
Opponent rank*	14	7	5	3	5	10	12	13
Match location	Home	Home	Home	Away	Away	Away	Home	Away
Match time of day (hh:mm)	18:00	18:00	19:00	17:00	18:00	18:00	16:30	17:00
Match outcome	Win	Loss	Loss	Loss	Loss	Loss	Loss	Win

Note: * end of in-season ladder position used out of 14 teams

impacts (count · min^{-1}), total accelerations (count; > 1 m · s^{-2}), relative total accelerations (count · min^{-1}), high-intensity accelerations (count; > 3 m · s^{-2}), relative high-intensity accelerations (count · min^{-1}), total decelerations (count; < -1 m · s^{-2}), relative total decelerations (count · min^{-1}), high-intensity decelerations (count; < -3 m · s^{-2}), and relative high-intensity decelerations (count · min^{-1}) were also measured in each match.

Statistical analysis

Overall, 86 (49%) individual player samples for trial matches and 88 (51%) individual player samples for in-season matches were used for analyses, with 101 (58%) samples provided by Team 1 and 73 (42%) samples provided by Team 2. Linear mixed models were fitted to the data for each outcome variable. Specifically, player was entered as a random effect (n = 39) and match type was entered as a fixed effect (trial and in-season), while team (Team 1 and Team 2) was used as a covariate. Histograms developed for each outcome variable according to match type revealed that most were normally distributed, with some possessing slightly skewed distributions. No outliers were identified in any outcome variable. Accordingly, to obtain robust models, each linear mixed model was constructed by obtaining the robust estimate of variance (Huber-White sandwich estimator) [17, 18]. An unstandardized regression coefficient (β) and its 95% confidence intervals (CI) along with the marginal means and standard errors (SE) for each match type [19] were calculated for each model. Linear mixed models have been advocated for comparisons in monitoring variables within applied sport science observational studies involving repeated measurements on players [20] and have been readily used to compare demands placed on players across different seasonal phases in team sports [21–24]. An alpha level was set at 0.05 to indicate statistical significance. Further, Cohen's *d* was computed for each model from values and the pooled standard deviation for each outcome variable [25], with the following interpretations applied: *trivial* = < 0.20; *small* = 0.20–0.59; *moderate* = 0.60–1.19; *large* = 1.20–1.99; *very large* = 2.00–3.99; and *extremely large* = > 4.00 [26]. All analyses were conducted using Stata/MP (version 17.0 for Windows; StataCorp LLC; College Station, TX, USA).

RESULTS

Results from the linear mixed model analyses including comparison statistics between trial matches and in-season matches are shown in Table 2. Furthermore, the individual data points for each outcome variable encompassing both seasons and both teams are shown in Figures 2 and 3. Statistically significant ($p < 0.05$) differences between match types were apparent for several variables. Specifically, players spent significantly more time on-field during in-season matches compared to trial matches (*moderate*), and thus attained significantly higher absolute outputs for total distance (*moderate*), HSR distance (*small*), LSR distance (*moderate*), accelerations (*moderate*), high-intensity accelerations (*small*), decelerations (*moderate*), and high-intensity decelerations (*small*). Players also attained a significantly higher average speed (*small*) and relative LSR distance (*small*) during in-season matches compared to trial matches. In contrast, non-significant ($p > 0.05$) differences were evident between match types for relative HSR distance (*trivial*), peak speed (*trivial*), total impacts (*small*), relative impacts (*trivial*), relative accelerations (*trivial*), relative high-intensity accelerations (*trivial*), relative decelerations (*trivial*), and relative high-intensity decelerations (*trivial*). Team, which was entered as a covariate, was not significant to any model ($p > 0.05$).

DISCUSSION

The aim of this study was to compare activity demands between trial matches and in-season matches in male rugby league players from two semi-professional Australian teams across two consecutive seasons. Our findings show players worked at similar peak (i.e., peak speed) and average intensities (for all outcome variables except average speed and relative LSR distance) in trial and in-season matches but lower activity volumes (for all outcome variables except impacts) were achieved in trial matches. These findings add to the limited evidence base outlining the activity demands imposed during trial matches compared to in-season matches in rugby league [13] and in wider team sports [27–29].

Our results provided for semi-professional rugby league players indicate pre-season trial matches induce similar activity intensities for most outcome variables, compared to early in-season matches. Specifically, peak speed, relative HSR distance, and relative total and high-intensity accelerations and decelerations were comparable ($p > 0.05$) across match types. These findings partly contrast those reported in professional, male rugby league players [13]. Specifically, Gabbett [13] showed players covered less ($p < 0.05$) relative HSR distance (> 18 km · h^{-1}) during trial compared to in-season matches. Reasons for variation in findings between our study and those previously reported [13] might be attributed to the different motivations underpinning performance during trial matches as well as psychological profiles [30] between male rugby league players competing at different playing levels. However, it is important to note that the previous study [13] monitored four trial matches and 13 in-season matches across multiple months, whereas we specifically monitored 2 trial matches and the first 2 in-season matches for each team across an acute 6-week period. Indeed, relative HSR distance [14] has been shown to increase during middle (matches 9–16) and late (matches 17–24) phases of the in-season compared to the early in-season phase (matches 1–8) in professional, male rugby league players. Consequently, the inclusion of matches beyond the early in-season phase in the previous study [13] may have augmented the in-season HSR demands relative to trial matches. Nevertheless, similar to the findings of Gabbett [13], our findings show that in-season matches are played at a higher ($p < 0.05$) average speed (m · min^{-1}) than trial matches. However, practically speaking, the differences in average speed in our study were small ($d = 0.31$; 85.5 ± 0.8 vs 87.5 ± 0.9 m · min^{-1}), compared to the large differences reported by

TABLE 2. Comparison of activity demands between trial and in-season matches in semi-professional, male, rugby league players (n = 39).

Outcome variable	Marginal mean ± SE		Statistical comparison		
	Trial	*In-season*	*β (95% CI)*	*p*	*d, interpretation*
Playing duration (min)	50.3 ± 2.2	63.1 ± 3.5	12.8 (8.2, 17.5)	< 0.001*	0.64, *moderate*
Total distance (m)	4266 ± 193	5477 ± 308	1,211 (812, 1,610)	< 0.001*	0.69, *moderate*
Average speed ($m \cdot min^{-1}$)	85.5 ± 0.8	87.5 ± 0.9	1.9 (0.5, 3.4)	0.008*	0.31, *small*
HSR distance (m)	306 ± 22	392 ± 34	86 (43, 129)	< 0.001*	0.45, *small*
Relative HSR distance ($m \cdot min^{-1}$)	6.02 ± 0.30	6.12 ± 0.30	0.09 (-0.42, 0.61)	0.72	0.04, *trivial*
LSR distance (m)	3957 ± 177	5086 ± 283	1,129 (759, 1,500)	< 0.001*	0.70, *moderate*
Relative LSR distance ($m \cdot min^{-1}$)	79.4 ± 0.9	81.3 ± 1.0	2.0 (0.6, 3.2)	0.005*	0.31, *small*
Peak speed ($m \cdot s^{-1}$)	7.63 ± 0.11	7.75 ± 0.09	0.12 (-0.03, 0.26)	0.11	0.17, *trivial*
Impacts (count)	13.3 ± 0.9	15.2 ± 1.2	2.0 (-0.1, 4.0)	0.06	0.25, *small*
Relative impacts ($count \cdot min^{-1}$)	0.29 ± 0.02	0.26 ± 0.02	-0.02 (-0.06, 0.02)	0.27	-0.13, *trivial*
Accelerations (count)	210 ± 9	265 ± 15	55 (35, 75)	< 0.001*	0.65, *moderate*
Relative accelerations ($count \cdot min^{-1}$)	4.32 ± 0.11	4.30 ± 0.12	-0.02 (-0.15, 0.12)	0.80	-0.02, *trivial*
High-intensity accelerations (count)	45.5 ± 2.0	54.6 ± 2.8	9.1 (4.6, 13.6)	< 0.001*	0.51, *small*
Relative high-intensity accelerations ($count \cdot min^{-1}$)	0.95 ± 0.04	0.91 ± 0.04	-0.04 (-0.09, 0.01)	0.15	-0.15, *trivial*
Decelerations (count)	205 ± 9	260 ± 14	55 (35, 75)	< 0.001*	0.67, *moderate*
Relative decelerations ($count \cdot min^{-1}$)	4.20 ± 0.10	4.21 ± 0.11	0.01 (-0.12, 0.14)	0.87	0.02, *trivial*
High-intensity decelerations (count)	56.7 ± 2.5	69.2 ± 3.8	12.5 (7.0, 18.0)	< 0.001*	0.56, *small*
Relative high-intensity decelerations ($count \cdot min^{-1}$)	1.19 ± 0.05	1.17 ± 0.06	-0.03 (-0.09, 0.03)	0.41	-0.07, *trivial*

Note: Comparisons are presented as in-season match vs. trial match (reference category). Player entered as random effect and match type entered as fixed effect with team used as a covariate in linear mixed models. * denotes significant difference with alpha set at < 0.05. ***Abbreviations***: SE = standard error; β = unstandardized regression coefficient; CI = confidence intervals; HSR = High speed running (> 18 $km \cdot h^{-1}$); LSR = low speed running (< 18 $km \cdot h^{-1}$).

Gabbett [13] (d = 1.03–2.06). Consequently, the collective evidence suggests players move at slower speeds during trial matches compared with in-season matches when not engaged in high-intensity passages of play, but these differences may be of smaller magnitude at the semi-professional level. These findings may be attributed to factors that promote more stationary and walking activity between high-speed running bouts in trial matches, such as the lower fitness capacities typically evident among players in the pre-season compared to mid-season [31]. Moreover, poorer skill execution due to less experienced players being trialled in the pre-season, or due to less cohesive team dynamics because of unfamiliar player combinations, may have promoted greater error rates in general play leading to more stoppages.

The comparable data we observed for peak speed and most relative activity demand variables reported per minute of play between trial and in-season matches has important implications for player preparation strategies in semi-professional rugby league teams. Although coaches likely adopt strategies that restrict the playing time of some players to evaluate a broader range of players within the squad during trial matches, it is essential that players are exposed to intensities akin to in-season matches when on the field. In this way, the observations made by coaching staff during trial matches will potentially carry stronger translation to in-season match-play if players demonstrate they can repeatedly execute fundamental activities and team strategies are effective in scenarios performed at intensities specific to official competition. Furthermore, given exercise intensity is an important mediator in acutely enhancing mitochondrial adaptations [32], repeated-sprint ability [33], and aerobic capacity [32, 34], our observations suggest trial matches may partly elicit suitable stimuli to promote physiological adaptations specific to in-season matches at the semi-professional level.

In line with the comparisons made for peak speed and most relative ($\cdot min^{-1}$) outcome variables, total impacts (count) and impacts per minute were comparable across match types in our study. These findings partly align with previous data reported in professional, male rugby league players [13] showing a similar number of ($p > 0.05$) total impacts (for adjustable and outside back positions) and impacts per minute (for forward, adjustable, and outside back positions) were encountered in trial and in-season matches. We speculate that poorer tackling proficiency may have contributed to comparable impact metrics between match types, despite lower average playing

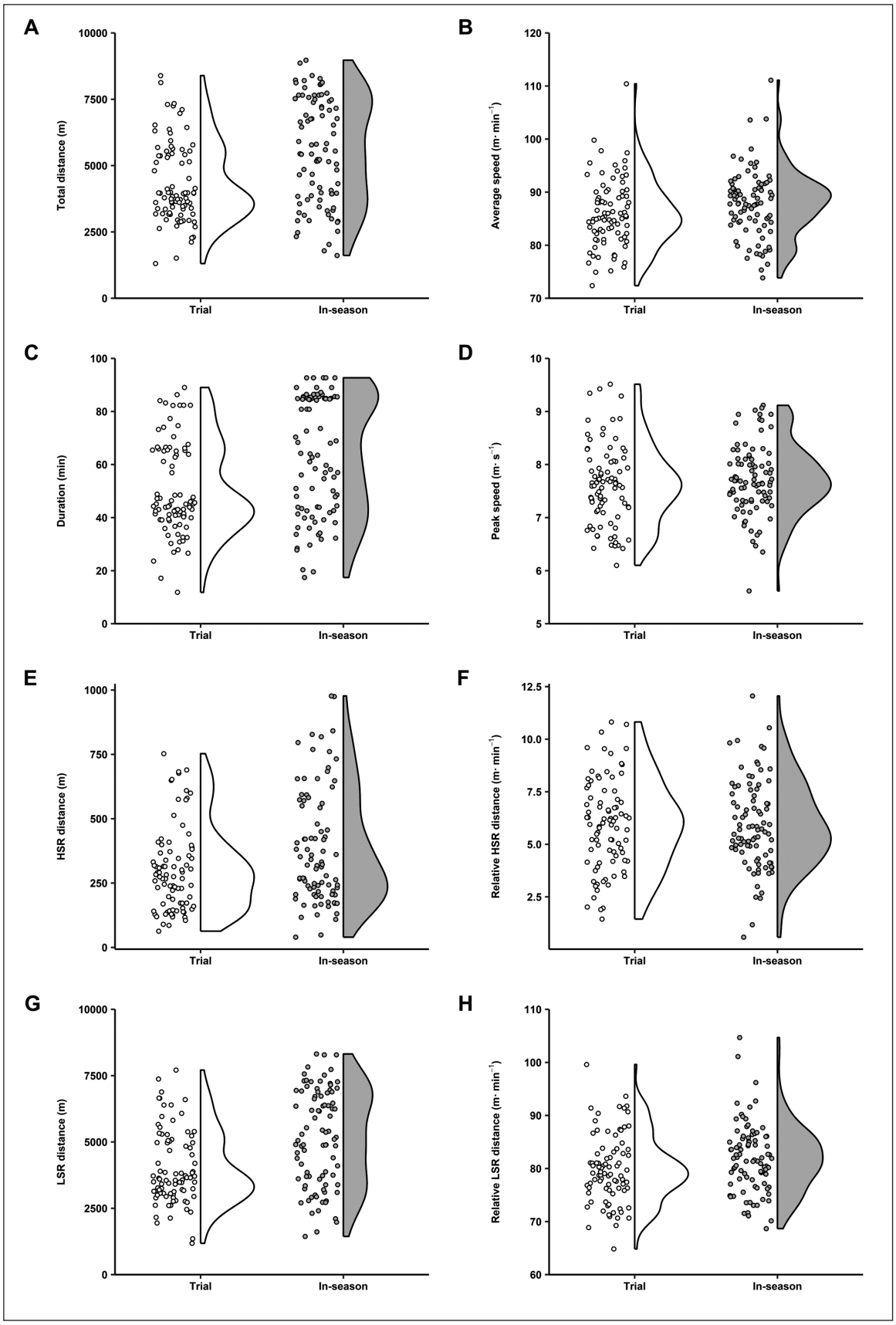


FIG. 2. Individual data points alongside half-violin plots for (A) total distance, (B) average speed, (C) duration, (D) peak speed, (E) high-speed running (HSR) distance, (F) relative HSR distance, (G) low-speed running (LSR) distance, and (H) relative LSR distance during trial and in-season matches among semi-professional, male rugby league players (n = 39).

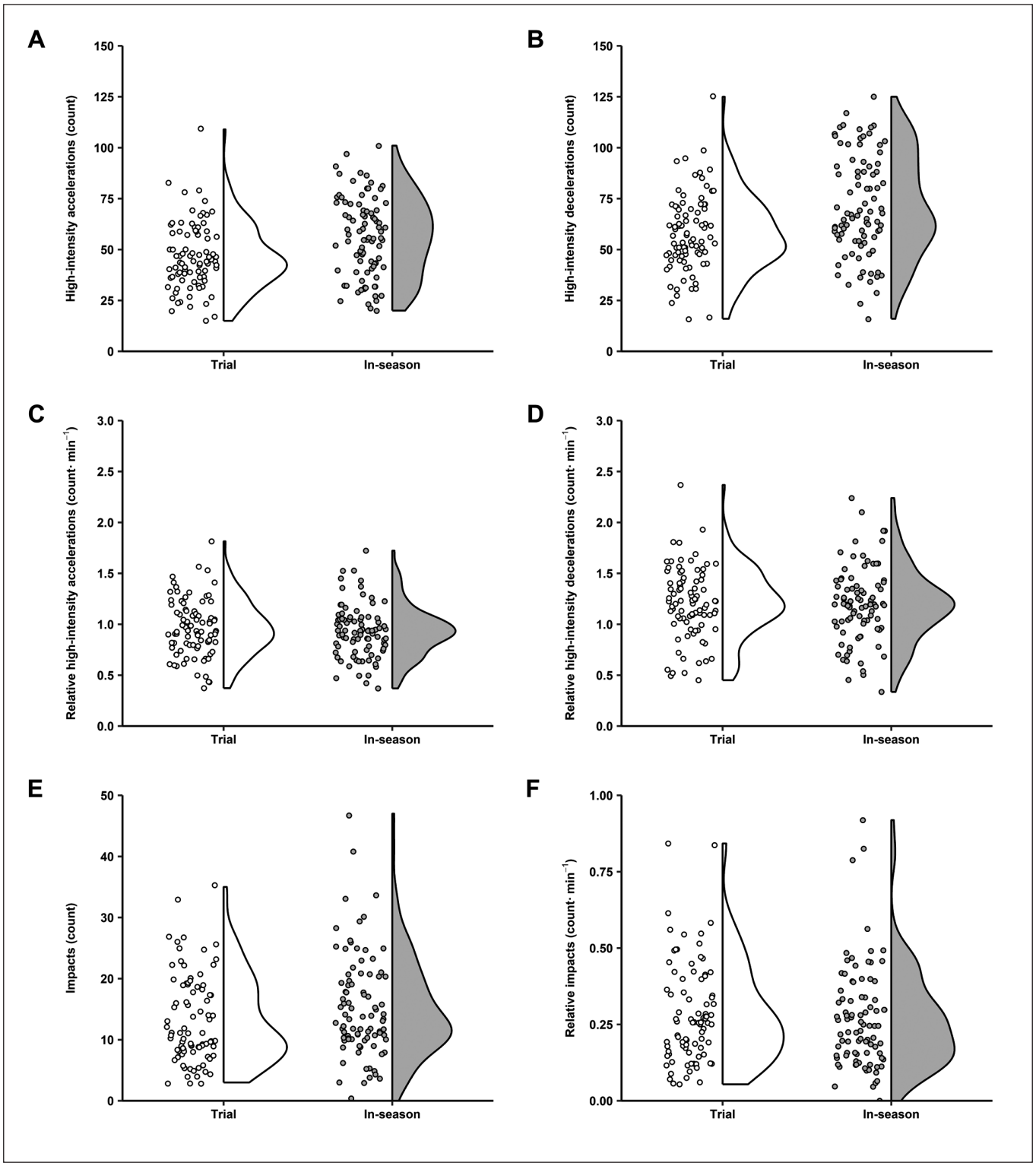


FIG. 3. Individual data points alongside half-violin plots for (A) high-intensity accelerations, (B) high-intensity decelerations, (C) relative high-intensity accelerations, (D) relative high-intensity decelerations, (E) impacts, and (F) relative impacts during trial and in-season matches among semi-professional, male rugby league players (n = 39).

durations in trial matches. For instance, poorer tackling ability (effect size = -0.24) has been observed in the pre-season compared to in-season [35], and repeated high-intensity efforts (i.e., sprints, tackling, and jogging) inducing fatigued states have been shown to diminish (effect size = -1.17) tackling ability [36] in semi-professional, male rugby league players. Consequently, lower tackling proficiencies and greater susceptibility to fatigue in the pre-season may lead to more missed tackles and faster opposition play-the-ball speeds, increasing tackling requirements during trial matches. However, outcome variables indicative of physical fitness and technical abilities were not measured in our study and should be included in future research on this topic to confirm these suppositions.

While the activity intensity data we collected yields some important insights, it should be interpreted alongside activity volume data to comprehensively understand the match stimuli encountered in trial matches and in-season matches. In our study, players underwent significantly greater playing durations during in-season matches compared to trial matches, which underpin the significantly greater activity volumes observed during in-season matches in the form of total, HSR, and LSR distances, as well as accelerations and decelerations. In this regard, a longer exposure to match-play provides increased opportunity for players to participate in more match tasks producing greater field coverage and changes in movement speed and direction, elevating total distance and acceleration variables. The reduced match exposure during trial matches is likely due to various coaching strategies employed in the pre-season, including trialling different players across positions for selection and limiting the match exposure for key players to minimise injury risk. These strategies are possible in trial matches given the unrestricted number of players able to be selected for matches and interchanges available during matches. Indeed, these patterns in match exposure, total distance, and HSR distance mirror those observed in professional rugby league [13] and other team sports such as Australian rules football [28], suggesting mismatches in activity volumes are common between trial matches and in-season matches in team sports. Given consistent training schedules were administered in weeks when trial matches and in-season matches were played in our study, the lower match activity volumes may not adequately prepare players for the overall weekly stimuli faced during the early in-season phase, but a detailed analysis of session and accumulated training load was outside the scope of this investigation.

Some limitations should be acknowledged when interpreting our findings. First, reported data are representative of two semi-professional, Australian, male rugby league teams and may not be representative of all semi-professional teams, teams competing at other playing levels, or female competitions. Second, although data support the validity (distance and peak speed) and reliability (distance and HSR distance) of running metrics derived from the PlayerTek™ devices [16] used for monitoring players in our study, accelerometer-derived variables are yet to be independently validated or tested for reliability. Third, despite the multi-season sample of included matches in our study being well-matched for wins and losses between match types, we acknowledge that differences in stoppages within play may influence mean intensity-related activity demands. Furthermore, despite conducting a multi-team study, we were unable to conduct analyses according to playing position due to an insufficient sample size. Finally, the perceptual and cardiovascular demands, as well as the technical and tactical demands encountered by players were not recorded in our study and may show useful differences between trial matches and in-season matches. Consequently, wider research on this topic is encouraged examining other teams, using additional outcome variables, and conducting positional analyses.

CONCLUSIONS

This study is the first to quantify and compare activity demands between trial matches and in-season matches in semi-professional, male rugby league players, providing important insights relevant to player preparation at this level of play. The activity intensities for most variables (i.e., peak speed, relative HSR distance, relative impacts, relative total and high-intensity accelerations and decelerations) and total impacts attained during trial matches were comparable to those attained during official matches held early in the in-season. In contrast, the activity volumes in in-season matches significantly exceeded those encountered during trial matches; the average speed and relative LSR distance in in-season matches were also higher than trial matches, but the differences were small (d = 0.31). These findings hold important implication to player preparation strategies for semi-professional rugby league teams. Specifically, given the importance of exercise intensity in facilitating positive aerobic adaptations in team sport players [37], the comparable activity intensities between match types in our study suggest trial matches may be useful for coaching staff to physically prepare semi-professional rugby league players for in-season match-play. Moreover, the impact exposure encountered during trial matches may also adequately replicate the demand during early in-season matches. However, the lower playing time and activity volumes during trial matches suggests players may not be adequately prepared for the entire in-season match stimuli without additional volume overload. Consequently, elevated match volume demands encountered in the early in-season may increase risk of maladaptive responses and injury, particularly for players expected to play entire matches.

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Conflict of interest declaration

The authors declare no conflict of interest.

REFERENCES

1. Clearinghouse for Sport. AusPlay results. Available at: https://www.clearinghouseforsport.gov.au/research/ausplay/results.
2. Roy Morgan. AFL grows TV viewership during 2020 to stretch lead over NRL. Available at: http://www.roymorgan.com/findings/8687-afl-vs-nrl-april-2021-202104260235.
3. Hausler J, Halaki M, Orr R. Application of global positioning system and microsensor technology in competitive rugby league match-play: A systematic review and meta-analysis. Sports Med. 2016; 46(4):559–588.
4. Jones R, Mahoney J, Gucciardi D. On the transition into elite rugby league: Perceptions of players and coaching staff. Sport Exerc Perform Psych. 2014; 3(1):28–45.
5. McLellan C, Lovell D. Performance analysis of professional, semiprofessional, and junior elite rugby league match-play using global positioning systems. J Strength Cond Res. 2013;27(12):3266-3274.
6. Sirotic A, Coutts A, Knowles H, Catterick C. A comparison of match demands between elite and semi-elite rugby league competition. J Sports Sci. 2009; 27(3):203–211.
7. Johnston R, Devlin P, Wade J, Duthie G. There is little difference in the peak movement demands of professional and semi-professional rugby league competition. Front Physiol. 2019; 10:1285.
8. Gabbett T. Effects of physical, technical, and tactical factors on final ladder position in semiprofessional rugby league. Int J Sports Physiol Perform. 2014; 9(4):680–688.
9. Hulin B, Gabbett T. Activity profiles of successful and less-successful semi-elite rugby league teams. Int J Sports Med. 2015; 36(6):485–489.
10. Gabbett T, Jenkins D, Abernethy B. Physical demands of professional rugby league training and competition using microtechnology. J Sci Med Sport. 2012; 15(1):80–86.
11. Redman K, Kelly V, Beckman E. Seasonal changes in strength and power in elite rugby league: A systematic review and meta-analysis. J Sports Sci Med. 2021; 20(4):721–731.
12. Crang Z, Hewitt A, Scott T, Kelly V, Johnston R. Relationship between preseason training load, match performance, and match activities in professional rugby league. J Strength Cond Res. 2022; 36(9):2581–2588.
13. Gabbett T. Influence of playing standard on the physical demands of professional rugby league. J Sports Sci. 2013; 31(10):1125–1138.
14. Kempton T, Coutts A. Factors affecting exercise intensity in professional rugby league match-play. J Sci Med Sport. 2016; 19(6):504–508.
15. Glassbrook D, Doyle T, Alderson J, Fuller J. The demands of professional rugby league match-play: A meta-analysis. Sports Med Open. 2019; 5(1):24.
16. Mooney T, Malone S, Izri E, Dowling S, Darragh I. The running performance of elite U20 Gaelic football match-play. Sports Sci Health. 2021; 17(3):771–779.
17. White H. A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. Econometrica. 1980; 48(4):817–838.
18. White H. Maximum likelihood estimation of misspecified models. Econometrica. 1982; 50(1):1–25.
19. Williams R. Using the margins command to estimate and interpret adjusted predictions and marginal effects. Stata J. 2012; 12(2):308–331.
20. Newans T, Bellinger P, Drovandi C, Buxton S, Minahan C. The utility of mixed models in sport science: A call for further adoption in longitudinal data sets. Int J Sports Physiol Perform. 2022; 17(8):1289–1295.
21. Williams M, Fox J, O'Grady C, Gardner S, Dalbo V, Scanlan A. Weekly training demands increase, but game demands remain consistent across early, middle, and late phases of the regular season in semiprofessional basketball players. Int J Sports Physiol Perform. 2022; 17(3):350–357.
22. Bruce L, Bardzinski T, Dwyer D. Understanding load in netball – An analysis of multiple seasons, phases, and teams. PLOS ONE. 2022; 17(4):e0266830.
23. Kelly D, Strudwick A, Atkinson G, Drust B, Gregson W. Quantification of training and match-load distribution across a season in elite English Premier League soccer players. Sci Med Football. 2020; 4(1):59–67.
24. Sansone P, Gasperi L, Tessitore A, Gomez M. Training load, recovery and game performance in semiprofessional male basketball: Influence of individual characteristics and contextual factors. Biol Sport. 2021; 38(2):207–217.
25. Lipsey M, Wilson D. Practical meta-analysis. Applied Social Research Methods Series. Vol. 49. Thousand Oaks, CA, USA: SAGE Publications Inc.; 2001.
26. Hopkins W, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009; 41(1):3–13.
27. Brooks E, Benson A, Fox A, Bruce L. Physical movement demands of training and matches across a full competition cycle in elite netball. Appl Sci. 2020; 10(21):7689.
28. Ritchie D, Hopkins W, Buchheit M, Cordy J, Bartlett J. Quantification of training and competition load across a season in an elite Australian football club. Int J Sports Physiol Perform. 2016; 11(4):474–479.
29. Vieira L, Doğramaci S, Barbieri R, Milioni F, Moura F, de Andrade V, Cesar G, Santiago P. Preliminary results on organization on the court, physical and technical performance of Brazilian professional futsal players: comparison between friendly pre-season and official match. Motriz Rev Educ Fis. 2016; 22(2):80–92.
30. Golby J, Sheard M. Mental toughness and hardiness at different levels of rugby league. Pers Individ Differ. 2004; 37(5):933–942.
31. Dobbin N, Highton J, Moss S, Twist C. Factors affecting the anthropometric and physical characteristics of elite academy rugby league players: A multiclub study. Int J Sports Physiol Perform. 2019; 14(7):958–965.
32. MacInnis M, Gibala M. Physiological adaptations to interval training and the role of exercise intensity. J Physiol. 2017; 595(9):2915–2930.
33. Edge J, Bishop D, Goodman C, Dawson B. Effects of high- and moderate-intensity training on metabolism and repeated sprints. Med Sci Sports Exerc. 2005; 37(11):1975–1982.
34. Wenger H, Bell G. The interactions of intensity, frequency and duration of exercise training in altering cardiorespiratory fitness. Sports Med. 1986; 3(5):346–356.
35. Speranza M, Gabbett T, Greene D, Johnston R, Sheppard J. Changes in rugby league tackling ability during a competitive season: The relationship with strength and power qualities. J Strength Cond Res. 2017; 31(12):3311–3318.
36. Gabbett T. Influence of fatigue on tackling ability in rugby league players: Role of muscular strength, endurance, and aerobic qualities. PLOS ONE. 2016; 11(10):e0163161.
37. Fox J, Stanton R, Sargent C, Wintour S, Scanlan A. The association between training load and performance in team sports: A systematic review. Sports Med. 2018; 48(12):2743–2774.

Large-scale sporting events during the COVID-19 pandemic: insights from the FIFA World Cup 2022 in Qatar with an analysis of patterns of COVID-19 metrics

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ABSTRACT: The 2022 FIFA World Cup (FIFA-WC) held in Qatar presented unique challenges, given the potential for rapid transmission of coronavirus disease 2019 (COVID-19) among over 1.4 million international fans attending the event. This study aimed to investigate the impact of the FIFA-WC 2022 on COVID-19 cases, deaths, and reproduction rate (R0) in Qatar. Additionally, it sought to understand the implications of hosting large-scale events during a pandemic without COVID-19 restrictive measures, providing critical insights for future decision-making. Data from "Our World in Data" were analysed for three distinct periods: one week before the FIFA-WC (week-preWC), the four weeks of the event (week-1WC to week-4WC), and one week after (week-postWC). The results revealed a significant increase in COVID-19 cases during week-3WC and week-4WC (compared to week-preWC) in Qatar, followed by a subsequent decrease during the week-postWC. Notably, Qatar experienced a more pronounced surge in positive cases than the global trend. Regarding COVID-19-related deaths, Qatar's peak occurred during week-2WC, while globally deaths peaked from week-3WC to week-postWC. Nevertheless, Qatar's death toll remained relatively low compared to the global trend throughout the event. The findings highlight that the FIFA-WC 2022 in Qatar demonstrated the feasibility of organizing large-scale sporting events during a pandemic with appropriate measures in place. They emphasize the importance of high vaccination coverage, continuous monitoring, and effective collaboration between event organizers, healthcare authorities, and governments. As such, the event serves as a valuable model for future gatherings, underlining the significance of evidence-based decision-making and comprehensive public health preparedness.

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INTRODUCTION

The outbreak of coronavirus disease 2019 (COVID-19) has had a significant impact on many aspects of society, including sports events [1–3]. As COVID-19 rapidly spread, many significant competitions, including the Olympic Games and the UEFA Champions League, were either cancelled or postponed [4, 5]. The effects of the pandemic on sports events have given rise to several concerns, such as the financial losses suffered by organizers, interruption of athletes' training and competition routines, and the negative impact on their mental and physical health [3, 5, 6].

The FIFA World Cup (FIFA-WC) is the largest international sports event, bringing together a diverse range of attendees from all over the world. Due to its scale and scope, hosting this event presents unique challenges to organizing countries in normal times, let alone in times of sanitary threat [4, 5]. Indeed, the 22nd FIFA-WC 2022, which took place in Qatar from 20 November to 18 December 2022, was unique in several ways. Firstly, this event was the first FIFA-WC to ever be hosted during an ongoing pandemic (i.e. COVID-19) [4, 5]. This was one of the key challenges because, due to close human proximity, there was a potential for rapid spread of highly transmissible infectious disease from imported or endemic communicable diseases. Secondly, Qatar FIFA-WC 2022 was the first World Cup to be held in such a small nation in terms of population size and geographic area [2, 5]. Besides the challenges that have been faced previously, it is worth noting that, unlike most major sporting events previously held during the pandemic, the FIFA-WC took place without any sanitary restrictions, as Qatar lifted all travel and local restrictions related to COVID-19 in September 2022 [7].

Therefore, the aims of this study were to: i) investigate the impact of organizing the FIFA-WC 2022 on COVID-19 cases, deaths, and reproduction rate (R0) in Qatar, and ii) understand the implications of hosting large-scale events during a pandemic in the absence of COVID-19 restrictive measures, for critical decision-making in the future.

MATERIALS AND METHODS

Event

The 22nd edition of FIFA-WC was held in Qatar from November 20th to December 18th, 2022. The event was scheduled for November and December to avoid Qatar's summer extreme heat. The tournament featured 64 matches played in eight venues in Doha and the surrounding areas of the capital over 29 days. The average turnout per match was 53,191 spectators, with a total attendance of 3,404,252 fans [8]. In addition, over 1.8 million fans watched the live broadcast of games and festivities at the FIFA Fan Festival held in Al Bidda Park, Doha [9]. The final match at Lusail Stadium drew an attendance of 88,966 spectators, and the FIFA-WC was viewed by over 5 billion TV viewers globally.

Data sources

We acquired data from publicly available sources, including government websites such as the Ministry of Public Health (MOPH) in Qatar, which provided local COVID-19 data for the country [10]. We also used other academic data sets, such as "Our World in Data", to investigate COVID-19 data in other countries and obtain the daily number of international newly infected cases, deaths, and the R0 [11]. Our primary dataset was "Our World in Data", which we cross-checked with the data provided by the MOPH to ensure accuracy. R0 data were not available on the MOPH website; therefore we retrieved the data from the "Our World in Data" website. In addition, we searched PubMed Central (PMC, last accessed on the 7th April 2023) for peer-reviewed studies on the impact of mass gatherings on the spread of COVID-19, which we used to write up our manuscript.

Data collection methods

The aforementioned sources provided us with the necessary data, which we subsequently organized into an Excel spreadsheet for analysis. The data were collected during three distinct time periods: before, during, and after the FIFA-WC 2022. Specifically, we collected data one week before the FIFA-WC (i.e. week-preWC: November 13th to 19th), during the FIFA-WC (i.e. four weeks from November 20th to December 18th, totalling 29 days), and one week after the FIFA-WC (i.e. week-postWC: December 19th to 25th). The period of "during FIFA-WC" was divided into four weeks (i.e. week-1WC: November 20th to 26th; week-2WC: November 27th to December 3rd; week-3WC: December 4th to 10th; and week-4WC: December 11th to 18th). This allowed us to compare COVID-19 cases, deaths, and R0 in Qatar to the world population before, during, and after the FIFA-WC event.

In addition to conducting a statistical analysis, we intentionally created a graph that features data – 10 days before the FIFA-WC (from November 10th to 19th), during the 29 days of the FIFA-WC (from November 20th to December 18th), and 10 days after the FIFA-WC (from December 19th to 28th) – from multiple countries across four continents: Asia (Qatar, Saudi Arabia, United Arab Emirates (UAE) and Russia), Africa (Tunisia and South Africa), Europe (United Kingdom), America (Canada and Mexico). The latter countries represented the region and different continents, and with the exception of Russia, South Africa and UAE, had their national teams participating in the event. Our objective was to illustrate to readers the approximate patterns of COVID-19 worldwide in comparison to Qatar.

Data

We analysed the following three key metrics related to COVID-19 in Qatar: daily new confirmed COVID-19 cases per million people, daily new confirmed COVID-19 related deaths per million people, and effective R0. R0 measures the average number of new infections caused by a single infected individual [12]. If R0 is > 1, the infection

is able to spread in the population. If R0 ≤ 1, the number of cases occurring in the population will gradually decrease until it reaches zero [12].

Ethical approval

Ethical approval was sought for this study by consulting with the Institutional Review Board (IRB) of the Primary Health Care Corporation (PHCC) on January 30th, 2023. As our study only involved the utilization of publicly available data, the IRB granted us approval of exempted review process application.

Statistical analysis

The daily COVID-19 related new confirmed cases and deaths, and effective R0 for the world and Qatar during the six weeks were expressed as mean ± standard deviation (95% confidence interval). Comparisons between the six weeks were made via an analysis of variance (ANOVA). If p was < 0.05, a post-hoc analysis (Tukey HSD test) was performed. All analyses were carried out using STATISTICA software version 12. The significance level was set at 5% ($p < 0.05$).

RESULTS

Confirmed cases, COVID-19 related confirmed deaths, and effective R0 in Qatar, the world, and selected countries

Figures 1, 2, and 3 illustrate the evolution of the confirmed COVID-19 cases per million people (Figure 1), confirmed deaths per million people (Figure 2), and the effective R0 (Figure 3) in Qatar, the world, and selected countries 10 days before the FIFA-WC, during the FIFA-WC, and 10 days after the FIFA-WC.

Table 1 presents the COVID-19 related confirmed cases per million people, confirmed deaths per million people, and effective R0 before, during, and after the FIFA-WC 2022 in Qatar and the world.

Figures 4, 5, and 6 present the evolution of the confirmed cases per million people (Figure 4), confirmed deaths per million people (Figure 5), and the effective R0 (Figure 6) in Qatar and the world one week before the FIFA-WC, four weeks during the FIFA-WC, and one week after the FIFA-WC.

TABLE 1. COVID-19 confirmed cases per million people, confirmed deaths per million people, and reproduction rate pre, during, and post the FIFA world-cup (WC) 2022: data from the world and Qatar.

Periods	Pre WC (7 days before)	During WC (29 days)				Post WC (7 days after)	ANOVA p-value	Tukey HSD test p-value
Weeks	W-preWC: November 13 to 19	W-1WC: November 20 to 26	W-2WC: November 27 to December 3	W-3WC: December 4 to 10	W-4WC: December 11 to 18	W-postWC: December 19 to 25		
CONFIRMED CASES								
World	48.70 ± 2.18 (46.68 to 50.72)	54.09 ± 1.52 (52.69 to 55.50)	61.60 ± 3.97 (57.92 to 65.28)	67.66 ± 1.24 (66.52 to 68.81)	72.14 ± 2.04 (70.43 to 73.84)	72.45 ± 0.85 (71.67 to 73.24)	$F_{(5,37)} = 142$ $p = 0.0001$	abcdefghijklmn
Qatar	120.23 ± 2.56 (117.87 to 122.60)	101.03 ± 9.43 (92.30 to 109.75)	109.55 ± 16.10 (94.66 to 124.44)	192.86 ± 24.67 (170.05 to 215.67)	152.15 ± 24.40 (131.75 to 172.55)	95.05 ± 9.50 (86.27 to 103.84)	$F_{(5,37)} = 35$ $p = 0.0001$	cdghjkmno
CONFIRMED DEATHS								
World	0.18 ± 0.01 (0.17 to 0.19)	0.19 ± 0.01 (0.18 to 0.19)	0.18 ± 0.01 (0.17 to 0.18)	0.20 ± 0.01 (0.19 to 0.21)	0.22 ± 0.01 (0.21 to 0.22)	0.23 ± 0.00 (0.23 to 0.23)	$F_{(5,37)} = 54$ $p = 0.0001$	cdehijklmn0
Qatar	0.00 ± 0.00	0.01 ± 0.02 (-0.01 to 0.04)	0.04 ± 0.02 (0.01 to 0.06)	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	$F_{(5,37)} = 8$ $p = 0.0001$	bjkl
REPRODUCTION RATE								
World	1.09 ± 0.02 (1.07 to 1.10)	1.11 ± 0.01 (1.09 to 1.12)	1.13 ± 0.01 (1.13 to 1.14)	1.09 ± 0.01 (1.08 to 1.09)	1.06 ± 0.02 (1.04 to 1.08)	0.99 ± 0.02 (0.97 to 1.01)	$F_{(5,37)} = 58$ $p = 0.0001$	behijkln
Qatar	0.89 ± 0.05 (0.84 to 0.93)	0.88 ± 0.07 (0.81 to 0.94)	1.26 ± 0.22 (1.06 to 1.46)	1.26 ± 0.22 (1.06 to 1.46)	0.79 ± 0.08 (0.73 to 0.86)	0.80 ± 0.09 (0.72 to 0.88)	$F_{(5,37)} = 18$ $p = 0.0001$	bcfgklmn

ANOVA: Analysis of variance. **COVID-19:** Coronavirus disease of 2019. **W**: Week.
Data were mean ± standard deviation (95% confidence interval).
ANOVA: Comparison between the 6 weeks for Qatar and the world.
Tukey HSD test ($p < 0.005$):
[a] W-preWC vs. W-1WC; [b] W-preWC vs. W-2WC; [c] W-preWC vs. W-3WC; [d] W-preWC vs. W-4WC; [e] W-preWC vs. W-postWC;
[f] W-1WC vs. W-2WC; [g] W-1WC vs. W-3WC; [h] W-1WC vs. W-4WC; [i] W-1WC vs. W-postWC;
[j] W-2WC vs. W-3WC; [k] W-2WC vs. W-4WC; [l] W-2WC vs. W-postWC;
[m] W-3WC vs. W-4WC; [n] W-3WC vs. W-postWC;
[o] W-4WC vs. W-postWC

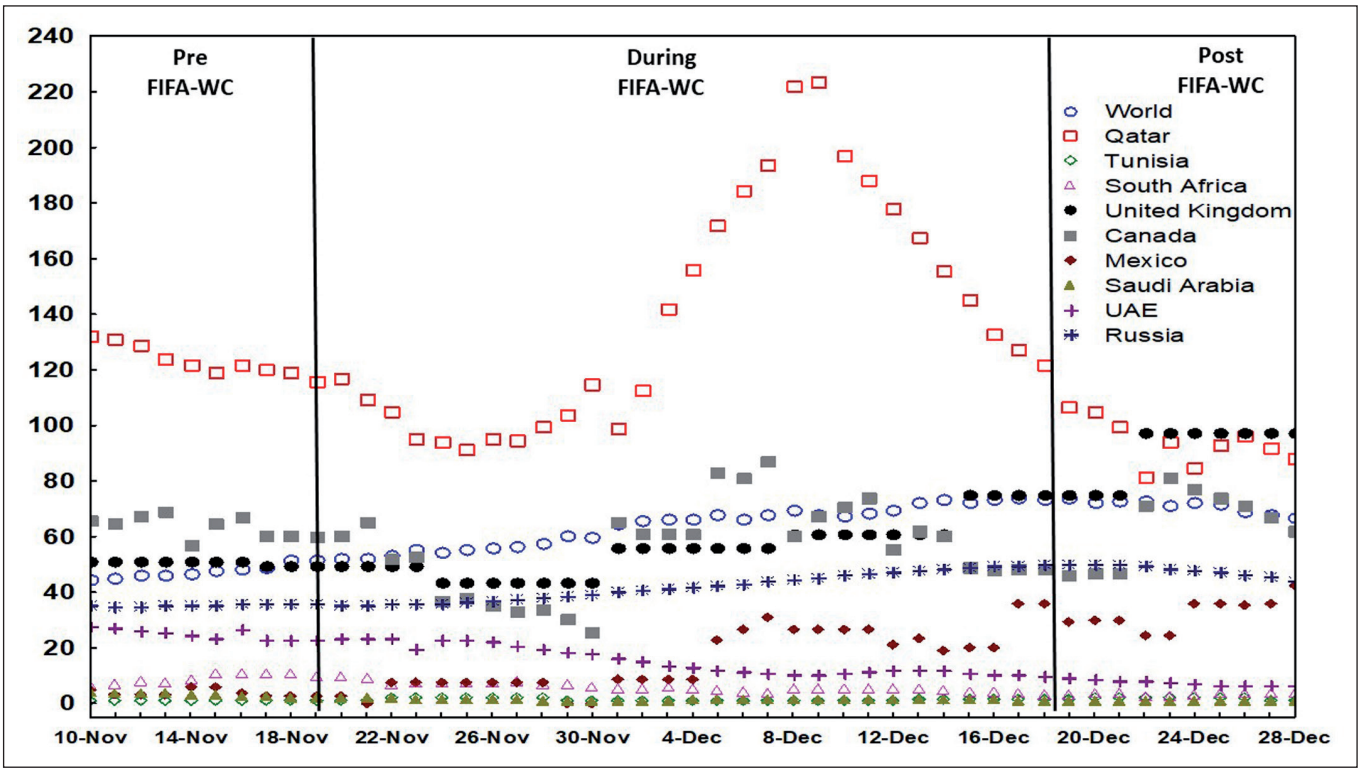


FIG. 1. Evolution of the confirmed COVID-19 related cases per million people in Qatar, the world, and multiple countries 10 days pre the FIFA World-Cup (WC), during the FIFA-WC, and 10 days post the FIFA-WC. COVID-19: Coronavirus Disease of 2019

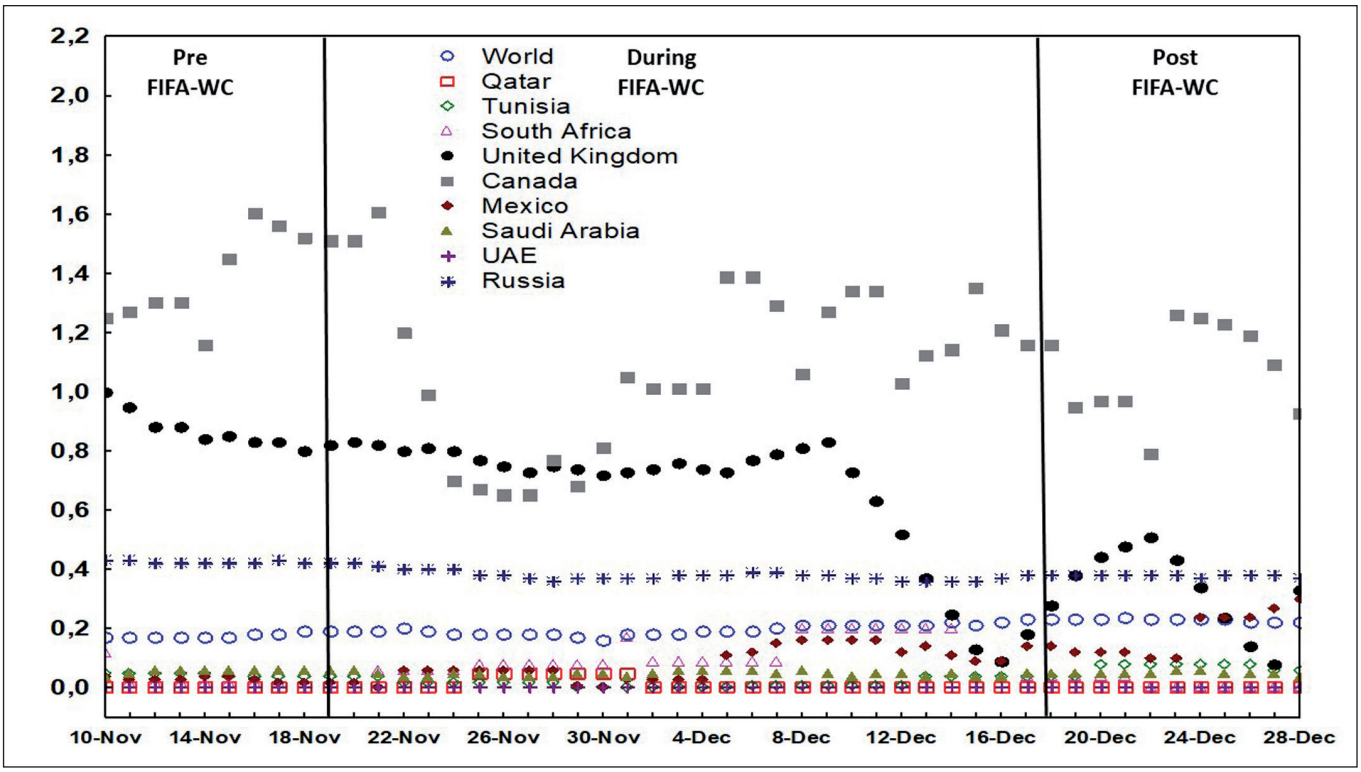


FIG. 2. Evolution of the COVID-19 related confirmed deaths per million people in Qatar, the world, and multiple countries 10 days pre the FIFA World-Cup (WC), during the FIFA-WC, and 10 days post the FIFA-WC. COVID-19: Coronavirus Disease of 2019.

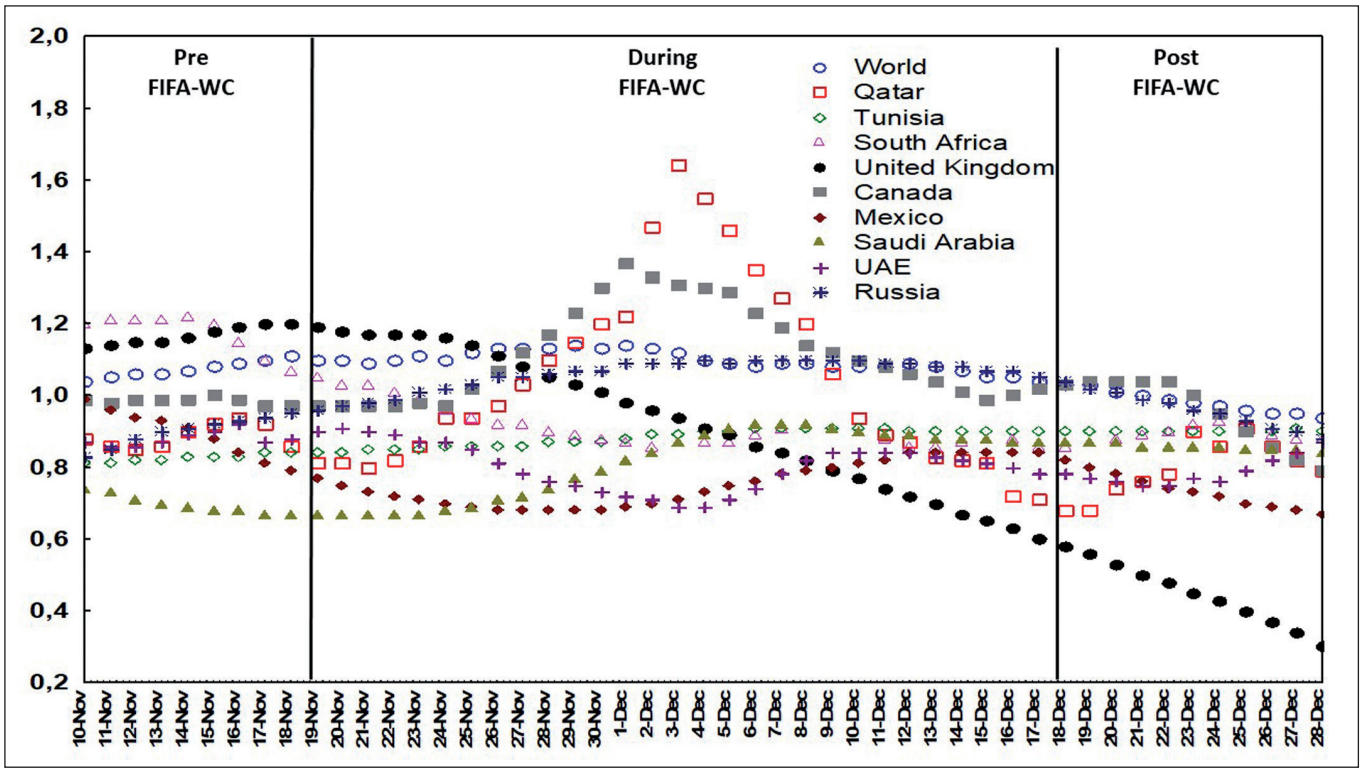


FIG. 3. Evolution of effective COVID-19 reproduction rate (R0) in Qatar, the world, and multiple countries 10 days pre the FIFA World-Cup (WC), during the FIFA-WC, and 10 days post the FIFA-WC. COVID-19: Coronavirus Disease of 2019.

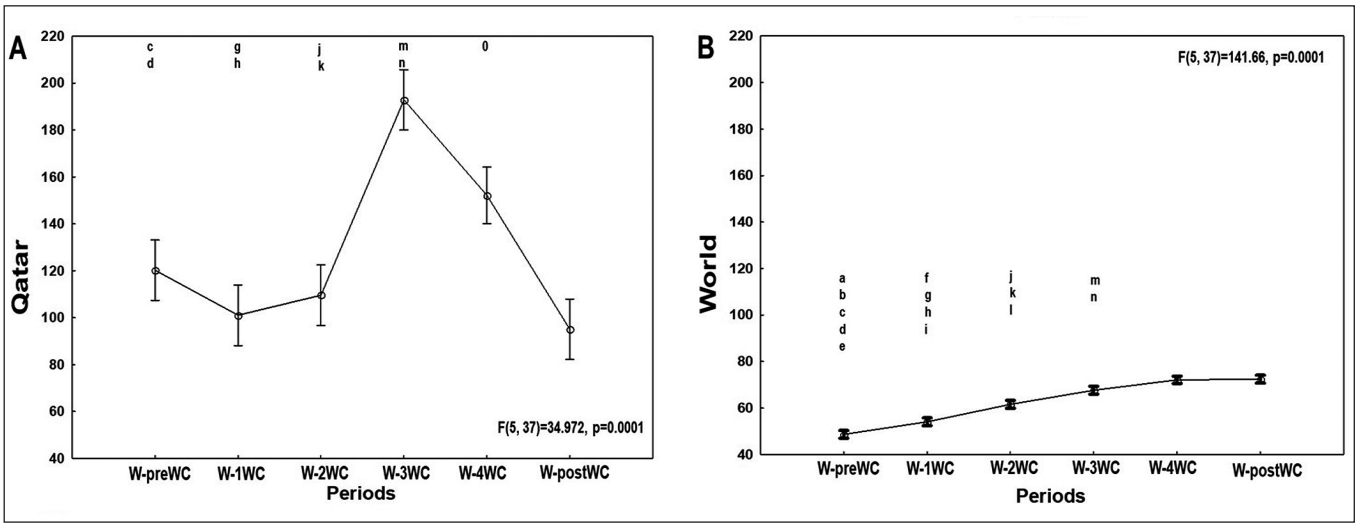


FIG. 4. Evolution of the COVID-19 confirmed cases per million people in Qatar (Figure 4A), and in the world (Figure 4B), one-week pre the FIFA world-cup (W-preWC), four weeks during the FIFA-WC (W-1WC to W-4WC), and one week post the FIFA-WC (W-postWC). Data were mean ± standard deviation (95% confidence interval). COVID-19: Coronavirus Disease of 2019.W: week. Analysis of variance (ANOVA): comparison between the 6 weeks for each region. Tukey HSD test ($p < 0.005$): W-preWC vs. [a] W-1WC; [b] W-2WC; [c] W-3WC; [d] W-4WC; [e] W-postWC; W-1WC vs. [f] W-2WC; [g] W-3WC; [h] W-4WC; [i] W-postWC; W-2WC vs. [j] W-3WC; [k] W-4WC; [l] W-postWC; W-3WC vs. [m] W-4WC; [n] W-postWC; [o] W-4WC vs. W-postWC.

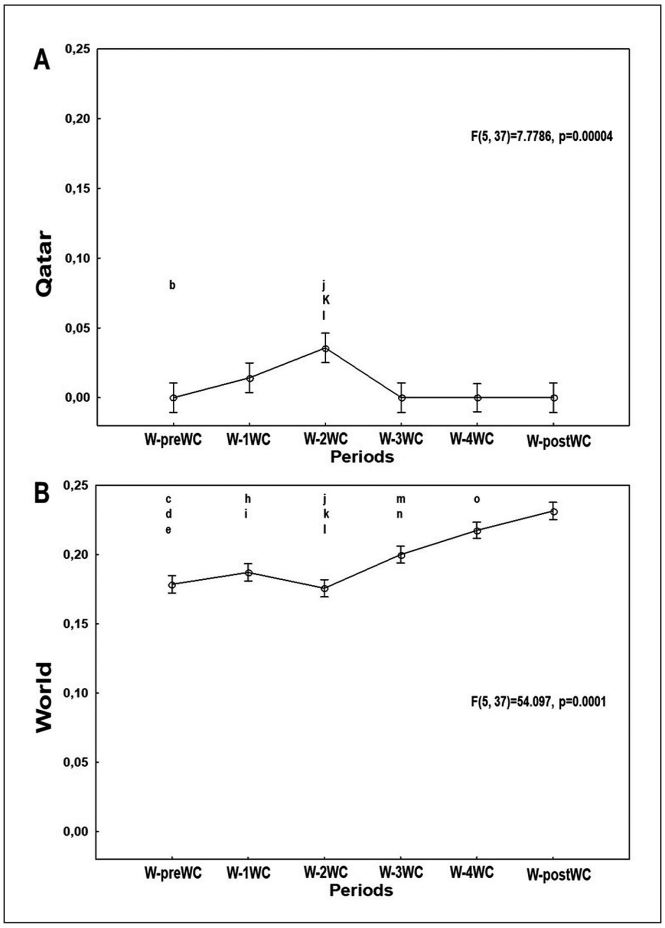


FIG. 5. Evolution of the COVID-19 confirmed deaths per million people in Qatar (Figure 5A), and in the world (Figure 5B), one-week pre the FIFA World-Cup (W-preWC), four weeks during the FIFA-WC (W-1WC to W-4WC), and one week post the FIFA-WC (W-postWC).
Data were mean ± standard deviation (95% confidence interval). COVID-19: Coronavirus Disease of 2019.W: week. "Analysis of variance (ANOVA): Tukey HSD test ($p < 0.005$): W-preWC vs. [a] W-1WC; [b] W-2WC; [c] W-3WC; [d] W-4WC; [e] W-postWC; W-1WC vs. [f] W-2WC; [g] W-3WC; [h] W-4WC; [i] W-postWC; W-2WC vs. [j] W-3WC; [k] W-4WC; [l] W-postWC; W-3WC vs. [m] W-4WC; [n] W-postWC; [o] W-4WC vs. W-postWC.

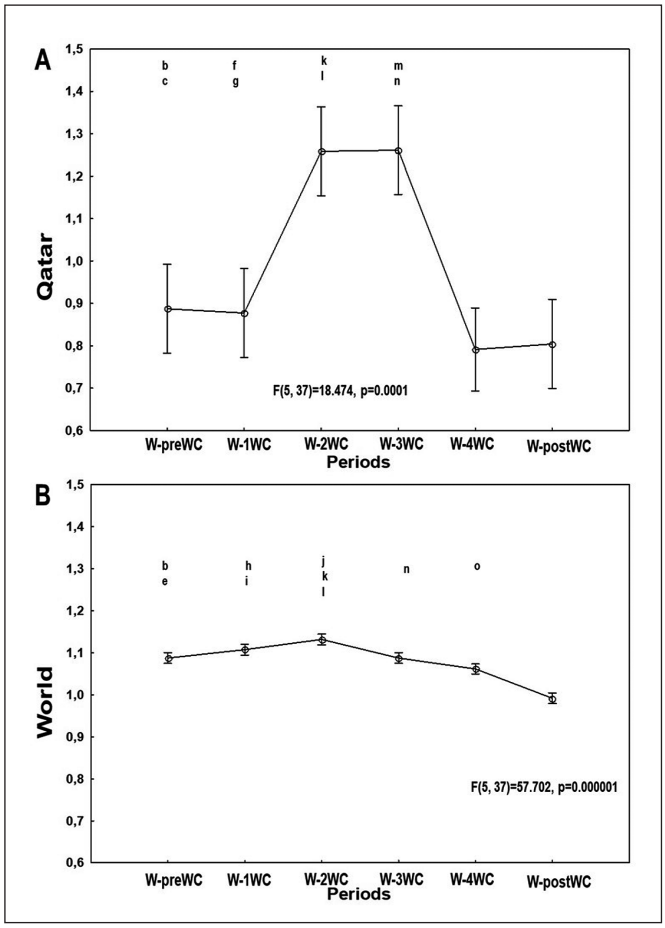


FIG. 6. Evolution of the COVID-19 reproduction rate in Qatar (Figure 6A), and in the world (Figure 6B), one-week pre the FIFA World-Cup (W-preWC), four weeks during the FIFA-WC (W-1WC to W-4WC), and one week post the FIFA-WC (W-postWC).
Data were mean ± standard deviation (95% confidence interval). COVID-19: Coronavirus Disease of 2019. W: week. Analysis of variance (ANOVA): Tukey HSD test ($p < 0.005$): W-preWC vs. [a] W-1WC; [b] W-2WC; [c] W-3WC; [d] W-4WC; [e] W-postWC; W-1WC vs. [f] W-2WC; [g] W-3WC; [h] W-4WC; [i] W-postWC; W-2WC vs. [j] W-3WC; [k] W-4WC; [l] W-postWC; W-3WC vs. [m] W-4WC; [n] W-postWC; [o] W-4WC vs. W-postWC

Confirmed cases in Qatar and in the world

ANOVA analysis revealed significant differences between the six weeks in both Qatar and the world (Table 1, Figure 4).

In Qatar (Table 1, Figure 4A), the mean number of confirmed cases increased significantly during week-3WC and week-4WC compared to : i) week-preWC; ii) week-1WC; and iii) week-2WC. The mean number of confirmed cases decreased significantly during : i) week-4WC and week-postWC compared to week-3WC; and ii) week-postWC compared to week-4WC.

In the world (Table 1, Figure 4B), the mean number of confirmed cases increased significantly during : i) week-1WC to week-4WC and week-postWC compared to week-preWC; ii) week-2WC to week-4WC and week-postWC compared to week-1WC; iii) week-3WC and week-4WC and week-postWC compared to week-2WC; and iv) week-4WC and week-postWC compared to week-3WC. The mean number of confirmed cases was comparable during week-4WC and week-postWC.

Confirmed deaths in Qatar and in the world

ANOVA revealed significant differences between the six weeks in both Qatar and he world (Table 1, Figure 5).

In Qatar (Table 1, Figure 5A), the mean number of confirmed deaths was significantly higher during week-2WC compared to week-

preWC, week-3WC, week-4WC, and week-postWC.

In the world (Table 1, Figure 5B), the mean number of confirmed deaths increased significantly during: i) week-3WC, week-4WC, and week-postWC compared to week-preWC; ii) week-4WC and week-postWC compared to week-1WC; iii) week-3WC, week-4WC, and week-postWC compared to week-2WC; iv) week-4WC and week-postWC compared to week-3WC; and v) week-postWC compared to week-4WC.

Effective R0 in Qatar and in the world

ANOVA analysis revealed significant differences between the six weeks in both Qatar and the world (Table 1, Figure 6).

In Qatar (Table 1, Figure 6A), the mean value of effective R0 i) increased significantly during week-2WC and week-3WC compared to week-preWC and week-1WC; and ii) decreased significantly during week-4WC and week-postWC compared to week-2WC and week-3WC.

In the world (Table 1, Figure 6B), the mean value of effective R0 increased significantly during week-2WC compared to week-preWC. However, the mean value of effective R0 decreased significantly during i) week-postWC compared to week-preWC; ii) week-4WC and week-postWC compared to week-1WC; iii) week-3WC, week-4WC, and week-postWC compared to week-2WC); and iv) week-postWC compared to week-3WC.

DISCUSSION

Our study investigated the potential consequences of the FIFA-WC 2022 for COVID-19 cases, deaths, and R0 in Qatar compared to the global situation. Specifically, we assessed the impact of a large-scale event conducted during the pandemic without implementing any COVID-19 restrictive measures, such as travel restrictions, social distancing, or mask-wearing, in Qatar.

We observed a significant increase in the number of COVID-19 confirmed cases in Qatar during week-3WC and week-4WC of the FIFA-WC 2022 compared to o week-preWC, week-1WC, and week-2WC. Intriguingly, there was a substantial decrease in the average number of cases during week-4WC and week-postWC compared to week-3WC. Furthermore, the increase in positive cases in Qatar was more pronounced than the global trend during the same period.

Mass gathering events have been linked to increased COVID-19 transmission among attendees [1, 2, 4, 5, 13–15]. For example, the Tokyo Olympic Games, held without spectators in July-August 2021, resulted in a surge of positive cases in Japan, prompting the Japanese government to declare an emergency situation during the Olympics. Despite efforts to minimise transmission risk, the highly transmissible Delta variant contributed to a spike in cases, hospitalisations, and deaths [4, 5].

The risk of COVID-19 transmission during large-scale events extends beyond the event venue itself, potentially impacting the home countries of attendees. This was demonstrated during the recent UEFA Euro 2020 tournament, where mass gatherings were followed by a significant increase in COVID-19 cases [13, 14]. For instance, in Finland, the rapid spread of the Delta variant was likely facilitated by travel-related imported cases from Euro 2020 [13, 14].

Interestingly, during the FIFA-WC, the global surge in positive cases followed a similar but less pronounced pattern to that of COVID-19 in Qatar. Mass gatherings occurred not only in Qatar but also worldwide, as families, friends, and sports enthusiasts convened to watch the event. The more pronounced effect in Qatar seems entirely expected due to the massive gathering of national and international fans, which may have facilitated the spread of COVID-19 among attendees in stadiums, fan zones, shopping centres, and other locations.

Our findings also revealed that by the end of the event (i.e. week-postWC), the number of positive cases had decreased, approaching its baseline values. This may be partially attributed to the potential benefits of Qatar's healthcare system readiness during the FIFA-WC, which encompassed the presence of sufficient healthcare workers, the availability of medications, and dedicated COVID-19 hotlines to effectively mitigate the infection rate at mass gatherings [16, 17]. Moreover, Qatar had high vaccination coverage, which may have reduced the severity of infections and the overall number of cases, potentially mitigating the impact of mass gatherings on local COVID-19 transmission.

Qatar's healthcare preparedness, including field hospitals and increased testing and tracing capacities, might also have contributed to early detection and isolation of cases, limiting large-scale outbreaks during the tournament. Furthermore, the study period coincided with the winter season in the Northern Hemisphere, which has been associated with increased respiratory infections, including COVID-19. It is possible that the global increase in cases and deaths during the study period was driven partly by seasonal factors [18], rather than the FIFA-WC itself.

Despite the absence of travel restrictions, social distancing, and mask-wearing measures during the FIFA-WC, other preventive measures, such as hand sanitizers at venues and frequent cleaning of high-touch surfaces, may have reduced the transmission risk. Analysing confirmed COVID-19 cases is essential for identifying the direct impact of the FIFA-WC on viral transmission and assessing the efficacy of public health measures in mitigating infection risk.

Furthermore, our analysis revealed a significant increase in the average number of COVID-19-related deaths in Qatar during week-2WC compared to week-preWC, week-3WC, week-4WC, and week-postWC. This suggests a temporary rise in COVID-19-related deaths during the event. However, it is challenging to establish a direct link between the organization of the event and the observed increase in deaths due to the long incubation period of the COVID-19 virus.

Examining the number of confirmed COVID-19-related deaths provides insight into the severity of the disease and the strain on healthcare systems during and after mass gathering events. An increase in deaths may indicate a higher disease burden and overwhelmed healthcare resources, which could have implications for future event planning and pandemic preparedness. Understanding

the trend in confirmed deaths allows for a more comprehensive evaluation of the overall impact of such events on public health.

Our findings align with a study by Ahammer et al. [19], who investigated the impact of sports events on COVID-19 deaths in the US and the effectiveness of cancelling mass gatherings as a non-pharmaceutical intervention. The study reported that one additional National Basketball Association or National Hockey League game increased the cumulative number of COVID-19 deaths in urban areas and surrounding counties by 10.3%. It is essential to note that the study's results are based on a time when facemasks were uncommon, vaccines were unavailable, and herd immunity had certainly not been reached.

During the Tokyo Olympic Games in Japan, a surge in COVID-19 cases and deaths was observed despite approximately 80% of the population being vaccinated [5]. Our findings suggest that the FIFA-WC in Qatar resulted in a significant number of deaths, but the number of cases was relatively small when compared to previous events such as the Tokyo Olympic Games. Moreover, the death rate in Qatar remained relatively low, below 0.05 per million population, compared to the global rate, ranging from 0.20 to 0.25. Nevertheless, the number of deaths returned to normal after the FIFA-WC. This observation might be attributable to the strength of herd immunity in Qatar compared to the global population, and Qatar's predominantly young, expatriate population, which has an average age of 32.3 years, among other factors [20].

Additionally, our findings revealed that the mean R0 in Qatar increased significantly during week-2WC and week-3WC compared to week-preWC and week-1WC. However, it decreased significantly during week-4WC and week-postWC compared to week-2WC and week-3WC. For the global population, the mean R0 increased significantly during week-2WC compared to week-preWC. The mean R0 decreased significantly during week-postWC compared to week-preWC, week-4WC, and week-postWC compared to week-1WC, week-3WC, week-4WC, and week-postWC compared to week-2WC, and week-postWC compared to week-3WC. These results suggest that there was a notable increase in COVID-19 transmission during the FIFA-WC in Qatar and worldwide. However, the effective R0 began to decline towards the end of the event and afterward, indicating that the increase in transmission was temporary and likely associated with the mass gathering event. The R0, although increasing during the event, remained relatively low, between 0.8 and 1.5, which, along with the reduced fatality rate, was much lower than the R0 observed during other mass gathering events. For example, during the Tokyo Olympic Games, due to the Delta variant, the R0 was higher than 5 [11]. These low R0 rates before, during, and after the FIFA-WC offer valuable insights into the event's low transmission dynamics of COVID-19 and the effectiveness of implemented public health measures in controlling disease spread globally, thanks to herd immunity.

In summary, several factors could have contributed to the observed trends in our study. First, the Qatari government's efforts in implementing strict health and safety standards for the event, including the widespread availability of hand hygiene liquid, dedicated healthcare staff at mass gatherings, and health hotlines for any health issues, might have played a crucial role in mitigating the spread of COVID-19 during the FIFA-WC 2022. Second, Qatar's highly vaccinated population [21], which reached over 90% coverage by the time of the event, might have provided a degree of herd immunity that limited the virus's transmission.

Study limitations

While our study provides valuable insights, it is important to recognize and address its inherent limitations. The first notable limitation pertains to the challenge of establishing causal inference. Given the observational nature of our study, we are unable to definitively establish a causal relationship between the FIFA-WC and the observed fluctuations in COVID-19 cases, fatalities, and R0 values in Qatar. The second limitation stems from the omission of key underlying confounding factors that could exert an influence on our results. Our investigation did not examine other potential contributing factors influencing COVID-19 metrics, such as shifts in public behaviour, vaccination rates, adherence to preventive measures, or unrelated infection control policies. These factors possess the potential to significantly impact the observed trends but remain unexplored in our study. A third limitation is due to discrepancies in data reporting, since our analysis fails to account for potential instances of underreporting, inconsistencies, or variations in data reporting methodologies across different countries. Such variations could potentially introduce bias and influence the precision of our comparative assessments. The fourth limitation revolves around the temporal scope of our study. The data collection window was relatively brief, spanning only a few weeks before, during, and after the FIFA-WC. This limited timeframe might not fully encapsulate the longer-term repercussions of the event on local and global COVID-19 caseloads. The effects of mass gatherings can unfold over the course of weeks or even months as individuals who were exposed return home, potentially triggering fresh outbreaks. In order to comprehensively comprehend the holistic impact of the FIFA-WC on COVID-19 transmission, it is imperative to undertake longitudinal investigations that analyse the prolonged effects on both local and global public health. The fifth limitation involves the extent to which our findings can be generalized. The applicability of our conclusions to other countries or events may be constrained due to the interplay of contextual variables that influence the impact of large-scale events on COVID-19 transmission dynamics. Notwithstanding these five limitations, our study provides valuable insights into the potential public health risks of conducting large events during an ongoing pandemic.

CONCLUSIONS

The FIFA-WC 2022 in Qatar showed that large-scale sporting events can be safely organized during a pandemic with proper measures. Our study highlights the impact of the event on COVID-19 cases and

deaths in Qatar. Despite initial challenges, effective infection control measures and local herd immunity helped control the virus's spread. The study emphasizes the importance of high vaccination coverage, continuous monitoring, and collaboration between organizers, healthcare authorities, and governments. The FIFA-WC 2022 serves as a model for future events, emphasizing evidence-based decision-making and public health preparedness. Further research is needed to understand long-term effects and to refine best practices for event organization during pandemics.

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Data availability statement

The data that support the findings of this study are openly available upon request from the corresponding author.

Declaration of interest

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants, or patents received or pending, or royalties. We declare that no Natural Language Processing or Large Language Model technologies have been used at any phase of the manuscript writing process [22].

REFERENCES

1. Chamari K, Dergaa I, Mujika I, Schumacher YO, Tabben M, Ben Saad H. Football in times of COVID-19: A recapitulation of preventive measures and infection control policies aiming at a safe game environment. Int J Sports Physiol Perform. 2022; 17(9):1448–51. Epub 20220830. doi: 10.1123/ijspp.2022-0254. PubMed PMID: 36041728.
2. Dergaa I, Varma A, Tabben M, Malik RA, Sheik S, Vedasalam S, Abbassi AK, Almulla J, Chaabane M, Chamari K. Organising football matches with spectators during the COVID-19 pandemic: What can we learn from the Amir Cup Football Final of Qatar 2020? A call for action. Biol Sport. 2021; 38(4):677–81. Epub 20210228. doi: 10.5114/biolsport.2021.103568. PubMed PMID: 34937978; PubMed Central PMCID: PMC8670791.
3. Washif JA, Farooq A, Krug I, Pyne DB, Verhagen E, Taylor L, Wong DP, Mujika I, Cortis C, Haddad M, Ahmadian O, Al Jufaili M, Al-Horani RA, Al-Mohannadi AS, Aloui A, Ammar A, Arifi F, Aziz AR, Batuev M, Beaven CM, Beneke R, Bici A, Bishnoi P, Bogwasi L, Bok D, Boukhris O, Boullosa D, Bragazzi N, Brito J, Cartagena RPP, Chaouachi A, Cheung SS, Chtourou H, Cosma G, Debevec T, DeLang MD, Dellal A, Dönmez G, Driss T, Peña Duque JD, Eirale C, Elloumi M, Foster C, Franchini E, Fusco A, Galy O, Gastin PB, Gill N, Girard O, Gregov C, Halson S, Hammouda O, Hanzlíková I, Hassanmirzaei B, Haugen T, Hébert-Losier K, Muñoz Helú H, Herrera-Valenzuela T, Hettinga FJ, Holtzhausen L, Hue O, Dello Iacono A, Ihalainen JK, James C, Janse van Rensburg DC, Joseph S, Kamoun K, Khaled M, Khalladi K, Kim KJ, Kok LY, MacMillan L, Mataruna-Dos-Santos LJ, Matsunaga R, Memishi S, Millet GP, Moussa-Chamari I, Musa DI, Nguyen HMT, Nikolaidis PT, Owen A, Padulo J, Pagaduan JC, Perera NP, Pérez-Gómez J, Pillay L, Popa A, Pudasaini A, Rabbani A, Rahayu T, Romdhani M, Salamh P, Sarkar AS, Schillinger A, Seiler S, Setyawati H, Shrestha N, Suraya F, Tabben M, Trabelsi K, Urhausen A, Valtonen M, Weber J, Whiteley R, Zrane A, Zerguini Y, Zmijewski P, Sandbakk Ø, Ben Saad H, Chamari K. Training during the COVID-19 lockdown: Knowledge, beliefs, and practices of 12,526 athletes from 142 countries and six continents. Sports Med. 2022; 52(4):933–48. Epub 20211023. doi: 10.1007/s40279-021-01573-z. PubMed PMID: 34687439; PubMed Central PMCID: PMC8536915.
4. Dergaa I, Ben Saad H, Souissi A, Musa S, Abdulmalik MA, Chamari K. Olympic Games in COVID-19 times: lessons learned with special focus on the upcoming FIFA world cup Qatar 2022. Br J Sports Med. 2022; 56(12):654–6. Epub 20220301. doi: 10.1136/bjsports-2021-105276. PubMed PMID: 35232751.
5. Dergaa I, Musa S, Romdhani M, Souissi A, Abdulmalik MA, Chamari K, Saad HB. FIFA world cup 2022: What can we learn from the inspiring Tokyo 2020 Olympic Games held in COVID-19 times? Biol Sport. 2022; 39(4):1073–80. Epub 20220210. doi: 10.5114/biolsport.2022.113293. PubMed PMID: 36247947; PubMed Central PMCID: PMC9536391.
6. Washif JA, Sandbakk Ø, Seiler S, Haugen T, Farooq A, Quarrie K, Janse van Rensburg DC, Krug I, Verhagen E, Wong DP, Mujika I, Cortis C, Haddad M, Ahmadian O, Al Jufaili M, Al-Horani RA, Al-Mohannadi AS, Aloui A, Ammar A, Arifi F, Aziz AR, Batuev M, Beaven CM, Beneke R, Bici A, Bishnoi P, Bogwasi L, Bok D, Boukhris O, Boullosa D, Bragazzi N, Brito J, Palacios Cartagena RP, Chaouachi A, Cheung SS, Chtourou H, Cosma G, Debevec T, DeLang MD, Dellal A, Dönmez G, Driss T, Peña Duque JD, Eirale C, Elloumi M, Foster C, Franchini E, Fusco A, Galy O, Gastin PB, Gill N, Girard O, Gregov C, Halson S, Hammouda O, Hanzlíková I, Hassanmirzaei B, Hébert-Losier K, Muñoz Helú H, Herrera-Valenzuela T, Hettinga FJ, Holtzhausen L, Hue O, Dello Iacono A, Ihalainen JK, James C, Joseph S, Kamoun K, Khaled M, Khalladi K, Kim KJ, Kok LY, MacMillan L, Mataruna-Dos-Santos LJ, Matsunaga R, Memishi S, Millet GP, Moussa-Chamari I, Musa DI, Nguyen HMT, Nikolaidis PT, Owen A, Padulo J, Pagaduan JC, Perera NP, Pérez-Gómez J, Pillay L, Popa A, Pudasaini A, Rabbani A, Rahayu T, Romdhani M, Salamh P, Sarkar AS, Schillinger A, Setyawati H, Shrestha N, Suraya F, Tabben M, Trabelsi K, Urhausen A, Valtonen M, Weber J, Whiteley R, Zrane A, Zerguini Y, Zmijewski P, Ben Saad H, Pyne DB, Taylor L, Chamari K. COVID-19 lockdown: A global study investigating the effect of athletes' sport classification and sex on training practices. Int J Sports Physiol Perform. 2022; 17(8):1242–56. Epub 20220708. doi: 10.1123/ijspp.2021-0543. PubMed PMID: 35894967.
7. Gulf times. Easing of travel policy to further boost Qatar's tourism: experts. Available from this URL: https://www.gulf-times.com/story/723804/easing-of-travel-policy-to-further-boost-qatars

-tourism-experts/ (Last visit: August 19th 2023).
8. The independent. Record breaking fan attendance registered in FIFA world cup Qatar 2022. Available from this URL: https://www.independent.co.ug/record-breaking-fan-attendance-registered-in-fifa-world-cup-qatar-2022/ (Last visit: August 19th 2023).
9. FIFA. Nearly 2 million fans from across the world enjoy the FIFA Fan Festival™ in Doha. Available from this URL: https://www.fifa.com/tournaments/mens/worldcup/qatar2022/news/nearly-2-million-fans-from-across-the-world-enjoy-the-fifa-fan-festival-tm/ (Last visit: August 19th 2023).
10. Ministry of public health- state of Qatar. COVID-19 status in Qatar (Last Update: 2023-01-23). Available from this URL: https://www.data.gov.qa/pages/dashboard-covid-19-cases-in-qatar/ (Last visit: August 19th 2023).
11. Our World in data. COVID-19 data explorer. Available from this URL: https://ourworldindata.org/coronavirus#explore-the-global-situation/ (Last visit: August 19th 2023).
12. Delamater PL, Street EJ, Leslie TF, Yang YT, Jacobsen KH. Complexity of the basic reproduction number (R(0)). Emerg Infect Dis. 2019; 25(1):1–4. doi: 10.3201/eid2501.171901. PubMed PMID: 30560777; PubMed Central PMCID: PMC6302597.
13. Dehning J, Mohr SB, Contreras S, Dönges P, Iftekhar EN, Schulz O, Bechtle P, Priesemann V. Impact of the Euro 2020 championship on the spread of COVID-19. Nat Commun. 2023; 14(1):122. Epub 20230118. doi: 10.1038/s41467-022-35512-x. PubMed PMID: 36653337; PubMed Central PMCID: PMC9849464.
14. Sarvikivi E, Salminen M, Savolainen-Kopra C, Ikonen N, Kontio M, Isosomppi S, Jamanca S, Hannila-Handelberg T, Vapalahti O, Smura T, Lappalainen M, Helve O. COVID-19 cases in spectators returning to Finland from UEFA Euro 2020 matches in Saint Petersburg. Epidemiol Infect. 2022; 150:e121. Epub 20220318. doi: 10.1017/S0950268822000437. PubMed PMID: 35300748; PubMed Central PMCID: PMC9254151.
15. Cuschieri S, Balzan M, Gauci C, Aguis S, Grech V. Mass events trigger Malta's second peak after initial successful pandemic suppression. J Community Health. 2021; 46(3):618–25. Epub 20200916. doi: 10.1007/s10900-020-00925-6. PubMed PMID: 32936428; PubMed Central PMCID: PMC7493701.
16. Dergaa I, Chamari K, Farahat RA, Romdhani M, Taheri M, Memish ZA, Al Abdulla SA. Telemedicine during the FIFA world cup 2022: a potential tool to curtail the spread of infectious disease during times of pandemic. Int J Surg. 2023; 109(2):147–9. Epub 20230201. doi: 10.1097/JS9.0000000000000004. PubMed PMID: 36799832; PubMed Central PMCID: PMC10389446.
17. Farahat RA, Setti MO, Benmelouka AY, Ali I, Umar TP, Alabdallat Y, Abdelaal A, Dergaa I. Monkeypox emergence and hosting a safe FIFA World Cup 2022 in Qatar: Challenges and recommendations. Int J Surg. 2022; 106:106935. Epub 20220918. doi: 10.1016/j.ijsu.2022.106935. PubMed PMID: 36130706; PubMed Central PMCID: PMC9533952.
18. Neumann G, Kawaoka Y. Seasonality of influenza and other respiratory viruses. EMBO Mol Med. 2022; 14(4):e15352. Epub 20220214. doi: 10.15252/emmm.202115352. PubMed PMID: 35157360; PubMed Central PMCID: PMC8988196.
19. Ahammer A, Halla M, Lackner M. Mass gatherings contributed to early COVID-19 mortality: Evidence from US sports. Contemp Econ Policy. 2023; 41(3):471–88. doi: 10.1111/coep.12602.
20. Qatar population. Available from this URL: https://www.worldometers.info/world-population/qatar-population/ (Last visit: August 19th 2023).
21. Musa S, Dergaa I, Abdulmalik MA, Ammar A, Chamari K, Saad HB. BNT162b2 COVID-19 vaccine hesitancy among parents of 4023 young adolescents (12–15 Years) in Qatar. Vaccines (Basel). 2021; 9(9). Epub 20210902. doi: 10.3390/vaccines9090981. PubMed PMID: 34579218; PubMed Central PMCID: PMC8473301.
22. Dergaa I, Chamari K, Zmijewski P, Ben Saad H. From human writing to artificial intelligence generated text: examining the prospects and potential threats of ChatGPT in academic writing. Biol Sport. 2023; 40(2):615–22. Epub 20230315. doi: 10.5114/biolsport.2023.125623. PubMed PMID: 37077800; PubMed Central PMCID: PMC10108763.


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