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Pupillometry as a new window to player fatigue? A glimpse inside the eyes of a Euro Cup Women's Basketball team

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ABSTRACT: A rapidly emerging area of interest in high-pressure environments is that of pupillometry, where handheld quantitative infrared pupillometers (HQIPs) are able to track psycho-physiological fatigue in a fast, objective, valid, reliable, and non-invasive manner. However, the application of HQIPs in the context of athlete monitoring is yet to be determined. Therefore, the main aim of this pilot study was to examine the potential usefulness of a HQIP to monitor game-induced fatigue inside a professional female basketball setting by determining its (1) test-retest repeatability, (2) relationship with other biomarkers of game-induced fatigue, and (3) time-course from rested to fatigued states. A non-ophthalmologic practitioner performed a standardized Pupil Light Reflex (PLR) test using a medically graded HQIP among 9 professional female basketball players (2020–2021 Euro Cup) at baseline, 24-h pre-game (GD-1), 24-h post-game (GD+1) and 48-h post-game (GD+2). This was repeated over four subsequent games, equalling a total of 351 observations per eye. Two out of seven pupillometrics displayed good ICCs (0.95–0.99) (MinD and MaxD). Strong significant relationships were found between MaxD, MinD, and all registered biomarkers of game-induced fatigue ($r = 0.69–0.82$, $p < 0.05$), as well as between CV, MCV, and cognitive, lower-extremity muscle, and physiological fatigue markers ($r = 0.74–0.76$, $p < 0.05$). Three pupillometrics were able to detect a significant difference between rested and fatigued states. In particular, PC (right) ($F = 5.173$, $\eta^2 = 0.115$ $p = 0.028$) and MCV (right) ($F = 3.976$, $\eta^2 = 0.090$ $p = 0.049$) significantly decreased from baseline to GD+2, and LAT (left) ($F = 4.023$, $\eta^2 = 0.109$ $p = 0.009$) significantly increased from GD-1 to GD+2. HQIPs have opened a new window of opportunity for monitoring game-induced fatigue in professional female basketball players. However, future research initiatives across larger and heterogenous samples, and longer investigation periods, are required to expand upon these preliminary findings.

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INTRODUCTION

In high-performance sports, excessive levels of fatigue can inhibit the desired adaption to training, increase injury risk, and potentially hinder athletic performance [1]. Therefore, continuously exploring new ways to quantify player readiness is considered a priority within elite sporting organizations [1, 2]. In light of this pursuit, numerous fatigue monitoring tools have emerged [1, 2]. However, from a practical perspective, traditional fatigue monitoring tools often remain exhaustive (e.g., maximal-effort physical testing) [2, 3], subjective (e.g., self-reported questionnaires) [2, 4], invasive (e.g., blood sampling) [2, 5], expensive (e.g., electroencephalogram) [2, 6], or relatively slow to conduct (e.g., 5-min recordings of heart rate indices in standing and lying postures) [7]. Hence, there's an ongoing need for innovative solutions that enable real-time, multi-modal, non-invasive, cost-effective, valid, and reliable insights into player fatigue, and in turn, improve the day-to-day decision-making processes of coaches and support staff personnel [1, 2].

Some of the most promising innovations to date in this space have emerged from collaborative initiatives between engineers, developers, scientists, and practitioners who operate in high-pressure environments (i.e., transatlantic flights, space shuttle missions, military combat, medical surgery, long-haul truck driving, etc.) as a lack of operational readiness in these positions could lead to lethal consequences [8, 9, 10]. Consequently, pupillometry has gained a rapid surge in interest by the research community across high-stake industries [9, 10]. Pupillometry can be defined as the study of the the central opening of the iris through which light passes before reaching the lens and being focused onto the retina [11]. Because the pupils are directly innervated by the second cranial nerve (CN II) and third cranial nerve (CN III) [11], measuring pupil reflexes provides an objective representation of the autonomic nervous system (ANS) [12–15] as well as cognitive, emotional, physical, and physiological status in real time [16, 17, 18]. Since the first discovery of pupillometry as a human fatigue detection tool in 1936 [19], the field has rapidly advanced in recent years due to the emergence of Handheld Quantitative Infrared Pupillometers (HQIPs) [19, 20, 21, 22]. In particular, HQIPs are now able to repeatedly measure the pupil diameter (1 measurement every 30 ms) with a minimum detectable change of < 0.03 mm (i.e., practical error of 0.88% in relation to the average pupil diameter) [22, 23]. Consequently, a vast range of Intensive Care Units (ICUs) settings [24] and high-stake occupations are progressively integrating HQIPs as a first-point-of-care instrument [25, 26, 27].

Surprisingly, the use of modern HQIPs in professional sports remains bounded by a few use cases (e.g., concussion-related diagnostics [28, 29, 30] and "quiet eye" analytics [31]). While some researchers have introduced HQIPs as a method to evaluate ANS function in athletes [12, 14, 15], the validity and reproducibility of their methods and findings remains unclear. For instance, the investigations typically followed a cross-sectional study design, adopted non-standardized and non-validated pupil testing procedures, executed in laboratory conditions, and involved only amateur and subelite athletes. Besides the application of HQIPs to monitor ANS function, researchers have also demonstrated its effectiveness to monitor cognitive effort (i.e., pupil dilation can be viewed as an indirect index of effort in cognitive control tasks across the domains of updating, switching and inhibition) [32]. This could imply an important discovery as player performance and fatigue originates from the complex state of both physiological and psychological processes [33]. Hence, HQIPs may potentially reveal itself as a multi-model at monitoring instrument.

Acknowledging the inherent potential of HQIPs, and appreciating the efforts made by previous researchers on this research line, this pilot study aims to explore the potential usefulness of a medically graded HQIP to monitor game-induced fatigue in nine professional female basketball players by determining (1) the test-retest repeatability, (2) the relationship between pupillometrics and other biomarkers of game-induced fatigue, and (3) the time-course of pupillometrics from baseline and 24 h before games up to 24 h and 48 h following games. In turn, the reported baseline findings and methodological framework may serve as a valuable reference for future research initiatives on this topic.

MATERIALS AND METHODS

Experimental approach to the problem

This pilot study followed a prospective observational study design and was conducted in non-experimental conditions, so the coaching staff, support staff personnel, and participants did not receive any input from the research team. Training data, competitive schedule and fixture outcomes were supplied by the coaching staff of the team. Two weeks prior to the investigation period, a baseline pupil test was performed after two consecutive off days (i.e., no scheduled or organized practices or workouts during these days) to optimize physical and psychological recovery. Subsequently, the participants played four home games over a 5-week investigation period (1 week apart, all games commenced between 8:00 – 8:30 PM). For each game, a pupil testing sequence was executed at the following timepoints: 24-h pre-game (GD-1), 24-h post-game (GD+1), and 48-h post-game (GD+2). All pupil tests were completed and performed inside a standard clinical testing room during regular pre-practice physiotherapy session hours (6:00 PM – 7:30 PM) to emulate a standardized clinical testing time and environment.

Participants

Nine female Belgian professional basketball players (n = 9) competed in the 2020–2021 Euro Cup Women's Basketball Tournament and voluntarily participated in this study. All participants were aged 18 years or older (range: 18–33 years; mean age: 21.20 ± 4.92 years), with a mean height of 181 ± 5.36 (cm) and body mass of 80.61 ± 10.73 (kg). Based on positional groupings: 45% were grouped as Posts, 33% as Guards, and 22% as Wings. Based on the role: 55% were starters and 45% non-starters.

Players were not eligible to participate when they encountered at least one of the following criteria: < 18 years of age; unable to participate in individual and/or team practices due to injury or illness at any point of the investigation period; unable to sit for testing; history in genetic syndromes, neurologic pathologies (including intracranial masses) or intraocular pathologies that would affect pupillary function (e.g. uveitis, cataracts, diabetes, glaucoma, optic nerve dysfunction); ingestion of alcoholic and/or caffeinated foods, drinks, or substances within < 12 h of any pupil examinations; use of ergogenic aids and/or medical support that may have altered the neurophysiological state of the athlete at any point of the investigation period. Prior to the investigation, this study was approved by the Institutional Review Board of UCAM University, Murcia, Spain (code: CE122002) and conformed to the requirements of the European Union General Data Protection Regulation and United States Health Insurance Portability and Privacy Act with adherence to the tenets of the Declaration of Helsinki with Fortaleza actualization 2013 [34]. All test procedures strictly adhered to the World Health Organization (WHO), European Commission, and local government safety guidelines regarding scientific research during the COVID-19 pandemic.

Testing procedure

To verify whether any pupillometrics could detect a significant change in game-induced fatigue and recovery, participants were instructed to go through a comprehensive fatigue test battery at each allocated timepoint (i.e., baseline, GD-1, GD+1, GD+2). The fatigue test battery consisted of the pupil test in combination with four other fatigue tests: cognitive fatigue test (i.e., visuomotor reaction time) [35, 36], lower-extremity muscle fatigue test (standing postural sway) [37, 38], perceptual fatigue test (self-perceived exertion) [38], and ANS fatigue test (heart rate variability indices) [40–44]. More specifically, upon arrival to the clinical testing room, the player was instructed to wear the Polar H10 heart rate chest strap (Polar

Electro Oy, Kempele, Finland) and complete a 5-min heart rate variability (HRV) test in rested condition and seated posture using the EliteHRV software (Asheville, NC, United States) [44] on an iPhone SE (Apple Inc., Los Altos, California, United States). The Polar H10 was selected based on its underlying support as a medically graded heart rate sensor [40, 41] and the EliteHRV was selected based on its ability to record, store, and export HRV data in a secure and user-friendly manner [44]. Particularly, the natural log of the root-mean-square difference of successive normal RR intervals (ln-RMSSD) was used for HRV analyses given its well-documented support for monitoring physiological fatigue in young female basketball players [41] as well as numerous other sport athletes [43]. Following the HRV test, the player completed two subsequent Sway tests using the Sway Medical, Inc. software (Tulsa, Oklahoma, United States) [35–38] via touch screen display as well as tri-axial accelerometry (i.e., motion detection) on an iPad (6^{th} generation) by Apple Inc. (Los Altos, California, United States). The Sway test protocols have been established as an objective and reliable method for assessing reaction time, impulse control, timed visual processing, and working memory [35–38]. Particularly, the first Sway test examined the cognitive fatigue status through the Simple Reaction Time (SRT) test (ms) [35]. During this test, the player held the iPad horizontally (landscape mode) and moved it as fast possible in any direction when the screen display changed from a white to orange color. Each SRT test started after a variable delay of 2–4 s in order to prevent the player from anticipating the stimulus ahead of time. Each player completed five trials. The fastest and the slowest SRT scores were excluded in order to remove outliers and reflect only the typical response times of the player [34]. Subsequently, the scores of the three remaining trials were averaged to calculate the individual score for each player. Following the SRT test, the player performed the Sway Balance test, which quantified postural sway during the performance of a series of tasks to reflect lower-extremity muscle fatigue [45]. Specifically, the Sway Balance test consisted of five stance conditions (10-s in duration per stance) on a firm surface and with the eyes closed. The postural sway was quantified through the iPad's triaxial accelerometer, and the units that corresponded with the accelerations were used to calculate the final proprietary Sway Balance score [38].

Subsequently, the test administrator manually performed the standard Pupil Light Reflex (PLR) test [12, 28] in each player's eye respectively, using the NeurOptics NPi-200 pupillometer (NeurOptics, Laguna Hills, CA, U.S.A.), a medically graded HQIP (Class I medical device as listed under 21CFR 886.1700) [11, 46]. More specifically, this HQIP integrated a calibrated full-field white light stimulus with peak wavelengths comprised of red, green, and blue at a fixed intensity (1000 Lux) and fixed flash duration (0.8 s) to simulate a standard pupil light reflex (PLR) [11, 46]. Subsequently, this HQIP digitally registered the pupil light response as a video (sampling rate of 30 Hz) for a duration of 3.5 s, followed by a display of numeric results on a screen for each eye respectively [11, 46]. The device highlighted an outline of the pupil and graphed its displacement over time with an accuracy of 0.03 mm (i.e., practical error of 0.88% in relation to the average pupil diameter) [11, 46]. Scotopic lighting conditions (434–440 lumen/m^2) were verified prior to each pupil exam by measurement of luminance of less than 2 Lumens with a luminometer (Dr. Meter LX1330B Digital Illuminance/Light Meter, Hisgadget, Union City, CA, U.S.A.) at the level of the players' eyes. Furthermore, normal forehead temperature was measured and controlled (35.4 °C to 37.4 °C) prior to each test via a forehead thermometer (iProven DMT-489, Beaverton, Oregon, U.S.A.). Each pupil test was conducted sitting stationary looking straight ahead. Each player was prompted to maintain a forward head posture and binocular viewing conditions in a seated position throughout the test. The non-test eye was fixated on a neutral wall at 3-m distance to the chair's front leg. The right eye was tested first, immediately followed by the left eye. This sequence was completed three consecutive times using 60-s intervals to allow sufficient recovery of the pupil before the next light stimulus [11, 46, 47]. A retest was taken

TABLE 1. Descriptions of All Pupillometrics.

	Pupillometrics	Units	Description
MaxD	Maximum Diameter	Mm	Maximum pupil size before constriction.
MinD	Minimum Diameter	Mm	Pupil diameter at peak constriction.
PC	Percentage of Change	%	The change in pupil size over time, computed as: $PC = \left(\frac{MaxD - MinD}{MaxD}\right) * 100$
LAT	Latency	mm/s	Time of onset of constriction following initiation of the light stimulus.
CV	Constriction Velocity	mm/s	Average of how fast the pupil is constricting after exposure to light.
MCV	Maximum Constriction Velocity	mm/s	Represents the maximum velocity of pupil constriction.
DV	Dilation Velocity	mm/s	The average pupillary velocity when, after having reached the peak constriction, the pupil tends to recover and dilate back to the initial resting size.

whenever the HQIP was held incorrectly, or blinking was detected by the HQIP. All pupil tests were relatively quick to conduct and did not exceed ~4 min in duration per player, and ~60 min in total duration for the entire team. Notably, ease of use was reported by the test administrator (i.e., performance coach without previous clinical experience in using HQIPs). In particular, a total of 351 pupillary measurements were recorded in each eye, without any interference with the daily predetermined schedule of the team.

The selected HQIP extracted seven pupillometrics, which represented parameters of both the Sympathetic Nervous System (SNS) function and Parasympathetic Nervous System (PNS) function [11]. Furthermore, the HQIP used an algorithm to calculate the overall reactivity of the pupil (proprietary score), called the Neurological Pupil Index (NPi) [11]. However, the authors excluded the NPi pupillometric from the final analyses as the company did not publicly provide any details on the computation of the NPi. Descriptions and calculations for the seven remaining pupillometrics are presented in Table 1.

Finally, within < 1 h following any practice or game, the players completed an online survey to record their RPE score based on Borg's rate of perceived recovery status scale of 100 points [38], in which 0 means 'very poorly recovered/extremely tired,' 20 represents 'poorly recovered/very tired,' 40 means 'minimally recovered/ tired,' 50 denotes 'slightly recovered/somewhat tired,' 60 signifies 'moderately recovered,' 80 represents 'well recovered,' and 100 represents 'very well recovered/highly energetic' [39].

Statistical Methods

Prior to the statistical analyses, normal distribution of the dataset was confirmed (Shapiro-Wilkinson test; n > 50). Participant demographic information, including: age, height, body mass, playing position and role were calculated using descriptive statistics. The pupillometrics were compared between the left and the right eye through a paired t-test. The intraclass correlation coefficients (ICCs) were computed to examine test-retest reliability for each pupillometric using the thresholds outlined by Martins et al. (2014) for the assessment of technological equipment in research and clinical practice: very poor: ICC < 0.70, poor: ICC = 0.70–0.90, moderate: ICC = 0.90–0.95, good: ICC = 0.95–0.99, and very good: ICC > 0.99 [48]. The Pearson's Product Moment Correlation (r) examined the linear relationship between each pupillometric and various other measures of game-induced fatigue and recovery, including: perceptual fatigue (i.e., average daily Borg Rating of Perceived Exertion scores) [39], lower-extremity muscle fatigue (i.e., Sway Balance Error Scoring System test scores) [45]; cognitive fatigue (i.e., Sway reaction time score) [34], and ANS fatigue (i.e., lnRMSSD) [42]. The Pearson's correlation coefficients were interpreted using the reference standards by Hopkins et al. (2009): trivial: $r < 0.1$; small: $0.1 < r < 0.3$; moderate: $0.3 < r < 0.5$; large: $0.5 < r < 0.7$; very large: $0.7 < r < 0.9$; nearly perfect: $r > 0.9$; perfect: $r = 1$ [49, 50]. To explore whether any pupillometrics differed between rested conditions (baseline and GD-1) and fatigued conditions (GD+1 and GD+2) at the group level, the Levene test was applied as a derivation of the classical one-way analysis of the variance (ANOVA) to compute the F-statistics, Effects sizes (expressed as "η^2" or Eta Squared), Coefficient of Variation (CV), absolute and relative differences, Confidence Intervals at 95% (CI95), and p-values. The post-hoc Tukey test was examined for pairwise comparisons. The η^2 was interpreted with the following thresholds: small effect: $\eta^2 = 0.01$; medium effect: $\eta^2 = 0.06$; large effect: η2 = 0.14 [49, 50]. Additionally, the magnitude of these differences were visually presented by a 'percentage difference' in which postgame data (value) was subtracted by either baseline data or pregame data (value) represents, and divided by the baseline or pregame data (value). The significance of all inferential statistics was set for $p < 0.05$. All analyses were performed at 95%-Confidence Interval. All statistical tests were performed using IBM SPSS Version 28.0.0.0.

RESULTS

Descriptive statistics

A paired sample t-test revealed statistically significant difference between left and right eye pupillometrics at the group level (mean difference = -0.034; *p*-value < 0.001). Therefore, all statistical tests and analyses were performed and analyzed for each eye separately. The normative data (means and standard deviations) of all pupillometrics (at the group level) of both eyes are displayed in Table 2a and Table 2b.

Test-retest repeatability

Table 3 displays the ICC's of all pupillometrics, which range from very poor to good (0.286 to 0.963). Particularly, LAT, DV, and MCV showed very poor ICCs (< 0.70), whereas CV and PC showed poor ICCs (0.70–0.90). However, MinD (left eye), and MaxD (both eyes) showed good ICCs (0.95–0.99). Minimal measurement bias was detected for all pupillometrics with the maximum bias for the left eye being +2.9% (MaxD) and right eye being +1.98% (MaxD). The average bias across all pupillometrics was 0.001 ± 0.450. When comparing baseline (BL) to post-game (GD+1 and GD+2) timepoints, the smallest read difference (SRD) was widest for MaxD (R = 0.340; L = 0.318) and MCV (R = 0.304; L = 0.263), and least for LAT (R = 0.005; L = 0.005) and DV (R = 0.074; L = 0.085). When comparing pre-game (GD-1) to post-game (GD+1 and GD+2) timepoints, the SRD was widest for MaxD (R = 0.285; L = 0.266) and MCV (R = 0.249; L = 0.199) and least for LAT (R = 0.007; L = 0.007) and DV (R = 0.066; L = 0.068).

Relationships with other biomarkers of game-induced fatigue

With regards to perceptual fatigue, the findings demonstrated a very large positive significant correlation between average RPE and MinD ($r = 0.78$, $p < 0.05$) and MaxD ($r = 0.77$, $p < 0.05$). With regards to lower-extremity muscle fatigue, Sway Balance (left and right) showed a very large positive significant association with MaxD, MinD,

TABLE 2A. Descriptive statistics of all pupillometrics (right eye).

		N	Mean	Std. Deviation	Std. Error	95% CI		Min	Max
						Lower Bound	Upper Bound		
MaxD (right)	GD-1	35	6.3223	1.02479	.17322	5.9703	6.6743	4.01	8.11
	GD+1	35	6.3500	1.01662	.17184	6.0008	6.6992	3.97	7.91
	GD+2	34	6.3224	1.06745	.18307	5.9499	6.6948	4.16	8.22
	Baseline	8	6.4775	1.06054	.37496	5.5909	7.3641	4.63	7.97
	Total	112	6.3421	1.02446	.09680	6.1502	6.5339	3.97	8.22
MinD (right)	GD-1	35	3.9794	.76203	.12881	3.7177	4.2412	2.58	5.85
	GD+1	35	3.9837	.69930	.11820	3.7435	4.2239	2.58	5.23
	GD+2	34	4.0256	.73358	.12581	3.7696	4.2815	2.62	5.65
	Baseline	8	3.8788	.76868	.27177	3.2361	4.5214	2.74	5.38
	Total	112	3.9876	.72542	.06855	3.8518	4.1234	2.58	5.85
PC (right)	GD-1	35	.3720	.03437	.00581	.3602	.3838	.28	.44
	GD+1	35	.3769	.03151	.00533	.3660	.3877	.32	.44
	GD+2	34	.3703	.03389	.00581	.3585	.3821	.27	.42
	Baseline	8	.4013	.03796	.01342	.3695	.4330	.32	.43
	Total	112	.3751	.03404	.00322	.3687	.3815	.27	.44
CV (right)	GD-1	35	3.2737	.46457	.07853	3.1141	3.4333	2.38	4.37
	GD+1	35	3.3029	.42080	.07113	3.1583	3.4474	2.37	4.23
	GD+2	34	3.2750	.45240	.07759	3.1171	3.4329	2.42	4.13
	Baseline	8	3.4250	.46605	.16477	3.0354	3.8146	2.65	4.08
	Total	112	3.2940	.44317	.04188	3.2110	3.3770	2.37	4.37
MCV (right)	GD-1	35	5.3266	.77629	.13122	5.0599	5.5932	3.49	6.52
	GD+1	35	5.1871	1.10929	.18750	4.8061	5.5682	.63	7.04
	GD+2	34	5.2035	.66672	.11434	4.9709	5.4362	4.02	6.37
	Baseline	8	5.7250	.66002	.23335	5.1732	6.2768	4.85	6.61
	Total	112	5.2741	.86056	.08132	5.1130	5.4352	.63	7.04
LAT (right)	GD-1	35	.2131	.02898	.00490	.2032	.2231	.17	.30
	GD+1	35	.2223	.02787	.00471	.2127	.2319	.17	.27
	GD+2	34	.2147	.02135	.00366	.2073	.2222	.17	.27
	Baseline	8	.2150	.01604	.00567	.2016	.2284	.20	.23
	Total	112	.2166	.02573	.00243	.2118	.2214	.17	.30
DV (right)	GD-1	31	1.4132	.25639	.04605	1.3192	1.5073	1.02	2.28
	GD+1	34	1.3756	.20289	.03480	1.3048	1.4464	.90	1.82
	GD+2	32	1.3850	.24336	.04302	1.2973	1.4727	.97	2.14
	Baseline	7	1.4343	.24845	.09391	1.2045	1.6641	1.18	1.84
	Total	104	1.3937	.23263	.02281	1.3484	1.4389	.90	2.28

TABLE 2B. Descriptive statistics of all pupillometrics (left eye).

		N	Mean	Std. Deviation	Std. Error	95% CI		Min	Max
						Lower Bound	Upper Bound		
MaxD (left)	GD-1	35	6.0817	.99069	.16746	5.7414	6.4220	3.49	7.68
	GD+1	35	6.0891	.95812	.16195	5.7600	6.4183	3.65	7.56
	GD+2	34	6.1238	.97442	.16711	5.7838	6.4638	3.94	7.85
	Baseline	8	6.2650	1.03907	.36737	5.3963	7.1337	4.39	7.73
	Total	112	6.1099	.96662	.09134	5.9289	6.2909	3.49	7.85
MinD (left)	GD-1	35	3.7314	.64574	.10915	3.5096	3.9532	2.34	5.21
	GD+1	35	3.6911	.60097	.10158	3.4847	3.8976	2.45	4.92
	GD+2	34	3.7662	.63090	.10820	3.5460	3.9863	2.48	5.20
	Baseline	8	3.7687	.66827	.23627	3.2101	4.3274	2.77	4.95
	Total	112	3.7321	.62115	.05869	3.6157	3.8484	2.34	5.21
PC (left)	GD-1	35	.3851	.03568	.00603	.3729	.3974	.30	.44
	GD+1	35	.3929	.03259	.00551	.3817	.4041	.32	.47
	GD+2	34	.3847	.02339	.00401	.3765	.3929	.34	.44
	Baseline	8	.3975	.02964	.01048	.3727	.4223	.36	.44
	Total	112	.3883	.03087	.00292	.3825	.3941	.30	.47
CV (left)	GD-1	35	3.3491	.56844	.09608	3.1539	3.5444	1.60	4.21
	GD+1	35	3.2971	.45486	.07689	3.1409	3.4534	2.18	4.16
	GD+2	34	3.3165	.46990	.08059	3.1525	3.4804	2.17	4.32
	Baseline	8	3.4075	.56835	.20094	2.9323	3.8827	2.23	3.96
	Total	112	3.3271	.49930	.04718	3.2337	3.4206	1.60	4.32
MCV (left)	GD-1	35	5.4780	.81903	.13844	5.1967	5.7593	3.20	6.67
	GD+1	35	5.3737	.77775	.13146	5.1065	5.6409	3.45	6.77
	GD+2	34	5.3509	.73337	.12577	5.0950	5.6068	3.64	6.91
	Baseline	8	5.6800	1.02745	.36326	4.8210	6.5390	3.94	7.18
	Total	112	5.4213	.79076	.07472	5.2732	5.5693	3.20	7.18
LAT (left)	GD-1	35	.2320	.02753	.00465	.2225	.2415	.20	.27
	GD+1	35	.2186	.02992	.00506	.2083	.2288	.17	.27
	GD+2	34	.2118	.02167	.00372	.2042	.2193	.17	.27
	Baseline	8	.2063	.03420	.01209	.1777	.2348	.13	.23
	Total	112	.2198	.02828	.00267	.2145	.2251	.13	.27
DV (left)	GD-1	34	1.3765	.24277	.04164	1.2918	1.4612	.96	1.84
	GD+1	33	1.3009	.21842	.03802	1.2235	1.3784	.87	1.79
	GD+2	33	1.3936	.24903	.04335	1.3053	1.4819	.94	2.09
	Baseline	7	1.5057	.43412	.16408	1.1042	1.9072	.82	2.04
	Total	107	1.3669	.25499	.02465	1.3180	1.4158	.82	2.09

TABLE 3. ICC scores for all 7 pupillometrics

Pupillometrics	ICCs (CI_{95})	
	Right	Left
MaxD (mm)	0.955 (0.937–0.968)**	0.963 (0.949–0.974)**
MinD (mm)	0.945 (0.920–0.962)**	0.955 (0.935–0.970)**
PC (%)	0.756 (0.680–0.819)**	0.749 (0.674–0.813)**
CV (mm/sec)	0.755 (0.679–0.818)**	0.827 (0.770–0.873)**
MCV (mm/sec)	0.626 (0.528–0.714)**	0.667 (0.575–0.748)**
LAT (sec)	0.452 (0.335–0.566)**	0.287 (0.165–0.413)**
DV (mm/sec)	0.501 (0.379–0.616)**	0.656 (0.558–0.742)**

** p < 0.001

TABLE 4. Pearson's correlation coefficients between the 7 pupillometrics and other biomarkers of game-induced fatigue and recovery.

Pupillometrics	Sway SRT	lnRMSSD	Sway Balance (Right)	Sway Balance (Left)	Average RPE
MaxD	**0.70***	**-0.82***	**0.77***	**0.79***	**0.77***
MinD	**0.69***	**0.77***	**0.78***	**0.78***	**0.78***
PC	-0.17	0.22	-0.28	-0.20	0.28
CV	-0.62	**0.74***	**-0.75***	**-0.75***	0.45
MCV	-0.62	**0.74***	**-0.75***	**-0.76***	0.44
Lat	0.14	-0.22	-0.10	-0.10	0.10
DV	-0.20	0.22	-0.10	0.00	0.24

* Coefficients presented in bold are significant (p < 0.05)

CV, and MCV ($r = 0.75–0.78$, $p < 0.05$). With regards to cognitive fatigue, a large significant positive relationship was identified between Sway SRT scores and MinD ($r = 0.69$, $p > 0.05$) and a very large significant positive relationship between Sway SRT scores and MaxD ($r = 0.70$, $p > 0.05$). Finally, with regards to physiological fatigue, a very large positive significant relationship was detected between lnRMSSD scores and MinD ($r = 0.77$, $p < 0.05$), CV ($r = 0.74$, $p < 0.05$), and MCV ($r = 0.74$, $p < 0.05$) whereas a very large inverse significant relationship was found between MaxD and lnRMSSD ($r = -0.82$, $p < 0.05$) (Table 4). All significant correlations have been highlighted in bold in table 4. Overall, the combination of MaxD, MinD, CV and MCV demonstrated to be the most representative of overall game-induced fatigue.

Time course of pupillometrics following games (at the group level)

Initially, the ANOVA analysis revealed that there was no statistically significant difference in pupillometrics between rested states (baseline and GD-1) and fatigued states (GD+1, GD+2) ($p < 0.05$), except for LAT (left) in which a medium-to-large difference was detected ($F = 4.023$, $\eta^2 = 0.109$ $p = 0.009$). In particular, a post-hoc Tukey HSD test revealed that LAT (left) on GD-1 (0.232 ± 0.027 mm/s) was significantly higher than on GD+2 (0.212 ± 0.216 mm/s) (mean difference = 0.202, std. error = 0.006, $p = 0.013$, $\eta^2 = 0.101$), thus the time from onset of the light stimulus to pupil constriction in the left eye typically took longer on GD-1 than on GD+2. Although LAT (left) was the only pupillometric that could detect a statistically significant change between rested conditions and fatigued conditions ($p < 0.05$), small-to-moderate effect sizes were detected for PC (right) ($\eta^2 = 0.052$, $p = 0.121$), MCV (right) ($\eta^2 = 0.026$, $p = 0.410$), LAT (right) ($\eta^2 = 0.023$, $p = 0.470$), PC (left) ($\eta^2 = 0.021$, $p = 0.518$), and MCV (left) ($\eta^2 = 0.013$, $p = 0.587$). All other pupillometrics showed very small ($\eta^2 < 0.01$) and non-significant effects ($p > 0.05$) across all timepoints. With regards to the magnitude of change between timepoints (% difference using Equation 1), the largest differences were found between baseline and GD+2, in which MCV (both eyes) represented the largest relative difference (left = -7.77%; right = -5.64%) (Table 5a and 5b; Figure 1).

TABLE 5A. ANOVA results of the pupillometric changes between baseline (BL) and post-game timepoints (GD+1 and GD+2)

ANOVA results	BL to GD+1					BL to GD+2				
	Mean Difference	*Std. Error*	*F*	η^2	*p*	*Mean Difference*	*Std. Error*	*F*	η^2	*p*
MaxD (mm) (R)	.127	.406	.101	.002	.752	.155	.407	.137	.003	.713
MinD (mm) (R)	-.104	.287	.142	.003	.709	-.146	.288	.255	.006	.616
PC (%) (R)	.024	.013	3.623	.081	.064	**.030**	**.013**	**5.173**	**.115**	**.028**
CV (mm/s) (R)	.122	.175	.528	.013	.472	.150	.175	.704	.017	.406
MCV (mm/s) (R)	.537	.337	1.884	.040	.197	**.521**	**.338**	**3.976**	**.090**	**.049**
LAT (s) (R)	-.007	.010	0.502	.012	.483	.000	.010	.001	.000	.971
DV (mm/s) (R)	.058	.097	.451	.011	.506	.049	.981	.234	.006	.631
MaxD (mm) (L)	.175	.383	.213	.005	.647	.141	.384	.133	.003	.718
MinD (mm) (L)	.077	.246	.104	.003	.748	.002	.247	.000	.000	.992
PC (%) (L)	.004	.012	.136	.003	.714	.012	.012	1.752	.042	.193
CV (mm/s) (L)	.110	.197	.350	.008	.557	.091	.198	.225	.006	.638
MCV (mm/s) (L)	.306	.312	.896	.021	.349	.329	.312	1.116	.027	.297
LAT (s) (L)	-.012	.010	1.050	.025	.312	-.005	.010	.333	.008	.567
DV (mm/s) (L)	.204	.168	3.464	.084	.070	.112	.169	.885	.023	.353

* Coefficients presented in bold are significant ($p < 0.05$)

TABLE 5B. ANOVA results of the pupillometric changes between pre-game (GD-1) and post-game timepoints (GD+1 and GD+2)

ANOVA results	GD-1 to GD+1					GD-1 to GD+2				
	Mean Difference	*Std. Error*	*F*	η^2	*p*	*Mean Difference*	*Std. Error*	*F*	η^2	*p*
MaxD (mm) (R)	-.028	-.248	.013	.000	.910	-.000	.249	.000	.000	1.000
MinD (mm) (R)	-.004	.175	.001	.000	.981	-.046	.176	.066	.001	0.799
PC (%) (R)	-.004	.008	.380	.006	.540	.001	.008	.430	.001	0.836
CV (mm/s) (R)	-.029	.106	.076	.001	.784	-.001	.107	.000	.000	0.991
MCV (mm/s) (R)	.139	.205	.371	.005	.544	.123	.207	.498	.007	0.483
LAT (s) (R)	-.009	.006	1.810	.026	.183	-.001	.010	.065	.001	0.800
DV (mm/s) (R)	.037	.058	.435	.007	.512	.028	.059	.201	.003	0.656
MaxD (mm) (L)	-.007	.233	.001	.000	.975	-.042	.235	.032	.000	0.859
MinD (mm) (L)	.040	.150	.073	.001	.788	-.034	.151	.051	.001	0.822
PC (%) (L)	-.007	.007	.892	.013	.348	.000	.007	.004	.000	0.952
CV (mm/s) (L)	.052	.120	.179	.003	.674	.032	.121	.068	.001	0.796
MCV (mm/s) (L)	.104	.190	.298	.004	.587	.104	.190	.460	.007	0.500
LAT (s) (L)	.013	.006	3.819	.053	.055	**.020**	**.006**	**11.469**	**.146**	**0.001**
DV (mm/s) (L)	.075	.061	1.790	.027	.186	-.017	.061	.82	.001	0.776

* Coefficients presented in bold are significant ($p < 0.05$).

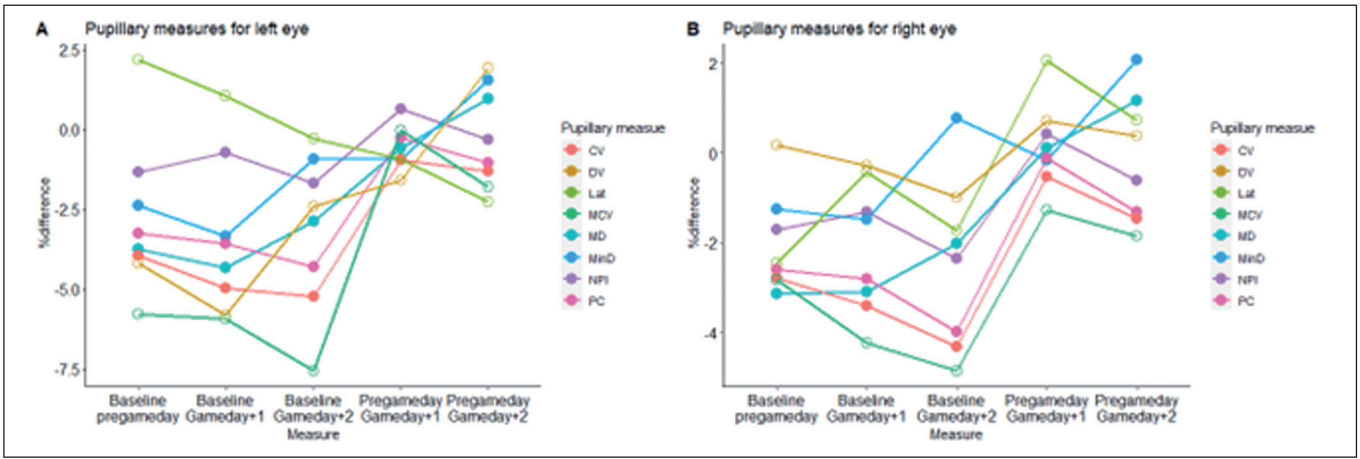

FIG. 1. The percentage difference of pupillometrics between test moments.

DISCUSSION

The main purpose of this pilot study was to explore the potential usefulness of HQIPs in the context of monitoring game-induced fatigue in professional female basketball players. The reported findings may not only serve as a benchmark for future comparisons and hypothesis testing in athletic populations that includes PLR data from automated pupillometry, but also provide point estimates and variance for PLR measures, as well as inferential statistics to describe the effect of game-induced fatigue on pupillary behaviour, when used in naturalistic elite sports environment. Overall, the main findings of this pilot study suggest that (1) two out of seven pupillometrics represented good repeatability scores (MinD and MaxD) (ICC = 0.95–0.99), (2) Statistical significant relationships were found between MaxD, MinD, and all other biomarkers of game-induced fatigue ($r = 0.69$–0.82, $p < 0.05$), as well as between CV, MCV, and biomarkers of cognitive, lower-extremity muscle, and physiological game-induced fatigue ($r = 0.74$–0.76, $p < 0.05$), and (3) Statistically significant differences were found between rested and fatigued states for three pupillometrics: PC (right) and MCV (right), and LAT (left) ($p < 0.05$).

The test-retest repeatability

In response to the first research question, good ICCs were reported for two out of seven pupillometrics, in particular: MinD (left) and MaxD (left and right) (0.95–0.99). Conversely, poor ICCs were reported for CV and PC (0.70–0.90) and very poor ICCs were reported for LAT, DV, and MCV (< 0.70). Nevertheless, the smallest read difference was extremely narrow for LAT in both eyes (0.005–0.007) as well as DV in both eyes (0.066–0.085). Therefore, the quantification of the maximum and minimum pupil diameter seem to be least prone to errors or noise due to external factors when examining professional female basketball players. However, this remains to be questioned as to the best of the authors knowledge, Swanson et al. (2017) [51] were the only researchers that provided open access to ICC results from PLR tests using the Neuroptics NPi-200 in an athletic population (i.e., 186 collegiate athletes across eight sports) [51]. Unfortunately, the only pupillometric reported in their investigation was the Neurological Pupil Index (NPI) (i.e., a proprietary score generated by the manufacturer). Furthermore, the PLR tests were completed at different time intervals, executed by multiple trained test administrators, and focused on a different use case (i.e., the detection of traumatic brain injury instead of fatigue monitoring). In turn, meta analyses and comparative inferences remain challenging. From a general viewpoint, the ICCs reported in this pilot study tend to follow the trend of various HQIPs applied in different use cases. For instance, Zheng et al. (2022) [52] also reported that LAT was the least reliable of all pupillometrics (i.e., very poor ICC of 0.65) using the RAPDx pupillometer (Konan Medical, Irvine, California, USA) and Chopra et al. (2020) [53] reported moderate to good ICCs for MinD and MaxD (ICC > 0.90) using the same RAPDx pupillometer.

Taking into account the abovementioned limitations, combined with the overall lack of consistency and transparency in pupillometric research over the past 50 years (as recently highlighted by an international panel of pupillometry experts across disciplines) [47], future researchers may use this pilot study as a baseline framework and prioritize transparency and standardization when executing their initiatives on this research topic.

The relationship between pupillometrics and other biomarkers of game-induced fatigue

In response to the second research question, four pupillometrics were identified as the strongest indicators of game-induced fatigue in professional female basketball players. In particular, MaxD and MinD represented the strongest indicators for all other biomarkers of game-induced fatigue ($r = 0.69$–0.82, $p < 0.05$), whereas CV and MCV were identified as the strongest indicators for cognitive, lower-extremity muscle, and physiological biomarkers of game-induced fatigue (r = 0.74–0.76, p < 0.05). Hence, keeping track of these four pupillometrics on a daily basis may present a multi-modal solution to better understanding the psycho-physiological processes that underpin game-play fatigue in elite sports settings. However, the lack of existing literature on pupillometry in relation to sports-specific fatigue creates barriers for deeper comparative analyses. From a general perspective, the reported findings in this pilot study tend to align with previous investigations that examined the role of pupillometry in acute human fatigue. For instance, previous researchers have revealed strong relationships between multiple pupillometrics and biomarkers of HRV indices (e.g., lnRMSSD) [12, 14, 15, 54], as well as lower-extremity muscle fatigue (e.g. Postural Sway) [55, 56], subjective ratings of effort and tiredness from prolonged listening and attentional efforts) [57], subjective ratings of perceived exertion from muscular contraction during a power grip task [58]. Neverthelesss, there was a clear lack of consistency in terms of the selected testing timeframes (i.e., measuring before, during, or after given tasks or events), testing conditions (i.e., naturalistics vs. laboratory settings), selected HQIPs (i.e., self-engineered vs. commercial instruments), extracted pupillometrics (i.e., standard vs. proprietary scores and algorithms), and none of the investigations involved professional basketball competition. Acknowledging these limitations, and given that pupil responses vary based on the sport and context in which players participate in [kaltsatou, filipe], more detailed comparative analyses remain inappropriate at this point of time. Hence, a vigilant, transparent, and consistent research strategy is required to expand upon our existing knowledge regarding this use case.

The time-course of pupillometrics from rested to fatigued states

In response to the third research question, three pupillometrics were capable of detecting a significant change from rested states (baseline and GD-1) to fatigued states (GD+1 and GD+2). In particular, PC (right) (F = 5.173, η^2 = 0.115 p = 0.028) and MCV (right) (F = 3.976, η^2 = 0.090 p = 0.049) significantly decreased from baseline to GD+2, while LAT (left) (F = 4.023, η^2 = 0.109 p = 0.009) significantly increased from GD-1 to GD+2. Hence, at timepoints where residual fatigue was expected to remain present (48 h following games), the pupils constricted slower (MCV), with a smaller magnitude (PC), while it took longer to begin its constriction phase (LAT). This further supports the underlying physiological concept of pupillary behavior as LAT can be regarded as an index of sympathovagal balance (i.e., higher values indicate sympathetic dominance) [14], whereas PC and MCV can be regarded as an index of parasympathetic activity (i.e. higher values indicate parasympathetic dominance) [14]. Hence, this confirms, at least in part, that the players' ANS were not fully reverted to normal levels 48-h following games. Interestingly, this trend of LAT, PC, and MCV is inconsistent with earlier findings by Kaltsatou et al. [14] who examined the immediate effects of physical exertion (maximal ergometer stress test) on pupillary behavior in power -and endurance-trained athletes. Specifically, in their investigation, LAT decreased, while MCV and PC increased from peak exertion to 5-min following the test (when heart rate return to baseline levels). Consequently, similar to how sports scientists typically evaluate traditional game-induced fatigue markers (e.g. Heart Rate Variability indices) [59, 60, 61], the before-after, day-to-day, and week-to-week fluctuations in pupillometics should be analyzed distinctively and individually, and contextualized against other external factors.

It is also important to acknowledge that the reported findings in this pilot study does not inform about the underlying factors that may have contributed to its overall acute fatigue state, nor does it imply the practical relevance of it. For instance, in a recent systematic review on post-game recovery kinetics in team ball sport athletes, Doeven et al. [62] highlighted the many covariables that play an influential role on the recovery dynamics of each player (e.g., menstrual cycle, physical fitness, role within the team, playing time, exertion, playing level, playing style, age, gender, genetic make-up, game location, preceding travel duration, opponent quality, imposed workload, lifestyle habits, sleep quantity and quality) [62]. Hence, future researchers are encouraged to integrate these cofactors in future investigations in order to pinpoint the underlying mechanisms for pupillary change following games. Additionally, to determine the practical relevance of these changes, future researchers may include predetermined anchor points that are practically relevant to their organization (e.g., specific injury occurrence per minute of activity exposure, on-court game-play performance metrics, pre-game alertness levels) [1, 59, 60]. This anchoring approach, often referred to as the Minium Clinical Important Difference (MCID), would allow practitioners to track pupillometrics per player over time and transform them into a prediction or prescription tool informing the onset to critical states via real-time alerting or traffic-light based visualization systems [59, 60, 61, 62]. For instance, Umesh et al. (2015) [63] were able to predict a self-reported Visual Analogue Scale (VAS) state of sleepiness score of ≥ 6 (the target variable) by using a MCV threshold value (age adjusted) of 2.8, with a sensitivity of 83% and specificity of 84%. Similarly, future researchers could determine the MCID's for MaxD, MinD, CV, and MCV against their self-determined threshold values.

Finally, emerging technologies may enable faster interventions in the future. For instance, Stoeve et al. (2022) [64] created a VR-based stress test during a football goalkeeping scenario, and achieved a performance of 87.3% accuracy through the Random Forest classifier, claiming a comparable outcome to state-of-the-art approaches fusing eye tracking data and additional biosignals. Given the strong resurgence and further democratization of VR, Mixed Reality (MR) and augmented reality (AR) based eye-tracking applications in recent years [65–68], new opportunities may arise to accelerate pupillometric research in the context of real-time athlete monitoring.

In summary, the findings of this pilot study promotes HQIPs as a potential instrument for monitoring game-induced fatigue in female professional basketball players. From an ergonomic standpoint, the PLR testing routine took little time and effort on the practitioner's side, and good test-retest repeatability scores were reported for two pupillometrics (MaxD and MinD). Additionally, strong relationships were found for four pupillometrics (MaxD, MinD, CV, and MCV) and all other biomarkers of game-induced fatigue, and three pupillometrics were able to distinguish rested states from fatigued states (LAT, PC, and MCV). Although these preliminary findings tend to support the potential adoption of pupillometry as an athlete monitoring tool in elite sports settings, researchers should remain cautious when drawing conclusive inferences as the dataset was extracted from a relatively small and homogenous sample, tracked over a relatively short timeframe (4 games across 5 weeks). Therefore, future researchers should aim to cover a larger and more heterogenous sample across various time intervals to allow for more precise estimations of "normal pupillary behaviour" in elite athletes. The recent technological advancements in HQIPs that are compact and versatile (e.g., smartphone-based and VR-based pupillometers) [63–70] may further accelerate and facilitate investigations on this topic.

CONCLUSIONS

HQIPs have opened a new window of opportunities for sports practitioners given its ease of use and ability to extract objective insights on player fatigue in a quick, reliable, valid, and non-invasive character. Overall, the pupillometrics MinD, MaxD, CV, and MCV were identified as the most promising indicators of game-induced fatigue in female professional basketball players. However, it's important to acknowledge that this research line is still in its infancy, and the findings stem from a small homogenous sample, thus the statistical inferences remain indicative rather than confirmative or directive. However, future researchers are encouraged to leverage this pilot study as a baseline framework for future investigations, and ensure standardization is prioritized throughout the process in order to maximize the reproducibility of findings across a variety of sports, timeframes, contexts, and use cases.

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The UCAM University Institutional Review Board (code: CE122002) approved this study in accordance with the Helsinki Declaration and researchers were provided de-identified data to analyze.

Conflicts of interest

The authors declare no conflict of interest.

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Does sodium bicarbonate based extra-cellular buffering support reduce high intensity exercise-induced fatigue and enhance short-term recovery assessed by selected blood biochemical indices?

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ABSTRACT: Exercise-induced metabolic processes induce muscle acidification which contributes to a reduction in the ability to perform repeated efforts. Alkalizing agents such as sodium bicarbonate ($NaHCO_3$) prevent large blood pH changes, however, there is no evidence on whether regulation of acid-base balance may also support whole body homeostasis monitored through heamatological and biochemical blood markers in a dose-dependent manner. Thirty Cross-Fit-trained participants were studied in a randomized, multi cross-over, placebo (PLA)-controlled double-blind manner in which they performed a control session (CTRL, without supplementation), three $NaHCO_3$ visits (three different doses) and PLA (sodium chloride in an equimolar amount of sodium as $NaHCO_3$). Each visit consisted of two 30-s Wingate tests separated by CrossFit-specific benchmarks (Wall Balls and Burpees – both performed for 3 min). Blood samples were collected at rest, immediately post-exercise and after 45 min recovery. Significant differences between visits appeared for blood pH, percentage of lymphocytes and granulocytes, red blood cells count and haemoglobin concentration at post-exercise and 45-min recovery, and for white blood cells count, percentage of monocytes, concentration of magnesium and creatinine at 45-min recovery. Most of the observed differences for heamatological and biochemical markers were significant compared to CTRL, but not different after PLA. $NaHCO_3$ supplementation compared to PLA did not significantly affect exercise or recovery shifts in studied blood indicators. However, the changes in these markers after $NaHCO_3$ and PLA in relation to CTRL indicate a possible role of sodium.

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INTRODUCTION

The high energy request of the organism during intensive efforts and the need for rapid anaerobic ATP resynthesis lead to the release of protons that decrease blood pH, and cause muscle acidification [1]. This occurs predominantly during high-intensity exercises and training programs, such as high-intensity interval training (HIIT) and/or high-intensity functional training (HIFT). It is well known that increased muscle acidification is one of the main suppressors of the ability to perform high-intensity exercise [2]. Moreover, HIIT/HIFT may influence homeostatic disturbances not only directly through the acid-base balance, but also indirectly affecting the various haematological and biochemical markers. However, post-exercise changes in these indices, especially haematological and muscle damage-specific markers, are equivocal.

White blood cell (WBC) count increases immediately after intense exercise [3, 4, 5]. Furthermore, despite an increase in WBC after HIIT and continuous aerobic exercise, WBC elevation is remarkably higher for HIIT than continuous aerobic exercise [6]. In addition, shifts in post-exercise haematological markers are related to an increase in the percentage of lymphocytes (LYM%) [4, 5, 6], monocytes (MON%) [4], and a decrease of granulocytes (GRA%) [6]. However, changes of the aforementioned markers are not always repeatedly recorded [6]. Similarly, ambiguous positions relate to exercise-induced changes of platelets (PLT), red blood cells (RBC) count and haemoglobin (HGB) concentration [3, 5, 7, 8].

Moreover, in most studies, relating to changes in blood biochemical markers, post-exercise increases in lactate dehydrogenase (LDH) [9], creatine kinase (CK) [3, 8, 9], alanine aminotransferase (ALT) and aspartate aminotransferase (AST) [10] activities or urea [11] and magnesium [7] concentrations have been shown, although changes in these indicators after intense efforts have not always been shown [10].

It is interesting to note that the aforementioned biochemical changes are sensitive to pH reductions induced by high-intensity exercise, which may affect the haematological profile in blood due to the role of haemoglobin as a buffer in the body [12] and increasing the risk of osmotic fragility of erythrocytes [13]. Furthermore, acidosis resulting from chronic kidney disease stimulates the activity of the ubiquitin-proteasome pathway and the formation of glucocorticoids, which contribute to the degradation of muscle proteins, and thus to an increase in blood urea concentration [14]. It would be reasonable to assume that this mechanism may also be reflected in acidosis resulting from highly intensive exercise.

While it is unwise to interfere with training and reduce the intensity of exercise (which may negatively affect adaptation and sports performance), an alternative to support the body's buffering needs is nutritional and/or supplementation support. Alkalizing agents, such as sodium bicarbonate ($NaHCO_3$), improve CrossFit-like performance [15] and have significant ergogenic effects [16] through increasing blood buffering capacity [17], which allows greater hydrogen ion (H^+) binding, H^+/lactate shuttle from working myocytes, and increases extra-cellular pH [16, 18].

$NaHCO_3$ intake increases pH, through an elevation of bicarbonate ion (HCO_3^-) concentration in the blood, which may be beneficial in exercises heavily reliant on anaerobic metabolism [16]. Excessive sodium bicarbonate administration may induce severe alkalaemia, hypernatraemia and hypokalaemia [19]. However, in sport practice commonly supplemented doses ranging from 0.1 to $0.5\ g \cdot kg^{-1}{}_{BM}$ $NaHCO_3$ [16, 20] do not appear to be a cause for concern. The ideal supplementation method appears to be ingestion in a solution or gelatine capsules at a dose of $\geq 0.3\ g \cdot kg^{-1}{}_{BM}$ $NaHCO_3$ 60–180 min before exercise [16, 20, 21]. However, there are also reports that do not confirm this positive influence of $NaHCO_3$ [22, 23]. This may be due to the large diversity of the organism's individual response to this agent and supplementation protocols [20, 24], or related to digestive system problems that can appear in some people [18, 25]. Due to lower tolerance, some athletes choose lower doses ($\sim 0.2\ g \cdot kg^{-1}{}_{BM}$) and lengthening the time between $NaHCO_3$ intake and exercise starting ($\sim$180 min), which may also have an ergogenic benefit [16, 20, 26]. On the other hand, Grgic et al. [20] reported the use of higher doses ($0.4–0.5\ g \cdot kg^{-1}{}_{BM}$) did not provide any additional benefits compared to the dose of $0.3\ g \cdot kg^{-1}{}_{BM}$ $NaHCO_3$. Therefore, despite performance effects, it is crucial to investigate the multidirectional impact of $NaHCO_3$ on whole-body homeostasis during intense exercise.

It is not known to what extent acute HIIT/HIFT-induced changes in haematological and biochemical indicators are modulated by $NaHCO_3$ supplementation. Extracellular buffering capacity elevation through $NaHCO_3$ intake, proportionally to the administered dose, may enhance acid-base balance during efforts and could translate into changes in haematological and blood biochemical markers. The aim of this study was to verify the extent to which $NaHCO_3$ would affect the acute changes of haematological and blood biochemical markers following intense exercise. We hypothesized that $NaHCO_3$ would minimize exercise-induced changes in these markers in a dose-dependent manner.

MATERIALS AND METHODS

Participants

Thirty-four Cross-Fit-trained participants were initially enrolled in the study. Due to personal and professional reasons (business trips) 4 subjects (3 males (M)/1 female (F)) dropped-out of the study. Thirty athletes (16M/14F) completed the whole study protocol and were included in the analyses. The participants were regularly training HIFT in CrossFit-affiliated clubs in Poznań ("*Hangar*" and "*Stajnia CrossFit*") and Szczecin ("*Papaj CrossFit*") in Poland (Table 1).

The inclusion criteria were: a valid and up-to-date medical certificate that confirmed the athlete's ability to practice sports, good general health, at least 4 years of training experience and participation in a minimum of four CrossFit workout sessions a week. The exclusion criteria were: current injury, health-related contraindication,

TABLE 1. Somatic and physiological characteristics of participants training Cross-Fit® (n = 30).

Characteristics	Mean ± SD	95% CI
Age [years]	30.6 ± 4.3	(29.0–32.2)
Body mass [kg]	73.8 ± 12.1	(69.3–78.3)
Fat-free mass [kg]	59.8 ± 11.5	(55.4–64.1)
Fat mass [%]	19.1 ± 5.5	(17.1–21.2)
Body height [cm]	175 ± 9	(172–178)

SD – standard deviation; CI – confidence interval declared general feeling of being unwell and unwillingness to follow the study protocol.

The local institutional review board reviewed and approved the study protocol (Bioethics Committee at Poznan University of Medical Sciences, reference number: 1000/18 of 11 October 2018). The study protocol was also registered at *ClinicalTrials.Gov* (NCT03810404). All procedures were conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki and written informed consent was obtained from all participants before their participation in the study began.

The required sample size was calculated a priori using a computer statistical package Statistica 13.3 (StatSoft, Inc., Tulsa, OK, USA) based on results of other studies [27, 28]. It was estimated that a sample size of 28 would be suitable for detecting a difference between blood pH measurements to obtain a power of approximately 90% ($\alpha = 0.05$) in analysis of variance (ANOVA) with repeated measurements (RM) within factors.

Study design

Supplementation of various $NaHCO_3$ doses was evaluated in a randomized, multi cross-over, placebo (*PLA*)-controlled double-blind trial. The protocol of the study consisted of five visits (T_1–T_5) for each participant (Figure 1). In T1, a control (*CTRL*) phase was carried out where all tests without supplementation or *PLA* administration were performed. During subsequent visits (T_2–T_5), studies were conducted after three different doses of $NaHCO_3$ and *PLA* intake depending on a randomization-based supplementation order.

All participants had substantial experience in performing the exercise procedures. They were also obligated to eat a standardized meal (containing 2 g of carbohydrates per kilogram of body mass (BM), 30 g of protein and at least 7 ml of water per kilogram of BM) two hours before each visit. Diet of the participants was monitored by an experienced dietician who ensured that athletes met all recommended criteria in terms of nutritional standards [29]. Furthermore, participants did not follow any specific nutritional strategy and did not change any nutritional aspects during the study protocol.

The study visits (T_1–T_5) were separated by at least 7-days of washout.

Supplementation

The $NaHCO_3$ doses were provided relative to fat-free mass (FFM). The dose of supplemented $NaHCO_3$ was considered as *LOW* ($0.15\ g \cdot kg^{-1}{}_{FFM}$ of $NaHCO_3$), *MEDIUM* ($0.25\ g \cdot kg^{-1}{}_{FFM}$ of $NaHCO_3$, *MED*) and *HIGH* ($0.35\ g \cdot kg^{-1}{}_{FFM}$ of $NaHCO_3$). $NaHCO_3$ in the form of powder was used (Alkala N, Sanum-Kehlbeck GmbH & Co. KG, Germany; containing 89.1% of $NaHCO_3$, 9.9% of potassium bicarbonate, and 1.0% of sodium citrate). *PLA* preparation was provided in a similar powder form and contained sodium chloride in an equimolar amount of sodium as *MED* $NaHCO_3$. All preparations were dissolved in approximately 750 mL of fluid (600 mL of water and 150 mL of orange juice). Juice was provided as a source of CHO to alleviate GI symptoms [18, 25, 30] and improve the taste of the preparations. Athletes were obligated to drink the preparations 2 h before the exercise tests within 5 min and were supervised by a member of the research team.

Anthropometric measurements

Anthropometric measurements were performed according to recommendations as described previously [31]. Body mass and height were measured using a professional medical scale (WPT 60/150 OW, RADWAG, Radom, Poland). Body composition and total body water were assessed via bioelectric impedance, using Bodystat 1500MDD (Bodystat Inc., Douglas, UK).

Exercise tests

The exercise battery started 2 h after $NaHCO_3$/*PLA* intake (or fluid intake at *CTRL* – T_1 visit). Each visit consisted of two classic 30-s Wingate tests (WAnT_1 and WAnT_2) separated by CrossFit-specific benchmarks: a) Wall Balls (performed for 3 min) and (after a 30 s transition break) b) Burpees (performed for 3 min). The Wall Balls task started exactly 5 min after the completion of WAnT_1, and WAnT_2 started 5 min after the completion of the Burpees task. The actual high-intensity active effort lasted a total of 7 min.

The exercise tests were always preceded by a standardized 10 min warm-up as previously described [31]. WAnTs were performed on a Monark 894E cycloergometer (Varberg, Sweden) and external loading was adjusted individually at 7.5% body weight [31]. During the CrossFit-specific benchmarks, the participants were instructed to perform as many repetitions of each exercise as they could during 3 min. Repetitions were accounted for, only if the participant completed a full range of motion required for each exercise. The only difference in CrossFit-specific benchmarks between female and male participants was the weight of the medicine ball during wall balls (6 and 9 kg for females and males) [32]. Participants were verbally encouraged to exert maximum effort throughout the exercise tests.

Biochemical analyses

Capillary blood was obtained from the fingertip, at rest before supplementation (2 h before exercise), 3 min after (post-exercise) and 45 min (recovery) after exercise. Blood was collected according to the applicable and standardized procedures, from the finger of the non-dominant hand using Medlance Red lancet-spike (HTL-Zone, Berlin, Germany) with a 1.5 mm blade and 2.0 mm penetration depth. A heparinized capillary sample (65 μl; Radiometer, Copenhagen, Denmark) was taken to determine pH using a blood gas analyzer (ABL90 FLEX, Radiometer, Copenhagen, Denmark). Additionally, 300 μl of capillary blood was collected in a Microvette CB 300 tube (Sarstedt, Nümbrecht, Germany) containing EDTA dipotassium salt as an anticoagulant for WBC and their individual fractions (LYM%, MON%, GRA%), RBC, HGB, haematocrit (HCT) and PLT determination on a haematology analyzer (Mythic18, Orphèe, Geneva, Switzerland);

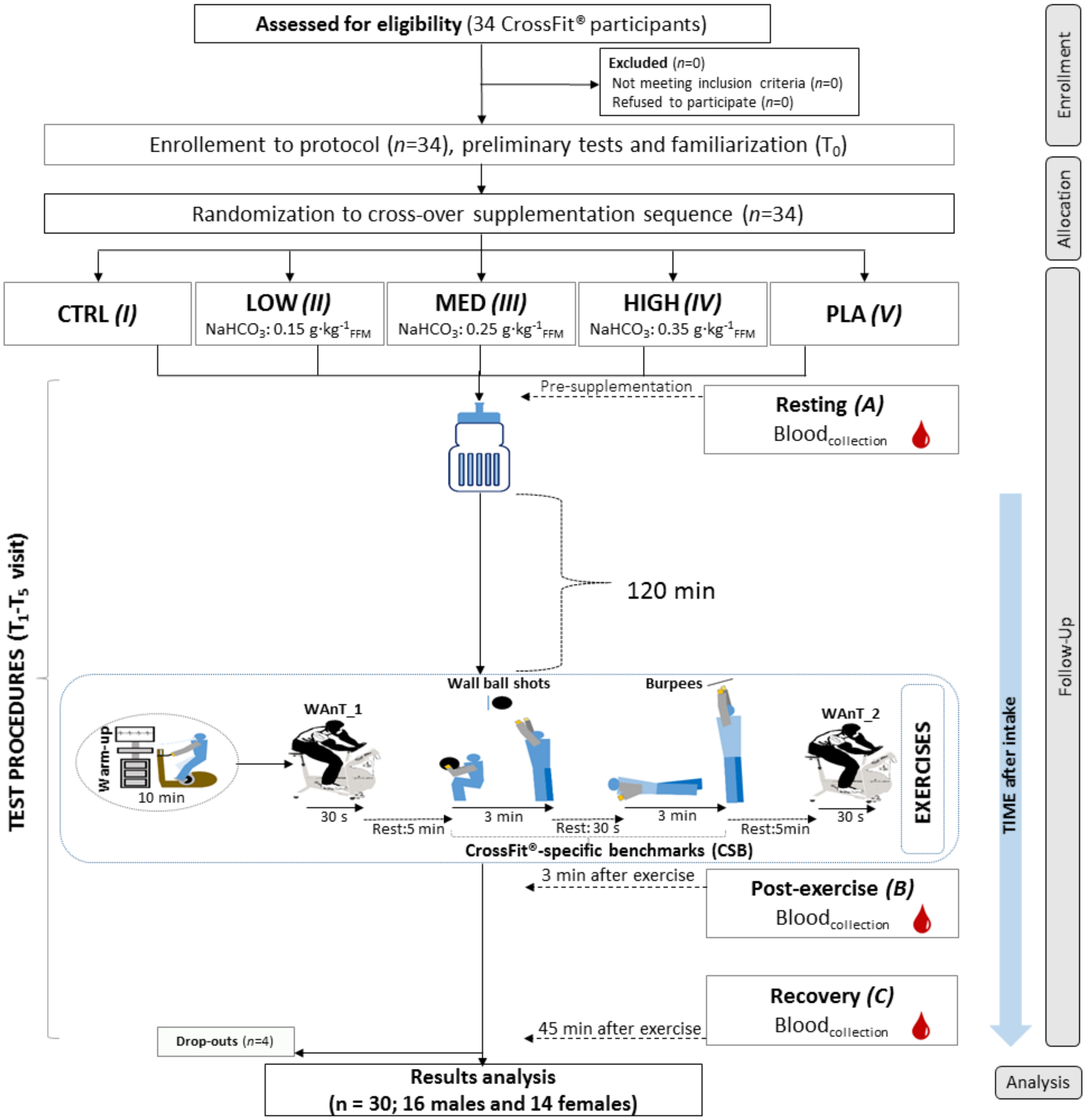

FIG. 1. A flow chart of the study design.
CTRL – control visit, without supplementation or placebo treatment; HIGH – visit with high $NaHCO_3$ dose (0.35 $g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); LOW – visit with low $NaHCO_3$ dose (0.15 $g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); MED – visit with medium $NaHCO_3$ dose (0.25 $g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); $NaHCO_3$ – sodium bicarbonate; PLA – placebo; T_0–T_5 – numbers of study visits; WAnT – 30-s Wingate Anaerobic Test.

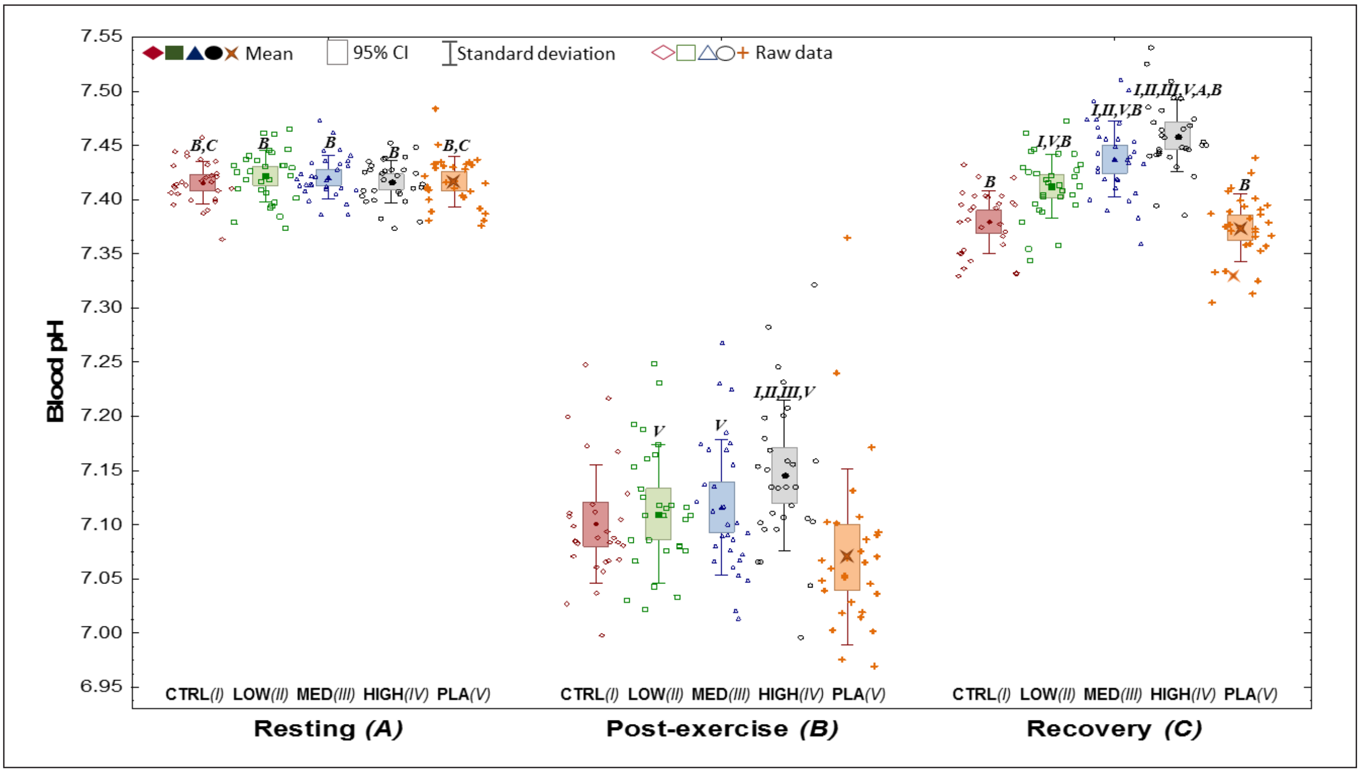

FIG. 2. Resting (A), post-exercise (B) and recovery (C) pH values in the five phases (I-V).
CI – confidence interval; CTRL – control visit, without supplementation or placebo treatment; HIGH – visit with high $NaHCO_3$ dose ($0.35\ g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); LOW – visit with low $NaHCO_3$ dose ($0.15\ g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); MED – visit with medium $NaHCO_3$ dose ($0.25\ g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); $NaHCO_3$ – sodium bicarbonate; PLA – placebo.
^{I,II,III,IV,V}The values of the phase, which number is in the superscript, are significantly lower than the values at which they are presented; ^{A,B,C}The values of the moment, which letter is in the superscript, are significantly lower than the values at which they are presented.

and after plasma separation concentration of urea and creatinine, and ALT, AST, CK, and LDH activities on the Accent 220S automatic biochemical analyser (Cormay, Łomianki, Poland). Another 300 μl of capillary blood was collected in a Microvette CB 300 Z tube (Sarstedt, Nümbrect, Germany) with a clotting activator, in which the serum concentration of magnesium was marked also on the Accent 220S automatic biochemical analyzer.

Additionally, to avoid misinterpretation of blood parameter results due to different hydration status of participants on different visits, haematology indicators were related to the number of cellular components (WBC, RBC, HGB, PLT) and all biochemical parameters were converted using the haematocrit correction formula [33, 34].

Statistical Analysis

Data are presented as the mean and standard deviation (± SD) and the 95% confidence interval for the mean (95% CI). The studied variables were checked for normal distribution using the Shapiro-Wilk test. For the comparison of the results between the five visits (T_1–T_5) and collection moment (rest, post-exercise and recovery), repeated measures ANOVA were performed for normally distributed data. For data that was not normally distributed, the Friedman ANOVA test was selected. Post-hoc (Tukey HSD test for parametric statistics and post hoc for Friedman for nonparametric statistics) analyses were then conducted for statistically significant data. The level of significance was set at $p < 0.05$. Statistical analysis was performed using a computer statistical package STATISTICA 13.3 (StatSoft, Inc., Tulsa, OK, USA).

RESULTS

The resting (rest) values of all haematological, biochemical and blood gas measures did not differ significantly from one another across T_1–T_5.

Blood pH value

All blood pH results are presented in Figure 2.

An exercise-induced decrease in pH ($p < 0.001$) was shown between post-exercise vs. resting values for each visit (*$NaHCO_3$'s*, *CTRL*, *PLA*). However, in the recovery period, pH returned or even significantly exceeded (in *MED* and *HIGH*) the resting values after $NaHCO_3$.

TABLE 2. Summary of the level of blood haematological parameters resting, post-exercise and recovery in the five visits of the study (n = 30).

Indicator	Measurement time	Study visits [Mean ± SD (95% CI)]					*p*-Value
		CTRL (I)	**LOW (II)**	**MED (III)**	**HIGH (IV)**	**PLA (V)**	
White blood cells [10^9/L]	Resting (A)	7.7 ± 1.6 (7.1–8.3)	7.6 ± 1.9 (6.9–8.3)	7.6 ± 1.7 (7.0–8.2)	7.7 ± 1.7 (7.0–8.3)	7.4 ± 1.9 (6.7–8.1)	0.286
	Post-exercise (B)	13.2 ± 3.9^{A,C} (11.8–14.6)	13.1 ± 2.5^{A,C} (12.2–14.1)	13.1 ± 2.7^{A,C} (12.1–14.1)	13.3 ± 2.8^{A,C} (12.2–14.3)	13.2 ± 2.9^{A,C} (12.1–14.3)	0.746
	Recovery (C)	9.6 ± 2.8^{II,III,IV,V,A} (8.6–10.7)	8.1 ± 2.3 (7.2–9.0)	8.4 ± 2.6 (7.4–9.4)	8.0 ± 2.2 (7.1–8.8)	8.3 ± 2.6^{A} (7.4–9.3)	**< 0.001**
	***p*-Value**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	
Lymphocytes [%]	Resting (A)	35.1 ± 7.0^{C} (32.4–37.7)	35.1 ± 6.7^{C} (32.6–37.6)	35.0 ± 7.4^{C} (32.2–37.7)	34.3 ± 6.6^{C} (31.8–36.7)	35.7 ± 7.1^{C} (33.0–38.3)	0.833
	Post-exercise (B)	44.1 ± 8.2^{A,C} (41.0–47.2)	46.4 ± 7.5^{A,C} (43.6–49.2)	47.1 ± 6.4^{A,C} (44.7–49.5)	44.9 ± 8.7^{A,C} (41.7–48.1)	47.0 ± 9.8^{A,C} (43.3–50.6)	**0.048***
	Recovery (C)	23.0 ± 7.7 (20.2–25.9)	28.3 ± 8.2^{I} (25.3–31.4)	28.8 ± 9.2^{I} (25.4–32.3)	28.6 ± 9.4^{I} (25.1–32.1)	28.3 ± 10.2^{I} (24.5–32.1)	**0.004**
	***p*-Value**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	
Monocytes [%]	Resting (A)	6.7 ± 1.7^{C} (6.1–7.4)	6.8 ± 1.9 (6.1–7.5)	7.2 ± 1.8 (6.5–7.9)	7.1 ± 2.3 (6.2–7.9)	6.8 ± 2.3 (6.0–7.7)	0.467
	Post-exercise (B)	7.2 ± 1.8^{C} (6.5–7.9)	7.5 ± 1.6^{A,C} (6.9–8.1)	7.8 ± 1.7 (7.1–8.4)	7.5 ± 1.6 (6.9–8.1)	7.4 ± 1.3^{A,C} (6.9–7.9)	0.200
	Recovery (C)	6.1 ± 2.2 (5.3–6.9)	6.7 ± 1.7 (6.1–7.3)	7.5 ± 2.6^{I} (6.5–8.4)	7.4 ± 2.9 (6.3–8.5)	6.7 ± 1.9 (6.0–7.4)	**0.012**
	***p*-Value**	**< 0.001**	**< 0.001**	0.209	0.121	**0.001**	
Granulocytes [%]	Resting (A)	58.2 ± 7.7^{B} (55.4–61.1)	58.1 ± 7.1^{B} (55.4–60.8)	57.8 ± 7.6^{B} (55.0–60.7)	58.7 ± 6.9^{B} (56.1–61.2)	57.5 ± 7.9^{B} (54.6–60.5)	0.714
	Post-exercise (B)	48.7 ± 9.0 (45.3–52.0)	46.1 ± 7.8 (43.2–49.0)	45.2 ± 6.8 (42.6–47.7)	47.6 ± 9.2 (44.1–51.0)	45.6 ± 10.4 (41.7–49.5)	**0.037***
	Recovery (C)	70.9 ± 8.9^{II,III,IV,V,A,B} (67.6–74.2)	65.0 ± 8.4^{A,B} (61.8–68.1)	63.7 ± 9.9^{A,B} (60.0–67.4)	64.0 ± 10.1^{A,B} (60.2–67.7)	65.0 ± 10.5^{A,B} (61.1–68.9)	**< 0.001**
	***p*-Value**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	
Red blood cells [10^{12}/L]	Resting (A)	5.96 ± 0.59^{B} (5.74–6.19)	5.94 ± 0.59^{B} (5.72–6.16)	5.92 ± 0.55^{B,C} (5.71–6.12)	5.91 ± 0.53^{B,C} (5.71–6.10)	5.90 ± 0.55^{B} (5.70–6.11)	0.119
	Post-exercise (B)	5.88 ± 0.59^{III} (5.66–6.10)	5.86 ± 0.60 (5.63–6.08)	5.81 ± 0.54 (5.61–6.01)	5.82 ± 0.53 (5.62–6.02)	5.83 ± 0.55 (5.62–6.03)	**0.033**
	Recovery (C)	5.96 ± 0.60^{III,IV,V,B} (5.74–6.18)	5.94 ± 0.59^{B} (5.72–6.16)	5.88 ± 0.53^{B} (5.68–6.08)	5.88 ± 0.52^{B} (5.69–6.08)	5.89 ± 0.56^{B} (5.68 ± 6.10)	**0.007**
	***p*-Value**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	
Haemoglobin [mmol/L]	Resting (A)	10.84 ± 0.40^{B,C} (10.69–10.98)	10.63 ± 0.48^{B,C} (10.45–10.81)	10.75 ± 0.45^{B,C} (10.58–10.91)	10.75 ± 0.48^{B,C} (10.57–10.94)	10.63 ± 0.46^{B,C} (10.45–10.80)	0.076
	Post-exercise (B)	10.56 ± 0.47^{II,V} (10.38–10.74)	10.29 ± 0.54 (10.09–10.49)	10.35 ± 0.51 (10.16–10.54)	10.43 ± 0.62 (10.20–10.66)	10.35 ± 0.52 (10.16–10.54)	**0.004**
	Recovery (C)	10.71 ± 0.37^{II,B} (10.57–10.84)	10.46 ± 0.55^{B} (10.26–10.67)	10.51 ± 0.50^{B} (10.32–10.69)	10.56 ± 0.60^{B} (10.33–10.78)	10.47 ± 0.53^{B} (10.27–10.66)	**0.015**
	***p*-Value**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	
Platelets [10^9/L]	Resting (A)	269 ± 95 (234–305)	280 ± 88 (247–313)	273 ± 89 (240–306)	272 ± 78 (243–301)	279 ± 97 (242–315)	0.081
	Post-exercise (B)	302 ± 114 (259–344)	319 ± 113^{A,C} (277–361)	308 ± 90^{A,C} (275–342)	302 ± 93^{A,C} (268 ± 337)	307 ± 107^{A} (267–347)	0.368
	Recovery (C)	264 ± 97 (228–300)	282 ± 94 (247–317)	288 ± 86 (256–320)	267 ± 82 (237–298)	288 ± 92 (254–322)	0.061
	***p*-Value**	0.131	**0.001**	**< 0.001**	**0.002**	**0.001**	

CI – confidence interval; CTRL – control visit, without supplementation or placebo treatment; HIGH – visit with high $NaHCO_3$ dose (0.35 $g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); LOW – visit with low $NaHCO_3$ dose (0.15 $g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); MED – visit with medium $NaHCO_3$ dose (0.25 $g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); $NaHCO_3$ – sodium bicarbonate; PLA – placebo; SD – standard deviation

^{I,II,III,IV,V}The values of the phase, which number is in the superscript, are significantly lower than the values at which they are presented

^{A,B,C}The values of the moment, which letter is in the superscript, are significantly lower than the values at which they are presented

*The post-hoc test did not show any significant difference between the terms

TABLE 3. Summary of the level of blood biochemical parameters resting, post-exercise and recovery in the five visits of the study (n = 30).

Indicator	Measurement time	STUDY VISITS [Mean ± SD (95% CI)]					*p*-Value
		CTRL (I)	LOW (II)	MED (III)	HIGH (IV)	PLA (V)	
Urea [mmol/L]	Resting (A)	7.2 ± 2.0^{B} (6.5–8.0)	7.3 ± 2.1^{B,C} (6.5–8.0)	7.2 ± 2.0^{B} (6.4–7.9)	7.0 ± 1.8^{B} (6.4–7.7)	7.2 ± 1.9^{B} (6.5–7.9)	0.955
	Post-exercise (B)	7.0 ± 1.9 (6.3–7.7)	6.6 ± 1.7 (6.0–7.3)	6.4 ± 1.7 (5.8–7.0)	6.6 ± 1.8 (5.9–7.2)	6.6 ± 1.6 (6.0–7.2)	0.455
	Recovery (C)	7.3 ± 1.9^{B} (6.6–8.0)	7.0 ± 1.9^{B} (6.3–7.7)	6.8 ± 1.8^{B} (6.2–7.5)	7.0 ± 1.9^{B} (6.3–7.7)	7.1 ± 1.8^{B} (6.4–7.7)	0.621
	***p*-Value**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	
Magnesium [mmol/L]	Resting (A)	1.01 ± 0.14 (0.96–1.07)	0.97 ± 0.13 (0.92–1.02)	1.01 ± 0.16 (0.95–1.07)	1.01 ± 0.15 (0.96–1.07)	0.99 ± 0.11 (0.95–1.03)	0.455
	Post-exercise (B)	1.04 ± 0.14 (0.98–1.09)	1.00 ± 0.12 (0.95–1.05)	1.01 ± 0.13 (0.96–1.06)	0.99 ± 0.14 (0.94–1.04)	1.00 ± 0.12 (0.95–1.04)	0.178
	Recovery (C)	1.15 ± 0.19^{IV,A,B} (1.08–1.22)	1.09 ± 0.14^{A,B} (1.03–1.14)	1.11 ± 0.16^{A,B} (1.06–1.17)	1.08 ± 0.16^{A,B} (1.02–1.14)	1.09 ± 0.14^{A,B} (1.04–1.15)	**0.034**
	***p*-Value**	**< 0.001**	**< 0.001**	**< 0.001**	**0.005**	**< 0.001**	
Alanine aminotransferase [U/L]	Resting (A)	32.4 ± 10.4 (28.5–36.3)	32.8 ± 13.6 (27.7–37.9)	31.4 ± 9.5 (27.8–34.9)	33.2 ± 13.8 (28.1–38.4)	31.8 ± 10.4 (27.9–35.7)	0.865
	Post-exercise (B)	34.6 ± 10.6^{A} (30.7–38.6)	35.2 ± 14.7^{A,C} (29.7–40.7)	32.5 ± 9.6^{A} (29.0–36.1)	35.9 ± 14.3^{A} (30.6–41.3)	34.5 ± 11.3^{A} (30.3–38.7)	0.610
	Recovery (C)	34.1 ± 10.2^{A} (30.3–37.9)	34.2 ± 13.5^{A} (29.1–39.2)	32.7 ± 9.7^{A} (29.0–36.3)	35.3 ± 14.3^{A} (30.0–40.7)	33.2 ± 10.6^{A} (29.2–37.1)	0.272
	***p*-Value**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	
Aspartate aminotransferase [U/L]	Resting (A)	37.1 ± 11.2 (32.9–41.3)	34.9 ± 9.8 (31.2–38.5)	33.9 ± 7.1 (31.3–36.6)	34.3 ± 10.5 (30.4–38.2)	33.6 ± 7.4 (30.8–36.3)	0.378
	Post-exercise (B)	39.6 ± 12.5^{A} (34.9–44.3)	36.6 ± 10.9^{A} (32.6–40.7)	35.2 ± 7.3^{A} (32.5–38.0)	36.0 ± 11.1^{A} (31.9–40.1)	35.7 ± 9.2^{A} (32.3 ± 39.1)	0.348
	Recovery (C)	38.9 ± 12.7^{A} (34.1–43.6)	36.1 ± 10.8 (32.1–40.1)	36.0 ± 10.3 (32.2–39.8)	36.4 ± 11.7^{A} (32.0–40.8)	35.3 ± 7.8 (32.4–38.2)	0.218
	***p*-Value**	**< 0.001**	**0.006**	**0.014**	**< 0.001**	**0.026**	
Creatine kinase [U/L]	Resting (A)	409.3 ± 360.6 (274.7–543.9)	346.3 ± 259.4 (249.5–443.2)	388.0 ± 339.2 (261.3–514.6)	361.7 ± 255.4 (266.4–457.1)	324.2 ± 238.7 (235.0–413.3)	0.615
	Post-exercise (B)	462.9 ± 414.6^{A} (308.1–617.8)	389.5 ± 281.7^{A} (284.3–494.7)	427.6 ± 369.5^{A} (289.6–565.6)	404.1 ± 282.2^{A} (298.7–509.5)	372.3 ± 258.9^{A} (275.6–469.0)	0.371
	Recovery (C)	472.3 ± 441.2^{A} (307.6–637.1)	392.3 ± 282.0^{A} (287.0–497.6)	441.9 ± 379.1^{A} (300.4–583.5)	405.8 ± 278.3^{A} (301.8–509.7)	374.8 ± 257.3^{A} (278.7–470.9)	0.471
	***p*-Value**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	
Lactate dehydrogenase [U/L]	Resting (A)	417 ± 75 (389–445)	407 ± 80 (377–436)	412 ± 50 (394–431)	400 ± 57 (378–421)	420 ± 79 (391–450)	0.731
	Post-exercise (B)	456 ± 81^{A} (426–486)	450 ± 91^{A} (417–484)	452 ± 51^{A,C} (433–471)	429 ± 64^{A} (405–453)	463 ± 95^{A} (427–498)	0.195
	Recovery (C)	442 ± 69 (416–468)	425 ± 82 (395–456)	446–122 (401–492)	420 ± 70^{A} (394–446)	440 ± 80 (410–470)	0.306
	***p*-Value**	**0.002**	**0.001**	**< 0.001**	**0.003**	**< 0.001**	

TABLE 3. Continue.

Indicator	Measurement time	STUDY VISITS [Mean ± SD (95% CI)]					*p*-Value
		CTRL (I)	LOW (II)	MED (III)	HIGH (IV)	PLA (V)	
Creatinine [μmol/L]	Resting (A)	98.1 ± 16.4 (92.0–104.2)	98.8 ± 13.5 (93.7–103.8)	100.0 ± 13.0 (95.2–104.9)	98.2 ± 15.2 (92.5–103.9)	99.9 ± 13.3 (95.0–104.9)	0.351
	Post-exercise (B)	112.1 ± 20.7[A,C] (104.3–119.8)	111.2 ± 15.9[A] (105.3–117.2)	109.5 ± 14.8[A] (104.0–115.0)	109.0 ± 15.9[A] (103.1–115.0)	110.5 ± 19.0[A] (103.4–117.6)	0.538
	Recovery (C)	107.8 ± 16.7[A] (101.5–114.0)	112.7 ± 14.5[I,A] (107.3–118.1)	111.9 ± 15.5[A] (106.2–117.7)	110.7 ± 17.6[A] (104.1–117.2)	112.9 ± 18.9[I,A] (105.8–120.0)	**0.003**
	***p*-Value**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	

CI – confidence interval; CTRL – control visit, without supplementation or placebo treatment; HIGH – visit with high $NaHCO_3$ dose ($0.35\ g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); *LOW* – visit with low $NaHCO_3$ dose ($0.15\ g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); MED – visit with medium $NaHCO_3$ dose ($0.25\ g \cdot kg^{-1}_{Fat\text{-}Free\ Mass}$); $NaHCO_3$ – sodium bicarbonate; PLA – placebo; SD – standard deviation

[I,II,III,IV,V]The values of the phase, which number is in the superscript, are significantly lower than the values at which they are presented
[A,B,C]The values of the moment, which letter is in the superscript, are significantly lower than the values at which they are presented

Differences were also visible after exercise ($p < 0.001$) between all $NaHCO_3$ doses and *PLA*. Additionally, post-exercise and recovery blood pH was greater *HIGH* in comparison to the other visits. Furthermore, at recovery, pH was higher in *LOW* and *MED* than *CTRL* and *PLA* ($p < 0.001$).

Blood Haematological Markers

All haematological results are presented in Table 2.

There were differences at recovery between visits for almost all haemotological measures (out of PLT count). For RBC count and HGB concentration, these differences were also apparent at post-exercise. WBC count ($p < 0.001$) and GRA% ($p < 0.001$) were higher in *CTRL* than all other study visits. Significant differences were shown for percentage of LYM ($p = 0.004$). MON% was higher only for *MED* vs. *CTRL* ($p = 0.012$). In the case of RBC count at post-exercise, *CTRL* was higher than *MED* ($p = 0.033$) and at recovery, *CTRL* was higher than *MED*, *HIGH* and *PLA* ($p = 0.007$). HGB concentration post-exercise was significantly higher in *CTRL* vs. *LOW* and *PLA* ($p = 0.004$), and at recovery *CTRL* was higher than *LOW* ($p = 0.015$). Furthermore, an increase at post-exercise vs. resting values were shown in all study visits for: "WBC count and LYM%, while GRA%, RBC count and HGB concentration were decreased. Post-exercise MON% was greater vs. resting and recovery values in *LOW* ($p < 0.001$) and *PLA* ($p = 0.001$). PLT count was higher for all doses of $NaHCO_3$ (*LOW*, $p = 0.001$; *MED*, $p < 0.001$; *HIGH*, $p = 0.002$) at post-exercise in comparison to resting and recovery values, and *PLA* post-exercise vs. rest ($p = 0.001$).

Comparison between resting and recovery values showed differences for all study visits only for LYM%, GRA% and HGB concentration. WBC count had higher recovery values in *CTRL* ($p < 0.001$) and *PLA* ($p < 0.001$), but not any $NaHCO_3$ visit. For MON%, decreased values at recovery vs. rest were shown only in *CTRL* ($p < 0.001$), and for RBC count in *MED* ($p < 0.001$) and *HIGH* ($p < 0.001$).

WBC count and LYM% were decreased ($p < 0.001$) at recovery vs. post-exercise in all visits, while there was an increased %GRA, RBC count and haemoglobin concentration ($p < 0.001$). Additionally, MON% was lower at recovery vs. post-exercise in *CTRL*, *LOW* and *PLA*, as was PLT count in *LOW*, *MED* and *HIGH*.

Blood Biochemical Markers

All biochemical results are presented in Table 3.

There were significant differences between visits only for magnesium and creatinine concentration at recovery. Blood magnesium concentration was higher in *CTRL* vs. *HIGH* ($p = 0.034$), while creatinine concentration was lower in *CTRL* vs. *LOW* and *PLA* ($p = 0.003$).

There was an increase at post-exercise vs. rest in all study visits for ALT, AST, CK, and LDH, and creatinine, while urea concentrations were decreased. There were no significant differences for magnesium concentration.

Some of the exercise-induced biochemical markers returned to their resting values after a short period of recovery (except magnesium and creatinine concentrations, and ALT and CK activities). Moreover, in comparison to resting values, lower urea concentration ($p < 0.001$) was observed only in *LOW*, while higher AST occurred in *HIGH* ($p < 0.001$) and *CTRL* ($p < 0.001$). LDH was higher at recovery than at rest in *HIGH* ($p = 0.003$).

Urea and magnesium concentration were increased (all $p < 0.001$) at recovery vs. post-exercise in all visits. Additionally, lower ALT in *LOW* ($p < 0.001$), creatinine concentration in *CTRL* ($p < 0.001$) and LDH in *MED* ($p < 0.001$) were shown.

DISCUSSION

To our knowledge, this study is the first to assess different $NaHCO_3$ dose supplementation-induced changes for haematological and biochemical indicators at rest, immediately after high-intensity exercises and after a 45-min recovery period. Undertaking such research could be extremely important to broaden the definition of the effect of this ergogenic agent to human (athlete) metabolism.

Resting values of pH and all haematological and biochemical blood indices did not differ across the five study visits (*CTRL*, *$NaHCO_3$'s*, *PLA*), which proves the homogeneity of the group for the studied indicators. This is an important aspect of research in order to properly compare the studied variables.

Post-exercise changes in blood pH values after taking different $NaHCO_3$ doses compared to *CTRL* and *PLA*, were improved and consistent with those reported so far in the literature [27, 28, 30, 35]. The higher the $NaHCO_3$ dose, the lower the post-workout acidification of the organism and more effective recovery of the index values back to resting values. Such an improvement in regeneration, acid-base balance indicators, when using $NaHCO_3$ before exercise was also presented in the work by Siegler et al. [36] and Mündel [37]. On the other hand, taking $NaHCO_3$ after exercise did not accelerate acid-base balance recovery, as indicated by Gurton et al. [38]. Thus, it seems clear that the ingestion of $NaHCO_3$ has to be performed before efforts and preferably according to specific absorption time [16].

Interestingly, post-exercise WBC counts returned to baseline values faster with all $NaHCO_3$ doses than with *CTRL* or *PLA*. However, these results did not have a direct impact on individual leukocyte subpopulations. The percentage values of LYM and GRA, despite differences between the *CTRL* phase and the remaining visits of study, do not indicate any effect of $NaHCO_3$ intake. In contrast, MON% remained stable throughout the study period with *MED* and *HIGH* $NaHCO_3$ supplementation doses. Such differences might be explained by the fact that the WBC count increases to counter exercise-induced inflammation [39]. Moreover, acidification of the body contributes to such an increase in inflammation [40]. Thus, if athletes supplement alkaline agents before exercise (e.g. with $NaHCO_3$), inflammation may not be aggravated by acidosis and blood leukocytes count will be able to return to the resting state faster. Furthermore, extracellular buffering support may also hamper low blood pH-induced increase of the concentration of magnesium (Mg), due to the release of magnesium ions from complexes with proteins (mainly albumin), which, while buffering the blood, replace Mg with hydrogen (H^+) ions [41].

No effect of $NaHCO_3$ supplementation was noted for the HGB concentration and PLT count. Nevertheless, a relationship between $NaHCO_3$ *MED* or *HIGH* dose supplementation and the lower RBC count between recovery *vs.* resting values was found. This is a surprising result as reducing the acidity of the organism should reduce the risk of osmotic fragility of erythrocytes [42] and thus more RBC with increased buffering capacity would be expected. However, the mechanism of this phenomenon (a decreased of RBC count after $NaHCO_3$ supplementation or metabolic alkalosis) is unknown and according to our literature review no research has been carried out in this respect.

Physical effort, especially of a high intensity nature, leads to substantial changes in the activity of intramuscular enzymes, especially CK and LDH [43]. The elevated level of these indicators persists for a long time after finishing intensive exercise and their return to reference values may last even several days [44]. Alkalizing factors, i.e. $NaHCO_3$, should hypothetically protect muscles against increased damage by hydrogen ions generated during intense exercise. It should be noted that physical efforts also lead to an increase in body temperature, which can additionally damage cells. Interestingly, studies on cell cultures indicate that the presence of $NaHCO_3$ combining with vitamin C protects them from heat damage by increasing their antioxidant capacity [45]. In addition, studies in horses show that the administration of $NaHCO_3$ reduces the symptoms of rhabdomyolysis [46]. After adding this supplement to the diet, the activity of muscle enzymes such as CK and AST were significantly reduced [46]. Similar results should be expected in athletes, although we did not show this in the current study as there was no relationship between the dose of $NaHCO_3$ and their protective role against muscle fibers. However, it should be underlined that no studies have been conducted in this aspect. In addition, our investigation indicated that $NaHCO_3$ does not affect the urea concentration in blood which confirm similar observations in animal (rats) *in vivo* studies [47].

It could also be assumed that highly-trained athletes may have a strengthened buffering capacity potential, while less trained athletes seems to be more dependent on additional $NaHCO_3$ supplementation [48]. In our work, studied participants had substantial training experience (at least 4 years of training experience), so the lack of changes of muscle metabolites and enzymes activity may be the result of their adaptation to HIFT effort.

The strength of the described research is related primarily to the multi-crossover research design and novelty of supplementation of various FFM-adjusted doses in each participant. Much attention was also paid to compliance and control of the protocol, and use of recommended research methods allowing for biochemical monitoring and induction of innovatory divided high-intensity exercises procedure. It is important that the haematological and biochemical indicators determined constitute a kind of novelty in this matter. In addition, they were attended by people who train CrossFit on a daily basis, so the efforts established in the test protocol were familiar to them. It is also important to note that the participants of the research were highly involved in it and received feedback at the end, which increased their compliance and awareness of supplementation with $NaHCO_3$.

Interestingly, it could be suggested that the observed similarities in analyzed results could be linked to the equimolar amount of sodium in $NaHCO_3$ and *PLA* which should be confirmed in further studies.

Finally, the presented study brings a lot of new and important scientific and practical approaches. It seems important to monitor the influence of bicarbonate not only on acid-base balance, but also on other blood measures (haematological and biochemical).

CONCLUSIONS

The present study confirms the positive and dose-dependent alkalizing effect of $NaHCO_3$ after exercise and during a short term recovery period which may be desirable in terms of effective sport practice. The use of $NaHCO_3$ supplementation has a similar effect on haematological markers as a placebo apart from MON%, or WBC count, where a beneficial effect of supplementation on the faster return of the above-mentioned indicators to resting values was observed. Nevertheless, supplementation with $NaHCO_3$ did not affect the post-exercise and recovery efficiency changes of the blood biochemical indicators in any way. The role of sodium intake in this process warrants further studies.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of interest

I.Ł. is a shareholder of an alkali products distributor and has received honoraria from the Sanum Polska sp. z o. o. However, the content of this study was not constrained by this fact in absolutely no extend. K.D.-M., J.K., B.S., A.P., M.S., and T.P. report no conflicts of interest. The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Author Contributions

Study design/planning: K.D.-M.; data collection/entry: K.D.-M., J.K., T.P; data analysis/statistics: K.D.-M, J.K.; data interpretation: K.D.-M., J.K., T.P.; preparation of manuscript: K.D.-M, J.K., B.S., A.P., M.S., T.P.; literature analysis/search: K.D.-M., J.K.; collection of funds: K.D.-M.

Ethics approval

The study protocol was reviewed and approved by the local institutional review board (Bioethics Committee at Poznan University of Medical Sciences, reference number: 1000/18 of 11 October 2018) and registered at *ClinicalTrials.gov* (NCT03810404). All procedures were conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki.

Patients' consent

Written informed consent was obtained from all participants before their participation in the study began.

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Effect of goalkeepers' offensive participation on team performance in the women Spanish La Liga: a multinomial logistic regression analysis

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ABSTRACT: This study aimed to examine the effect of goalkeeper distribution on offensive team performance, during the 2018/2019 and 2019–2020 seasons of the Women Spanish La Liga. A total of 10,868 distributions, during 376 matches were analyzed by systematic observation. Two UEFA PRO coaches designed an ad hoc observation instrument "GOALDFOOT" and one observer coded the data after a training process. An intra-observer reliability kappa index of 0.94 was established. Results show how the offensive effectiveness of the goalkeepers was similar to outfield players, with 0.4% of possessions ending in a goal, 2.2% ending in an attempt on goal, with 79.4% ending unsuccessfully. The goalkeeper lost possession from their distribution 32.5% of the time. Multivariate analysis identified several predictors of goalkeepers' distributions. The results show that teams classified in the middle zone of the final classification of the regular league had 1.2 times more probability of being successful compared with the lowest ranked teams ($p < 0.05$). Goalkeeper's distribution beginning during Open play after a transition, represented an increase success rate of almost 3 times compared to being performed from a free kick ($p < 0.05$). Passes from outfield players to a goalkeeper made from distant zones to the own goal, decreased the probability of success ($p < 0.001$). The pitch location of the distribution outcome near to the opponent goal offered the best probability of success. In conclusion, the most effective offensive sequences occur with dynamic transitions initiated with short passes. This information can provide coaches and players with insights to improve the offensive performance of goalkeepers.

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INTRODUCTION

The specific position of afootball goalkeeper has undergone a remarkable evolution in recent times. A key factor in this transformation, is the regulatory change that prevents the goalkeeper from receiving the ball from a teammate with their hands (1992). This rule allows opponents to press the ball, while the goalkeeper is in possession of the ball, and forces the goalkeeper to play the ball with their feet, requiring greater technical mastery [1, 2]. The goalkeeper has ceased to be solely responsible for the defence of the goal, to have a much more active role, both in the defensive and offensive phases of open play. For example, Pérez-Muñoz et al. [3] demonstrated the percentage of offensive technical actions represents 64.72% of goalkeeper actions during a match. Furthermore, research has identified the predominant technical-tactical actions in football goalkeepers in the Spanish La Liga are foot controls, short passes and goal kicks [1, 4].

Offensively, the football goalkeeper has become another outfield player, starting, and giving continuity to the game, offering a pass option to the player with the ball and becoming a fundamental part in determining the team's offensive game model. Defensively, in addition to being responsible for defending the goal, on many occasions, they are also required to play away from it and to become another defender in defensive transitions [5, 6]. Consequently, this role has increased its relevance in today's football, and it would be interesting to know how the goalkeeper participates in the offensive phase of the team and their importance in its performance. However, scientific knowledge, to date, is scant. In the limited research, there has been investigations into the number and type of offensive and defensive technical actions performed by goalkeepers during matches [3] and a comparative analysis of the technical-tactical actions of goalkeepers based on the competitive category and the location of the match, which reported significant differences in both cases [1]. The only study like the one we propose here, is that of Seaton and Campos [7], who found significant differences in the type of distribution and the success of these, between goalkeepers of teams of different skill levels. But research to date has not attempted to establish a direct relationship between the characteristics of the goalkeeper's offensive participation and the team's offensive performance.

If we focus on women's football, the number of works published to date is even lower. We have only found the work of Sainz de Baranda et al. [6], who carried out an analysis of the technical-tactical actions of the goalkeepers of the Women's FIFA World Cup 2011, to determine the relationship between these actions and the qualifying results of their respective teams, concluding that the goalkeepers of the teams that surpassed the group stages have a greater offensive participation, as well as a greater number of passes completed successfully in different areas of the field. While the goalkeepers of the unclassified teams show greater defensive actions, such as saves inside the penalty area, foot saves and failed punches. Therefore, we have not found any previous work that analyses whether there is a direct relationship between the type of distribution made by the goalkeeper and the team's offensive performance in any women's football competition.

Consequently, due to the non-existent scientific evidence on the influence of the offensive participation of the goalkeeper in the result of the offensive phase of the team in football, we propose the objectives of describing the characteristics of the offensive sequences in the offensive participation of the goalkeeper in the 2018/19 and 2019/20 seasons of the Women Spanish La Liga, to identify the Key Performance Indicators (KPI) in these game situations and, finally, to understand how these indicators can predict the final result of offensive sequences.

For this, we used an observational methodology, since, in team sports and specifically in football, notational analysis through systematic observation is an effective and objective instrument to collect information and identify the most relevant events that occur in them. As Carling et al. [8] highlights when affirming that match analysis has taken a transcendental role in sports. In many cases, observation is the only scientific method that allows data collection directly from the participants in competition without disturbing their action. This observation is typically performed by recording the data through an ad hoc observation instrument while participants act in their natural context [9].

The results will offer information on the characteristics of the distributions with the highest probability of offensive success, which players and coaches can use to apply it to their teams, to aid with performance improvement.

MATERIALS AND METHODS

Design and sample

The specific design corresponding to this systematic observation, according to Anguera et al. [10], was a nomothetic/follow up/multidimensional (N/F/M) design. Moreover, the recording used an intrasessional follow-up observation (frame-by-frame analysis of different

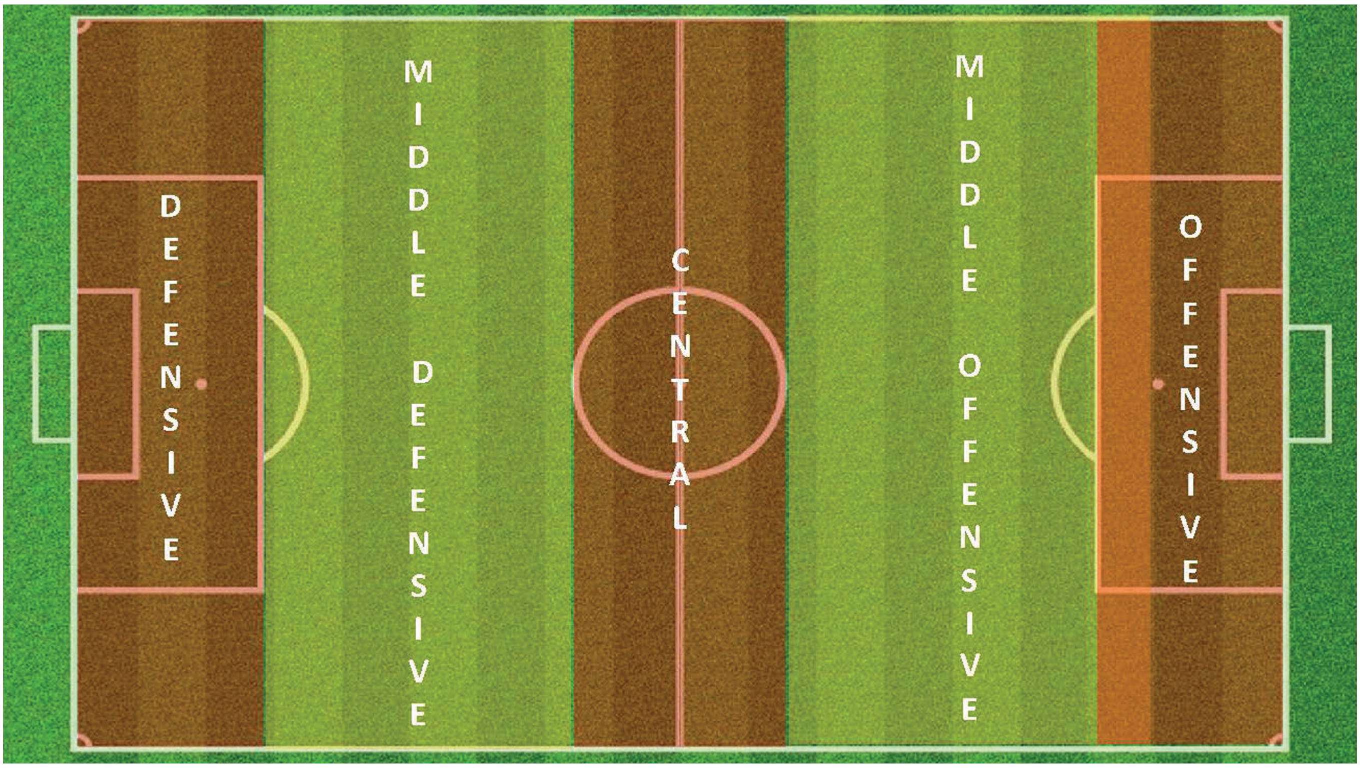

FIG. 1.

TABLE 1. Criteria, categories, and codes to observational instrument

Criteria	Category	Code
Location L	**Home**: The observed team plays at home	HM
	Away: The observed team plays away from home	AW
Team quality TQ	**Best teams:** The best five ranked teams at the end of the regular league	G1
	Medium teams: The six teams classified in the middle zone of the final classification of the regular league	G2
	Bottom teams: The five lowest ranked teams at the end of the regular league	G3
Time T	**0–15 Minutes:** The goalkeeper distribution started within 0–15 minutes of the match time	0–15
	15–30 Minutes: The goalkeeper distribution started within 16–30 minutes of the match time	15–30
	30–45 Minutes: The goalkeeper distribution started within 31 minutes – half time	30–45
	45–60 Minutes: The goalkeeper distribution started within 45–60 minutes of the match time	45–60
	60–75 Minutes: The goalkeeper distribution started within 61–75 minutes of the match time	60–75
	75–90 Minutes: The goalkeeper distribution started within 76 minutes – full time	75–90
Final Result FR	**Win:** The attacking team has scored more goals than the opponent and won the match	FW
	Draw: The attacking team has scored equal goals to the opponent and draw the match	FD
	Loss: The attacking team has scored fewer goals than the opponent and lost the match	FL
Match Status MS	**Winning:** The team in possession has scored more goals than the opposition and at the time of the goalkeeper distribution	WS
	Drawing: The team in possession has scored equal goals to the opposition at the time of the goalkeeper distribution or no goals had been scored	DR
	Losing: The team in possession has scored fewer goals than the opponent at the time of the goalkeeper distribution	LS
Distribution D	**Direct:** The goalkeeper distributes the ball to an attacking outfield player or an area of space in the middle or offensive locations of the pitch, the outfield player must have enough control over the ball to be able to have a deliberate influence on the ball's subsequent direction	DR
	Indirect: The goalkeeper distributes the ball to a defensive outfield player in the defensive zones of the pitch, the outfield player must have enough control over the ball to be able to have a deliberate influence on the ball's subsequent direction	ID
Distribution Type DT	**Goal Kick:** The distribution of play was started by the goalkeeper from a goal kick	GK
	Free Kick: The distribution of play was started by the goalkeeper from a free kick	FK
	Open play to continue the possession: The distribution of play was started by the goalkeeper from open play after a pass from a player from the same team	OP
	Open play after transition: The distribution of play is started by the goalkeeper from open play after the recovery of the ball and to start the offensive transition	OR
Distribution Zone DZ	**Inside the box:** The goalkeeper started the distribution inside the penalty area	IB
	Outside the box: The goalkeeper started the distribution outside the penalty area	OB
Defensive Pressure DP	**High Press:** A player from the opposing team is pressing the goalkeeper when they start the distribution	HG
	Low Press: The goalkeeper started the distribution without an opposition player near them	LW
Number of passes NP	**0:** No passes were completed, including the goalkeeper distribution, before an outcome was performed	0
	1–3: 1–3 passes were completed including the goalkeeper distribution before an outcome was performed	1–3
	4–6: 4–6 passes were completed including the goalkeeper distribution before an outcome was performed	4–6
	> 6: More than 6 complete passes occurred including the goalkeeper distribution before an outcome was performed	> 6
Pitch Location of Distribution PLD	**Defensive:** The ball is distributed by the goalkeeper into the defensive zone of the pitch	DF
	Middle Defensive: The ball is distributed by the goalkeeper into the middle defensive zone of the pitch	MD
	Central: The ball is distributed by the goalkeeper into the central zone of the pitch	CE
	Middle Offensive: The ball is distributed by the goalkeeper into the middle offensive zone of the pitch	MO
	Offensive: The ball is distributed by the goalkeeper into the offensive zone of the pitch	OF

TABLE 1. Continue

Criteria	Category	Code
Pitch Location of Outcome PLO	**Defensive:** The outcome of play is performed in the defensive zone of the pitch	DF
	Middle Defensive: The outcome of play is performed in the middle defensive zone of the pitch	MD
	Central: The outcome of play is performed in the central zone of the pitch	CE
	Middle Offensive: The outcome of play is performed in the middle offensive zone of the pitch	MO
	Offensive: The outcome of play is performed in the offensive zone of the pitch	OF
Pitch Zone of First Pass by Outfield Play PZFPO	**Ø:** Goalkeeper does not receive the ball by an outfield player	**Ø**
	Defensive: The ball is passed by the outfield player to the goalkeeper into the defensive zone of the pitch	DF
	Middle Defensive: The ball is passed by the outfield player to the goalkeeper into the middle defensive zone of the pitch	MD
	Central: The ball is passed by the outfield player to the goalkeeper into the central zone of the pitch	CE
	Middle Offensive: The ball is passed by the outfield player to the goalkeeper into the middle offensive zone of the pitch	MO
	Offensive: The ball is passed by the outfield player to the goalkeeper into the offensive zone of the pitch	OF
Outcome OUT	**Goal:** When the whole of the ball crosses over the line, between the goal posts and under the crossbar, provided no offence has been committed by the scoring team. The referee awarded a goal	GO
	Attempt ON Target: An attempt on goal by the attacking team that were heading towards the goal which was saved by the goalkeeper or blocked by a defensive player of the opposing team	AO
	Attempt OFF Target: An attempt by the attacking team which was not directed between the dimensions of the goal including hitting the crossbar or goal posts	AF
	Set-play: A set piece was awarded to the attacking team in the form of a free kick, corner, penalty kick or throw-in	SP
	Loss of Possession: The attacking team lost possession of the ball through the ball going out of the dimensions of the pitch or an opposing team player regaining possession of the ball, with enough control to have a deliberate influence over the ball's subsequent direction	LP
	Goalkeeper Loss of Possession: The attacking team lost possession of the ball through the ball going out of the dimensions of the pitch or directly to an opposition player directly from the goalkeeper's distribution of the ball	LG
	Returned to Goalkeeper: The team with possession pass the ball back to the goalkeeper. The goalkeeper has enough control over the ball to have a deliberate influence over the ball's subsequent direction	RG

matches) and was captured, post event, using the ad hoc observation instrument. Data analyzed is of type IV [11].

All teams (n = 18) and 376 games from the 2018/19 and 2019/20 seasons of La Liga Iberdrola were analyzed, resulting in 10,868 goalkeepers' distributions, cropped from full game footage obtained from InStat Ltd (http://instatsport.com). The recording of the information was carried out respecting the behavior spontaneity of the players and in their natural environment. According to the Belmont Report [12], the use of public images for research purpose does not require informed consent or the approval of an ethical committee.

Observation instrument

Anguera et al. [13] guidance was followed for the creation of the observation instrument. First, a hierarchical range of behavior units was established, which was implemented through the adoption of basic criteria for behavior segmentation. The creation of the observation instrument was based on the following pillars: i) a previous theoretical framework; ii) criteria and categories compiled empirically in other observational studies; iii) and, finally, novel criteria that were tested in this work. The methodological steps implemented were the following: First, the problem was identified, and an expert scientific group was formed, comprising of two academic (with PhDs in Physical Activity and Sports Sciences) and UEFA PRO coaches, with more than ten years of experience in observational methodology and performance football analysis. After consulting the theoretical framework and empirical evidence, a first post-event exploratory observation was made. Then, and after a discussion by the group of experts, the problem was divided into smaller units. Subsequently, an ad hoc observation instrument, denominated GOALDFOOT (Table 1), consisting of field format and category systems, was created, and tested in order to find weaknesses in the instrument itself. Then, after further discussion by the group of experts, the observation instrument was readjusted. Finally, the post-event viewing was carried out, to finalize the implementation of the observation instrument. The field format was divided into five zones parallel to the goal [14], (Figure 1).

Procedure and reliability

Data were coded by one observer and prior to the coding process, and to reduce intra-observer variability, eight training sessions, lasting two hours, were carried out following the Losada and Manolov [15] criteria and applying the criterion of consensual agreement [16] among the observer and the principal investigator, so that recording was only done when agreement was produced. A total of 857 distributions were analyzed in the training sessions. An intra-observer reliability test was conducted through reassessment of 1,087 goalkeeper distributions (10%), [17] randomly selected, four weeks after the initial analysis [18]. Cohens's Kappa coefficient calculation [19] was used to quantify the intra-observer reliability of the data collected by the researcher. Reliability of each category is presented in Table 2, with the number of passes presenting the lowest value (0.85), considered excellent according to Fleiss et al. [20] scale.

Data analysis

In accordance with the aims of the study, both descriptive (frequency distribution tables) and inferential statistics (bivariate and multivariate analysis) were used in the analysis. The bivariate analysis (Pearson's χ^2) examined the association between the outcome and explanatory variables and the effect size was calculated from the contingency coefficient. The effect size was calculated and described as small (ES = 0.10), medium (ES = 0.30) or large (ES > 0.50) [21]. For multivariate statistical analysis, first, we recoded the Outcome into three new criteria: Successful (goal, attempt on and off target), unsuccessful (loss of possession, goalkeeper loss of possession) and possession continued (set-play). All distribution, which resulted in a return to goalkeeper were excluded (1,011), as this was deemed a neutral outcome, and began a new goalkeeper distribution, therefore resulting in the final analysis of 9,857 distributions. Multinomial logistic regression analysis was then used to examine which factors significantly influenced the outcome sequences involving the goalkeeper. Our reference category in the regression analysis was the unsuccessful outcome, and the results of the multinomial logistic regression analysis are presented as odds ratios. We also calculated the effect size [22] based on the coefficient of determination $R^2_{N.}$ R program (v.3.4.1) using "nnet" library was used to run all analyses, and the level of significance for each performance indicator was set at 5% ($p < 0.05$) as usual in comparable scientific studies [23].

TABLE 2. Intra-observer reliability values for notational analysis data quantified using a Cohen's Kappa calculation

Criteria	Intra-rater value
Time	1.00
Distribution	1.00
Distribution Type	1.00
Distribution Zone	0.94
Defensive Pressure	0.89
Number of Passes	0.85
Pitch Location Distribution	0.96
Pitch Location Outcome	0.87
Pitch Zone of First Pass by Outfield Play	0.92
Outcome	0.98
KTotal	**0.94**

RESULTS

Descriptive and bivariate analysis

A total of 10,868 goalkeeper distributions were analyzed within the study, with an average of 28.9 per game, of which 0.4% ended in a goal, 2.2% ended with an attempt and in 79.4% of the occasions there was a loss of possession. The goalkeeper loss possession 32.5% of the time. Table 3 displays the results of the descriptive and bivariate analysis of the offensive play in which there was an offensive intervention by the goalkeeper. The best ($p < 0.001$), win ($p < 0.001$) and winning teams ($p = 0.005$) achieved more exits than the rest of the teams. There were significant differences ($p < 0.001$) between direct and indirect distributions. Indirect distributions were more successful than the direct distribution which usually ended with goalkeeper loss of possession (92.6%). Goalkeeper distributions were most common from Open play (38%). The offensive sequences with 4–6 passes were the most successful ($p < 0.001$). The pitch location distribution resulting in the most unsuccessful outcome was the offensive zone, with the middle defensive zone being the most successful ($p < 0.001$).

Multivariate analysis

Table 4 shows the results of the multinomial analysis comparing the unsuccessful results (NEX) with the successful ones (EX) and with continuing possession of the ball (CP). The model explained 87.66% of the changes in outcome of offensive sequences with goalkeeper distribution, suggesting that it is a good fit with the data. The accuracy of the test dataset was 0.17% higher compared to the training dataset, therefore we did not have an overfitting problem. The coefficient of determination R^2_N has a small value of 0.165, according to the Cohen's scale [21], (small, ES = 0.21–0.49; medium, ES = 0.50–0.70 or large, ES > 0.80).

Compared to the bottom teams (3), the medium teams (2) were 1.2 times more likely to continue possession. The open play after transition achieved 2.7 more probability of success than distribution from free kicks. Increasing the number of passes in offensive

TABLE 3. Absolute frequencies, percentage occurrence of total distribution and association with outcome

	Outcome								
	EX			NEX		CP		χ^2	
	Attempt Off Target	Attempt On Target	Goal	GK Loss of Possession	Loss of Possession	Set play	Returned to Goalkeeper	*P*-value	*ES*
Location								0.174	---
Home	70 (53.4%)	51 (46.8%)	29 (64.4%)	1529 (47.7%)	2757 (50.8%)	441 (47.0%)	490 (48.5%)		
Away	61 (46.6%)	58 (53.2%)	16 (35.6%)	1678 (52.3%)	2670 (49.2%)	497 (53.0%)	521 (51.5%)		
Team Quality								< 0.001	0.08
Best teams	79 (60.3%)	59 (54.1%)	29 (64.4%)	892 (27.8%)	2208 (40.7%)	365 (38.9%)	488 (48.3%)		
Medium teams	28 (21.4%)	36 (33.0%)	12 (26.7%)	1246 (38.9%)	1822 (33.6%)	349 (37.2%)	317 (31.4)		
Bottom teams	24 (18.3%)	14 (12.8%)	4 (8.9%)	1069 (33.3%)	1397 (25.7%)	224 (23.9%)	206 (20.4%)		
Time								0.579	---
0–15	17 (13%)	19 (17.4%)	12 (26.7%)	524 (16.3%)	1093 (20.1%)	174 (18.6%)	202 (20.0%)		
16–30	19 (14.5%)	21 (19.3%)	6 (13.3%)	474 (14.8%)	926 (17.1%)	171 (18.2%)	193 (19.1%)		
31–HT	22 (16.8%)	12 (11%)	4 (8.9%)	483 (15.1%)	857 (15.8%)	156 (16.6%)	202 (20.0%)		
46–60	22 (16.8%)	14 (12.8%)	10 (22.2%)	511 (15.9%)	864 (15.9%)	131 (14.0%)	159 (15.7%)		
61–75	24 (18.3%)	14 (12.8%)	9 (20.0%)	488 (15.2%)	814 (15.0%)	144 (15.4%)	134 (13.3%)		
76–FT	27 (20.6%)	29 (26.6%)	4 (8.9%)	727 (22.7%)	873 (16.1%)	162 (17.3%)	121 (12.0%)		
Final Result								< 0.001	0.050
Draw	30 (22.9%)	28 (25.7%)	3 (6.7%)	772 (24.1%)	1225 (22.6%)	213 (22.7%)	190 (18.8%)		
Loss	36 (27.5%)	31 (28.4%)	8 (17.8%)	1241 (38.7%)	2037 (37.5%)	337 (35.9%)	363 (35.9%)		
Win	65 (49.6%)	50 (45.9%)	34 (75.6%)	1194 (37.2%)	2165 (39.9%)	388 (41.4%)	458 (45.3%)		
Match Status								0.005	0.039
Drawing	55 (42.0%)	49 (45.0%)	18 (40.0%)	1505 (46.9%)	2577 (47.5%)	440 (46.9%)	435 (43.0%)		
Losing	28 (21.4%)	26 (23.9%)	5 (11.1%)	848 (26.4%)	1421 (26.2%)	249 (26.5%)	257 (25.4%)		
Winning	48 (36.6%)	34 (31.2%)	22 (48.9%)	854 (26.6%)	1429 (26.3%)	249 (26.5%)	319 (31.6%)		
Distribution								< 0.001	0.142
Direct	34 (26.0%)	36 (33.0%)	14 (31.1%)	2970 (92.6%)	1699 (31.3%)	313 (33.4%)	47 (4.6%)		
Indirect	97 (74.0%)	73 (67.0%)	31 (68.9%)	237 (7.4%)	3728 (68.7%)	625 (66.6%)	964 (95.4%)		
Distribution Type								< 0.001	0.074
Free Kick	4 (3.1%)	1 (0.9%)	1 (2.2%)	234 (7.3%)	243 (4.5%)	293.1%	38 (3.8%)		
Goal Kick	16 (12.2%)	18 (16.5%)	5 (11.1%)	947 (29.5%)	1343 (24.7%)	209 (22.3%)	261 (25.8%)		
OP	59 (45.0%)	50 (45.9%)	21 (46.7%)	1084 (33.8%)	2133 (39.3%)	397 (42.3%)	449 (44.4%)		
OR	52 (39.7%)	40 (36.7%)	18 (40.0%)	942 (29.4%)	1708 (31.5%)	303 (32.3%)	263 (26.0%)		
Distribution zone								0.208	---
Inside box	109 (83.2%)	89 (81.7%)	41 (91.1%)	2759 (86.0%)	4728 (87.1%)	830 (88.5%)	919 (90.9%)		
Outside box	22 (16.8%)	20 (18.3%)	4 (8.9%)	448 (14.0%)	699 (12.9%)	108 (11.5%)	92 (9.1%)		
Defensive pressure								0.06	---
High press	20 (15.3%)	15 (13.8%)	10 (22.2%)	912 (28.4%)	801 (14.8%)	155 (16.5%)	74 (7.3%)		
Low press	111 (84.7%)	94 (86.2%)	35 (77.8%)	2295 (71.6%)	4626 (85.2%)	783 (83.5%)	937 (92.7%)		
Number of passes								< 0.001	0.272
0	0 (0.0%)	0 (0.0%)	2 (4.4%)	3203 (99.9%)	7 (0.1%)	82 (8.7%)	2 (0.2%)		
1–3	39 (29.8%)	34 (31.2%)	12 (26.7%)	3 (0.1%)	3770 (69.5%)	591 (63.0%)	807 (79.8%)		
4–6	54 (41.2%)	34 (31.2%)	17 (37.8%)	0 (0.0%)	1136 (20.9%)	171 (18.2%)	161 (15.9%)		
> 6	38 (29.0%)	41 (37.6%)	14 (31.1%)	1 (0.0%)	514 (9.5%)	94 (10.0%)	41 (4.1%)		

TABLE 3. Continue

Pitch Location of Distribution								< 0.001	0.213
Defensive	17 (13.0%)	10 (9.2%)	8 (17.8%)	0 (0.0%)	1066 (19.6%)	167 (17.8%)	403 (39.9%)		
MD	88 (67.2%)	66 (60.6%)	27 (60.0%)	11 (0.3%)	3079 (56.7%)	522 (55.7%)	590 (58.4%)		
Central	23 (17.6%)	27 (24.8%)	5 (11.1%)	3 (0.1%)	1100 (20.3%)	144 (15.4%)	16 (1.6%)		
MO	3 (2.3%)	5 (4.6%)	3 (6.7%)	0 (0.0%)	166 (3.1%)	23 (2.5%)	0 (0%)		
Offensive	0 (0.0%)	1 (0.9%)	2 (4.4%)	3193 (99.6%)	16 (0.3%)	82 (8.7%)	2 (0.2%)		
Pitch Location of Outcome								0.532	---
Defensive	0 (0.0%)	0 (0.0%)	0 (0.0%)	40 (1.2%)	40 (0.7%)	17 (1.8%)	950 (94%)		
MD	0 (0.0%)	0 (0.0%)	1 (2.2%)	611 (19.1%)	736 (13.6%)	214 (22.8%)	59 (5.8%)		
Central	0 (0.0%)	0 (0.0%)	2 (4.4%)	1916 (59.7%)	1742 (32.1%)	319 (34.0%)	1 (0.1%)		
MO	44 (33.6%)	28 (25.7%)	4 (8.9%)	603 (18.8%)	1983 (36.5%)	270 (28.8%)	0 (0.0%)		
Offensive	87 (66.4%)	81 (74.3%)	38 (84.4%)	37 (1.2%)	926 (17.1%)	118 (12.6%)	1 (0.1%)		
Pitch Zone of First Pass by Outfield Play								0.416	---
Ø	72 (55.0%)	59 (54.1%)	24 (53.3%)	2136 (66.6%)	3309 (61.0%)	542 (57.8%)	562 (55.6%)		
Defensive	10 (7.6%)	7 (6.4%)	5 (11.1%)	222 (6.9%)	375 (6.9%)	70 (7.5%)	81 (8%)		
MD	41 (31.3%)	39 (35.8%)	16 (35.6%)	795 (24.8%)	1594 (29.4%)	304 (32.4%)	339 (33.5%)		
Central	8 (6.1%)	4 (3.7%)	0 (0.0%)	54 (1.7%)	144 (2.7%)	22 (2.3%)	29 (2.9%)		
MO	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	5 (0.1%)	0 (0.0%)	0 (0.0%)		

EX: successful; NEX: unsuccessful; CP: continued possession; OP: Open play to continue the possession; OR: Open play after transition; MD: Middle defensive; MO: Middle offensive; ES: Effect Size calculated as contingency coefficient

sequences were more likely to continue possession and finish successfully. Switching from making a pass from an outfield play from the DF zone to the MD or MO meant a decrease in the probability of continuing possession or finishing successfully. In relation to PLO, the zones furthest from the own goal (CE, MO and OF), compared to DF, showed greater probabilities of not succeeding than of continuing possession. All the zones furthest from the goalkeeper reported higher odds of success than non-success.

DISCUSSION

The aim of this study was threefold: to analyse how goalkeeper's distributions are produced in Women Spanish La Liga in terms of habitual practices, incidence, and efficiency, to identify KPI's and to check the power predictive of these KPI's. Here, the average number of goalkeeper's distribution was 28.9 per game which is similar to previous observations in men's [24, 25] and women's football [6] which analyzed the goalkeeper offensive actions.

Distributions from the goalkeeper, resulting in goals scored (0.4%) and attempts (2.2%) were low, with 79.4% of offensive sequences ending unsuccessfully, with the goalkeeper losing possession 32.5% of the time. These values are slightly lower than those reported by Iván-Baragaño et al. [26] who indicate that the possession of female teams end with no success in 75% of the occasions, 9% ended in a shot, and 1.1% with a goal. Maneiro et al. [27] also report slightly higher result, with 69% of ball possession ending unsuccessfully, 2.1% ending in a goal and 11.2% ending in shot. Although we must consider that in both studies the offensive sequences analyzed were initiated by all the players, not only the goalkeepers. Sainz de Baranda et al. [6] found that 37.7% of the attacks started by the goalkeeper lead to a loss of possession. Despite the matches corresponding to the FIFA Women's World Cup being analyzed in these studies, the goalkeeper's offensive efficiency was like that of the outfield players.

The bivariate analysis shows that the best teams, win and winning teams had more successful distributions than the rest of the teams. Surprisingly, two factors that, a priori, could influence the outcome of the offensive sequences, such as match location and defensive pressure, have not shown significant differences. Match location has been identified as a key factor in the offensive performance of women's teams [28] and defensive pressure over the goalkeeper, could lead to an increase in the number of errors, however, these circumstance did not led to a decrease in the goalkeeper's offensive effectiveness which coincides with work in men's football [29]. A possible explanation is an increase in the goalkeepers technical-tactic skill level with the feet, who are increasingly used to solve one-on-one offensive situations. Another possible explanation, is that opposing team only put pressure on the goalkeeper, but did not close the passing lines to their teammates, resulting on this type of pressure being ineffective. However, as pressure of teammates was not measured here, it is necessary to continue investigating these situations to understand the influence of these two factors on the offensive performance of goalkeepers and included the pressure over the rest of offensive player.

Indirect distributions were more effective in comparison to direct distributions. Logically, indirect distributions involve short passes to nearby players hence will be more effective in comparison to long passes to more distant players using a direct distribution. The probability of losing possession of the ball during direct distributions is higher, due to lower precision of the pass and greater difficulty of the reception with defensive players having increased time to decide and act to intercept or win the ball. In addition, a long pass by a goalkeeper in women's football does not usually exceed the midfield zone, so a second play against will be a disadvantage for the team as the defensive line faces the team's midfield and forward lines.

The greatest offensive participation of the goalkeeper consisted of giving continuity to the game, giving support to their teammates, and starting the game after an offensive transition. In addition, these interventions have shown greater effectiveness than static actions. Similarly, Sainz de Baranda et al. [6] indicated that the kick pass was most frequently used offensive action. This is a fundamental circumstance in today's football to ensure possession of the ball is retained when the team has no chance of progressing forwards, with back passes to the goalkeeper ensuring possession of the ball and result in more passing options by increasing the available field of play space. This situation means that the offensive participation of the goalkeeper has increased considerably, as corroborated by the work of Sainz de Baranda et al. [6] who suggest the goalkeeper had become another outfield player to keep possession of the ball and offer new attacking possibilities.

The number of passes also turned out to be an indicator of the offensive performance of goalkeeper distributions. As happens with possessions without the intervention of the goalkeeper, possessions with a greater number of passes offer greater guarantees of success than those of short duration. Finally, pitch location of distribution has also been shown to be a key performance indicator in goalkeeper's distributions. The goalkeeper's distributions were more effective to the middle defensive zone and were less effective to the offensive zone. These can be explained, like indirect distributions as the goalkeeper's short passes are to the areas closest to their goal and pose less risk than long passes to areas further away and with greater defensive density.

The multivariate analysis has allowed us to find five predictors of the outcome of the goalkeeper distributions (Team quality, Distribution type, Nº passes, Pitch zone of first pass by outfield play and Pitch location outcome). Being a team with a medium performance level offered 1.2 times more chances of being successful in offensive sequences in which the goalkeeper participates, supporting previous research that indicated the goalkeeper of higher level teams were more successful in distributions [6, 7, 30]. These results are likely explained by the higher technical-tactical level of the players of the best teams and by the tactical of these teams. The bottom teams usually have less tactical predisposition to start the offensive phase by playing the ball short.

Starting a goalkeeper distribution through Open play after transitions, that is, with a dynamic offensive transition, meant an increase of almost 3 times compared to doing it through a free kick. This result supports the idea of previous studies that indicate that transitions offer greater probabilities of offensive success than offensive sequences that start in a static way [29, 31, 32], due to the defensive imbalance of the rival team.

Number of passes also revealed as a good predictor, specifically, increasing the number of passes, increases the probability of success by more than 3 times, coinciding with the studies that indicate that possessions of longer duration are more effective offensively than those of short duration [14, 29, 31, 33, 34]. Here, the start of the offensive sequence is carried out from a position far from the opponent's goal and, therefore, it will be necessary to make a minimum of passes to be able to take the ball towards the goal area.

The passes of an outfield player with the highest probability of success were from the defensive zone. Receiving passes from further away areas, slightly lowered the chances of success and of continuing possession of the ball. The explanation of these results may be the same as that indicated for the type distributions (greater distance of the pass, less precision, greater difficulty in reception, and greater defensive possibilities).

Finally, Pitch location of outcome was the best predictor of distribution outcome. However, this data does not provide very relevant information, because it is obvious that the closer the offensive sequence ends to the rival goal, the greater the chances of success it will have, as the highest percentage of goals and shots are made from areas close to the rival goal [22].

The results of this research allow us to know the usual practices of the goalkeeper's distributions in elite women's football, their key performance indicators and how to modify these indicators to increase their effectiveness. This information can be used to design training programs with specific loads for goalkeepers and to try to promote the reproduction of behaviors that favor success and avoid less favorable behaviors in these game situations. In addition, this information could help coaches to select the strategy to execute this type of game situations and to justify their decisions to their players.

This study does includes some limitations. Firstly, only one national league has been analyzed, so the results will only be extrapolated to this population. In addition, since this is a league with large differences in team quality between the participating teams, the quality of opposition in the analyzed games could be a variable that affects the outcome of the analyzed actions. For this reason, future research approaches should be directed towards the study of different national leagues and/or national team championships to obtain a more homogeneous sample of matches. Lastly, this aspect could help to improve the predictive power of the statistical models proposed. In

TABLE 4. Multinomial logistic regression predicting to scoring, achieve scoring opportunity and continued possession vs. loss possession (Reference Category).

	Goalkeeper's Distribution Outcome							
	CP				EX			
Predictor	***β***	***P***	**Odds ratio**	**IC (95%)**	***β***	***P***	**Odds ratio**	**IC (95%)**
Team Quality								
1	0.02	0.80	1.0249	0.84–1.24	0.26	0.19	1.30	0.87–1.93
2	0.18	0.04	1.2037	1.00–1.44	0.09	0.63	1.10	0.73–1.65
3#								
Match Location								
Home	0.16	0.06	0.85	0.73–0.97	0.16	0.24	0.85	0.64–1.11
Away#								
Time								
16–30	0.14	0.23	1.15	0.91–145	-0.02	0.90	0–97	0.62–1.52
31–HT	0.15	0.21	1.16	0.91–1.49	-0.20	0.39	0.81	0.50–1.30
46–60	-0.02	0.84	0.97	0.75–1.26	0.07	0.77	1.07	0.66–1.72
61–75	0.12	0.32	1.13	0.88–1.47	0.07	0.76	1.07	0.67–1.72
76–FT	0.16	0.19	1.18	0.91–1.52	0.39	0.09	1.48	0.93–2.34
0–15#								
Final Result								
Draw	0.09	0.39	1.09	0.88–1.36	0.22	0.32	1.24	0.80–1.93
Win	0.16	0.15	1.18	0.94–1.48	0.35	0.12	1.41	0.90–2.23
Loss#								
Match Status								
Drawing	-0.05	0.63	0.94	0.76–1.18	-0.06	0.76	0.93	0.59–1.46
Winning	-0.10	0.42	0.89	0.68–1.17	0.03	0.90	1.03	0.61–1.72
Lossing#								
Distribution zone								
Outside box	21.31	0.06	1.80e0+9	1.20e0+9–2.69e0+9	34.41	0.072	8.85e+14	5.06e0+14–1.55e+15
Inside box#								
Dristribution Type								
Goal Kick	0.17	0.40	1.19	0.78–1.82	0.59	0.21	1.80	0.70–4.60
Open Play Continue	-0.27	0.68	0.75	0.20–2.88	0.42	0.69	1.52	0.18–12.36
Open Play Transition	0.38	0.06	1.46	0.97–2.20	0.98	0.03	2.68	1.10–6.51
Free Kick#								
Distribution								
Indirect	-0.01	0.90	0.98	0.76–1.26	-0.33	0.20	0.71	0.43–1.19
Direct#								
Nº passes								
4–6	0.09	0.35	1.10	0.90–1.34	0.74	< 0.001	2.10	1.51–2.91
> 6	0.35	0.007	1.42	1.10–1.85	1.15	< 0.001	3.19	2.22–4.57
1–3#								
Pitch Zone o First Pass by Outfield Play								
Central	-0.04	0.88	0.96	0.55–1.67	0.09	0.84	1.09	0.46–2.59
Middle Defensive	0.08	0.60	1.08	0.81–1.45	-2.60	< 0.001	0.07	0.07–0.07
Middle Offensive	-27.70	< 0.001	9.25e-13	9.25e-13–9.25e-13	-24.92	< 0.001	1.50e-11	1.50e-11–1.50e-11
Defensive#								

TABLE 4. Continue

Pitch Location of Distribution								
Central	0.01	0.95	1.01	0.71–1.43	0.47	0.17	1.60	0.81–3.15
Middle Defensive	0.09	0.41	1.09	0.88–1.34	0.08	0.71	1.08	0.71–1.65
Middel Offensive	0.21	0.47	1.23	0.70–2.15	0.19	0.70	1.20	0.47–35.50
Offensive	-0.55	0.58	0.57	0.08–4.13	1.24	0.30	3.46	0.34–35.50
Defensive#								
Pitch Location of Outcome								
Central	-0.88	0.003	0.42	0.23–0.74	8.42	< 0.001	4538.25	1374.93–14979.48
Middle Defensive	-0.38	0.19	0.68	0.38–1.20	8.70	< 0.001	6042.99	1246.18–29303.86
Middle Offensive	-1.14	< 0.001	0.32	0.18–0.57	11.80	< 0.001	133801.63	71905.97–248976.22
Offensive	-1.25	< 0.001	0.28	0.16–0.52	13.37	< 0.001	640716.10	345793.16–1.19e0+6
Defensive#								
Defensive Pressure								
High	26.47	0.08	3.14e+11	2.13e+11–4.62e+11	13.25	0.10	565577.77	32459.43–98548.55
Low#								

#, Reference category; β, Beta coefficient; CI, Confidence interval; $p < 0.05$, $p < 0.01$, $p < 0.001$.

this work we have only analyzed the pressure exerted on the goalkeeper, but not on the rest of the field players, nor have we analyzed the passing lanes offered by the outfield players, when the goalkeeper had possession, nor the spatial layout of the outfield players, both from the observed team and from the opponent. Therefore, future work could take these issues into consideration when designing the observation instrument, since it could help explain some of the results obtained. Considering these results, the technical staff should train the goalkeeper-initiated offensive dynamic transitions with the characteristics that show the results to increase performance in these game situations.

CONCLUSIONS

According to the results obtain in the current research, it can be concluded that the offensive effectiveness of the goalkeepers is like that all of outfield players, since the success of the exit of offensive sequences with goalkeeper's participation is like that of outfield players. The greatest offensive participation of the goalkeeper is carried out to give continuity to the game and in dynamic offensive transitions, the latter being the ones that offer a greater probability of success. To increase success in these game situations, passes to the goalkeeper should be from the defensive zone and the goalkeeper should send the ball to the near zones by means of a short pass and the offensive sequence should be built with 3–6 passes. Direct distributions by the goalkeeper, by means of long passes to areas away from the goal, frequently end with a loss of possession by the goalkeeper. Therefore, the goalkeeper plays an important role in ensuring possession of the ball and giving continuity to the game and in dynamic offensive transitions.

Conflicts of interest

The authors declare no conflicts of interest.

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Evaluation of the Vmaxpro sensor for assessing movement velocity and load-velocity variables: accuracy and implications for practical use

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ABSTRACT: We investigated the ecological validity of an inertial measurement unit (IMU) (Vmaxpro) to assess the movement velocity (MV) during a 1-repetition maximum (1RM) test and for the prediction of load-velocity (*L-V*) variables, as well as the ecological intra-day and inter-day reliability during free-weight bench press (BP) and squat (SQ). Furthermore, we provide recommendations for the practical use of the sensor. Twenty-three strength-trained men completed an incremental 1RM test, whereas seventeen men further participated in another 3 sessions consisting of 3 repetitions with 4 different loads (30, 50, 70 and 90% of 1RM) to assess validity and intra- and inter-day reliability, respectively. The MV was assessed using the Vmaxpro and a 3D motion capture system (MoCap). *L-V* variables and the 1RM were calculated based on submaximal velocities. The Vmaxpro showed high validity during the 1RM test for BP ($r = 0.935$) and SQ ($r = 0.900$), but with decreasing validity at lower MVs. The *L-V* variables and the 1RM demonstrated high validity for BP ($r = 0.808$–0.942) and SQ ($r = 0.615$–0.741) with a systematic overestimation. Coefficients of variance for intra- and inter-day reliability ranged from 2.4% to 9.7% and from 3.2% to 8.6% for BP and SQ, respectively. The Vmaxpro appears valid at high and moderately valid at low MVs. Depending on the required degree of accuracy, the sensor may be sufficient for the prediction of *L-V* variables and the 1RM. Our data indicate the sensor to be suitable for monitoring changes in MVs within and between training sessions.

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INTRODUCTION

Measuring movement velocity during strength training has become an increasingly important and versatile method for training monitoring and evaluation in both athletic [1] and clinical [2] populations. For example, training loads may be individualised by relative velocity loss thresholds [1], leading to favourable power adaptations compared to traditional strength training based on the percentage of the 1-repetition maximum (1RM) [3]. Furthermore, due to the linear load-velocity (*L-V*) relationship in multi-joint exercises, the determination of velocity at submaximal loads (i.e. within 30–80% of the 1RM) can be used as a time-efficient non-demanding method to predict the 1RM [4]. In line with this, other *L-V* relationship variables can provide a more complete evaluation of neuromuscular capacities. As such, the load-axis intercept (i.e., load at zero velocity: L_0), the velocity-axis intercept (i.e., velocity at zero load: v_0) and the area under the line of the *L-V* relationship ($A_{line} = L_0 \cdot v_0/2$) can be used to evaluate the ability of muscles to produce maximal force, velocity and power, respectively [5].

Optical 3-dimensional (3D) motion capture systems (MoCap, e.g. Vicon) are considered the gold standard for assessing movement velocity [6]. However, since this method is labour intensive and expensive, more practical technologies such as linear position-velocity transducers (e.g. GymAware, T-Force) and wearable wireless inertial measurement units (IMUs, e.g. Myotest, OUTPUT) are gaining popularity. Apart from the portability as well as the simplicity of use, linear position-velocity transducers and IMUs have the advantage of providing direct feedback on the movement velocity. In turn, using feedback was shown to have a positive impact on the movement velocity [7], possibly resulting in better power adaptations [8]. While linear position-velocity transducers are attached to the body or the barbell by a cable extension, IMUs are wireless and more cost-effective. However, IMUs are based on the combination of signals from multiple sensors (i.e., accelerometers, gyroscope and magnetic sensors) to estimate movement velocity, and therefore the validity and reliability of IMUs should be considered carefully [9].

One commercially available triaxial IMU that is gaining popularity among practitioners worldwide is the Vmaxpro sensor (Blaumann & Meyer-Sports Technology UG, Magdeburg, Germany). However, scientific data on the validity and the reliability of the Vmaxpro are lacking. In our previous study, the sensor showed high validity ($R^2 = 0.935$) compared to the criterion device (i.e., Vicon) and moderate to high interclass correlation coefficients (ICCs) for intra-day (ICC: 0.662–0.938; $p \leq 0.05$) and inter-day reliability (ICC: 0.568–0.837; $p \leq 0.05$) for the evaluation of mean velocity (MV) in the deep squat (SQ) [10]. The data, however, were obtained in a Smith machine with a guided barbell pathway. One advantage of IMUs is their capability to assess movement velocity in three axes, and the validity and the reliability of IMUs are influenced by the type of the resistance exercise [11].

Considering this, we aimed to investigate the ecological validity and test-retest reliability of the Vmaxpro using free weights in both bench press (BP) and SQ exercise. Furthermore, to better understand how the possible deviation of the Vmaxpro influences training practice, we assessed the validity of the Vmaxpro to predict *L-V* variables (i.e., L_0, v_0, A_{line}) and the 1RM. Taken together, the aims of our study were to investigate: (1) the ecological validity of the Vmaxpro during an 1RM test; (2) the ecological validity for the prediction of *L-V* variables; (3) the ecological intra-day reliability; and (4) the ecological inter-day reliability.

MATERIALS AND METHODS

Study design

The study employed a repeated-measures design (Figure 1), with participants completing a total of 4 sessions. During the first visit, participants were familiarised with the BP and SQ protocols and performed an incremental BP and SQ 1RM test. In the following three sessions (i.e. sessions 2–4), the participants performed an experimental session with 3 repetitions at 4 different loads (i.e., 30, 50, 70, and 90% of 1RM). The participants completed all sessions separated by a minimum of 48 h. Throughout all sessions, the MV for BP and SQ was assessed using the Vmaxpro (index device) and a MoCap (Vicon 3D Motion Systems, Oxford, United Kingdom), which was considered as the criterion device.

Participants

Twenty-three strength-trained men (age: 25 ± 3 years; height: 184.2 ± 7.7 cm; body mass: 82.3 ± 8.2 kg; relative BP 1RM: 1.08 ± 0.21 kg · kg bodyweight^{-1}; relative SQ 1RM: 1.37 ± 0.28 kg · kg bodyweight^{-1}) completed the incremental 1RM test to determine the ecological validity of the Vmaxpro. Out of these participants, seventeen men (age: 25 ± 3 years; height: 182.6 ± 6.2 cm; body mass:

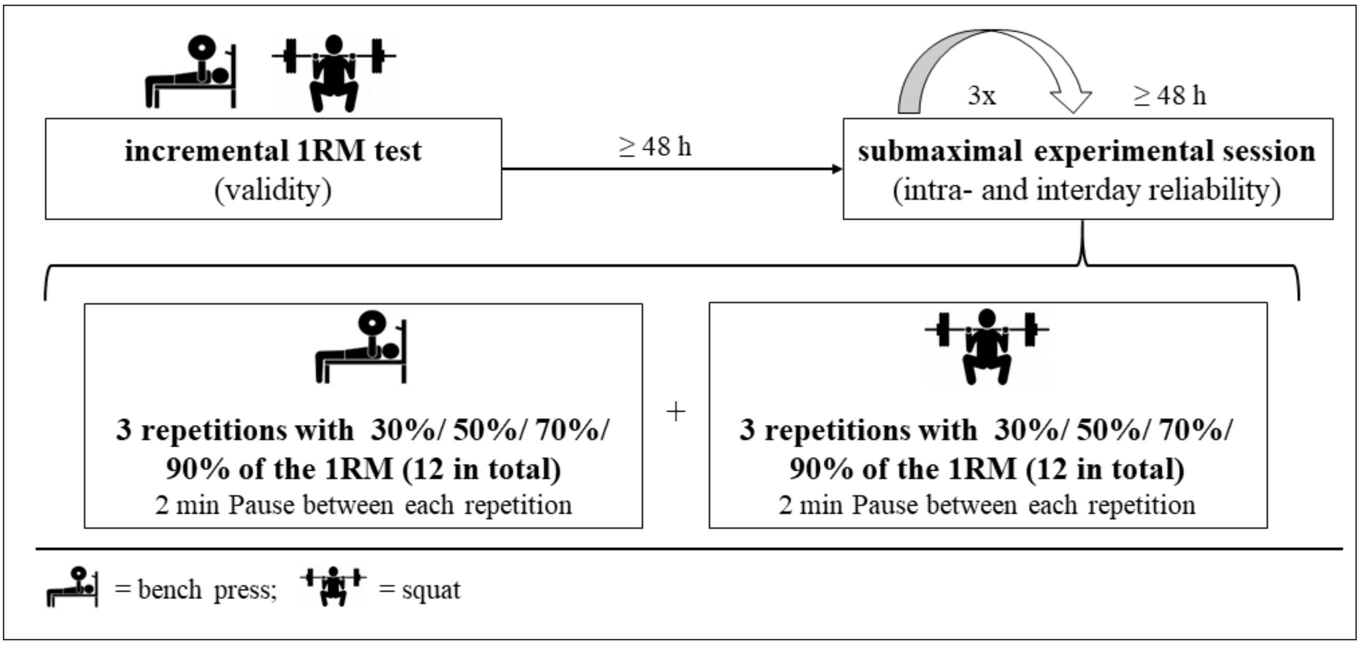

FIG. 1. Study design. 1RM = one-repetition maximum.

82.1 ± 5.1 kg; relative BP 1RM: 1.15 ± 0.18 kg · kg bodyweight^{-1}; relative SQ 1RM: 1.44 ± 0.26 kg · kg bodyweight^{-1}) further participated in the second part of the study, consisting of 3 additional experimental sessions with submaximal loads to determine the intra- and inter-day reliability of the sensor. Participants were eligible to participate in the study if they (1) were non-smokers; (2) had no chronic or acute injuries; (3) were between the ages of 18 and 40; (4) were physically active; and (5) had at least 1 year of strength training experience prior to enrolment in the study. All participants were instructed about possible risks associated with the study. A medical history questionnaire was reviewed and written informed consent was provided prior to inclusion. This study was approved by a local institutional ethic review board and was conducted according to the Declaration of Helsinki.

Procedures

In order to standardise the execution of the movement throughout every repetition in the 1RM test and the experimental sessions, participants' standing position and grip width were marked using a tape and the participants' BP and SQ depth was controlled using safety bars. To reduce the biological within-subject variance, all repetitions were performed with a controlled eccentric phase until the reversal point (i.e., contact of the bar and the safety bar) [12]. Additionally, participants were instructed to hold the position for a momentary pause of 1.5 seconds before performing the concentric phase with maximal velocity [13]. The 1RM was assessed in both BP and SQ (in that order). Testing started with a 5-minute warm-up at an individualised load (i.e., 1.5 times body weight) on a stationary cycle ergometer, followed by 10 repetitions with the unloaded bar (i.e., 20 kg) in both exercises. After performing the initial individualised load (i.e., 30% of the estimated 1RM), the load was progressively increased until the participants were unable to lift the load with the correct technique and without assistance. Every load was performed only once with 2 minutes rest in between. In order to investigate the ecological intra- and inter-day reliability of the Vmaxpro across the entire MV range, the experimental sessions consisted of 3 repetitions at 30, 50, 70, and 90% of the 1RM (12 repetitions in total) for both BP and SQ (in that order), separated by 2 minutes of rest between each repetition. The warm-up and execution of the movement were similar to those performed during the 1RM test.

To obtain the MV of each repetition, the Vmaxpro sensor was attached to the barbell on the basis of the manufacturer's specifications (i.e. in the centre of the barbell, Figure 2). Instant velocities were recorded at a sampling rate of 200 Hz and were calculated using the Vmaxpro application (version 1.1.4) that was connected to an IOS device (IPhone 11/IPhone 12; Apple, Inc., Cupertino, CA) via a Bluetooth 5.0 connection. Additionally, the MV was obtained using a MoCap with 3 infrared high-speed cameras (Vicon Motion Systems, Oxford, United Kingdom) with 1 reflective marker placed on the end of the barbell (Figure 2). The data were recorded at a frequency of 200 Hz using the software Vicon Nexus (version 2.6). The

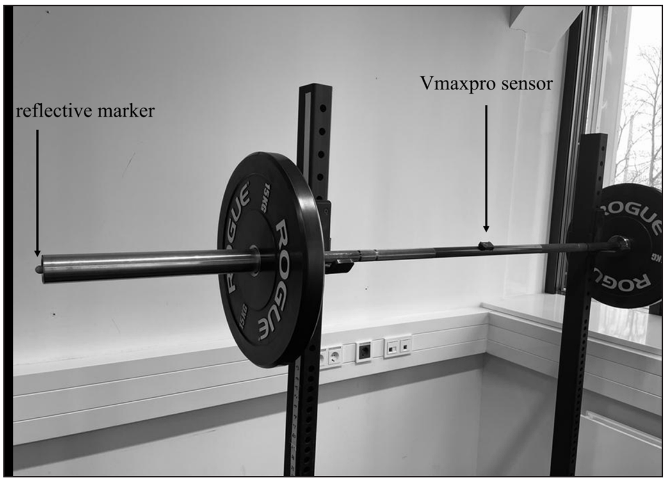

FIG. 2. Position of the reflective marker and the Vmaxpro on the barbell.

mean concentric resultant velocities ($v_{resultant}$) were then manually calculated by summing up the velocities for all three axes ($v_{resultant} = \sqrt{v_x^2 + v_y^2 + v_z^2}$). The initiation of the concentric phase was determined at the point where $v_{resultant} > 0$, while the end of the concentric phase was defined as the point where $v_{resultant} \leq 0$.

Calculation of L-V variables and 1RM

Mathematical calculation of the *L-V* variables and the 1RM requires the respective maximal MV at three or more incremental sub-maximal loads, which can be chosen within a range of 30–80% of the estimated 1RM [14]. Therefore, the *L-V* variables were calculated based on the highest MV at 30, 50 and 70% 1RM of each submaximal experimental session (sessions 2–4), for both Vmax and MoCap data. The calculation of the *L-V* variables and the 1RM was based on a least-square linear regression model ($L\,[V] = L_0 – sV$). L_0 represents the load at zero velocity and s is the slope of the *L-V* relationship. The maximal velocity at zero load (v_0) was calculated as follows: $v_0 = L_0/s$, while the maximal power capacity (A_{line}) was defined as the area under the *L-V* curve: $A_{line} = L_0 \cdot v_0/2$. For calculation of the predicted 1RM, the following equation was used: $1RM = (v_{1RM}\text{-}v_0)/s$, where v_{1RM} is defined as the MV at the maximal load obtained by the MoCap during the incremental 1RM test.

Statistical analyses

Normality of distribution was assessed by the Shapiro–Wilk test. To enable a differentiated perspective on the validity and reliability of the Vmaxpro as well as to ensure comparability to other studies, multiple measures of validity and reliability were used. For validity analysis, the agreement of the differences between the index and criterion (index – criterion) was assessed by Bland-Altman analysis [15]. Additionally, the Pearson product-moment correlation coefficient r was calculated between the index and the criterion for data of the incremental 1RM test, as well as the *L-V* variables (i.e., L_0, v_0, A_{line}) and the predicted 1RM, and classified as trivial ($r < 0.1$), low ($0.1 \leq r < 0.3$), moderate ($0.3 \leq r < 0.5$), high ($0.5 \leq r < 0.7$), very high ($0.7 \leq r < 0.9$), and nearly perfect ($r \geq 0.9$) [16]. To analyse whether the validity is velocity dependent, additionally a linear regression analysis was performed. Analysis of heteroscedasticity of errors within the linear model was performed using the studentized Breusch-Pagan test. In the case of non-normally distributed residuals, a modified studentized Breusch-Pagan test was performed. Additionally, for validity analysis, the mean absolute percentage error (MAPE) between the index and the criteria was calculated as follows: MAPE = (|Vmax-MoCap|) / Vmax · 100.

In order to provide information on how the possible deviation of the Vmaxpro influences training practice, the proportion of Vmax data of the incremental 1RM test, the submaximal strength sessions (for all loads together and separated by the intensities) and the *L-V* variables (i.e., L_0, v_0, A_{line}) within fixed absolute differences to the MoCap were calculated as follows: n(|Vmax-MoCap| ≤ x)/ n(|Vmax-MoCap|) · 100, where n is defined as the number of measures and x is defined as the fixed absolute difference. The following fixed absolute differences were used to provide a range of practically relevant deviations (in $m \cdot s^{-1}$) between Vmax and the MoCap: ≤ 0.01, ≤ 0.02, ≤ 0.05, ≤ 0.1, ≤ 0.2 for the velocities during the 1RM test, the submaximal sessions and v_0. Furthermore, for the predicted L_0 and the 1RM the following fixed absolute differences (in kg) were used: ≤ 1, ≤ 3, ≤ 5, ≤ 7, ≤ 10, while for the A_{line} the proportion of Vmax data is displayed for the following absolute differences (in $m \cdot s^{-1} \cdot kg$): ≤ 0.5, ≤ 1, ≤ 2, ≤ 5, ≤ 10.

For the determination of intra-day reliability, we evaluated the MV assessed at each load (i.e., 30, 50, 70 and 90% 1RM) within each session (3 repetitions at each load, separately during sessions 2–4). Additionally, for inter-day reliability, we evaluated the mean MV at each load (i.e., 30, 50, 70 and 90% 1RM) between the submaximal experimental sessions (2–4). For both inter- and intra-day reliability, coefficients of variation (CV) were calculated for each individual. Since the CV of MoCap indicates the actual variance (i.e. biological variance) between the repetitions, the absolute difference of the CVs between MoCap and Vmaxpro represents the variance caused by the Vmaxpro. Therefore, the 'true' CVs for the Vmaxpro were calculated as follows: $CV_{Vmaxpro} = (|absCV_{Vmax} - CV_{MoCap}|)$, where CVs < 10% were considered as a measure for acceptable reliability [17]. All CVs were calculated in Excel (Microsoft Corporation, version 2201, Redmond, USA), while all other statistical analyses were performed using SPSS (IBM SPSS Statistics, version 28, Chicago, IL). Statistical significance for all tests was set a $p \leq 0.05$.

TABLE 1. Proportion of Vmax data [%] within fixed absolute difference compared to the MoCap.

velocities during 1RM–test [$m \cdot s^{-1}$]					
+/-	**≤ 0.01**	**≤ 0.02**	**≤ 0.05**	**≤ 0.1**	**≤ 0.2**
BP	26.05	36.74	49.30	65.12	73.49
SQ	21.86	37.67	57.67	74.42	86.98
velocities during submaximal session with 30% 1RM [$m \cdot s^{-1}$]					
+/-	**≤ 0.01**	**≤ 0.02**	**≤ 0.05**	**≤ 0.1**	**≤ 0.2**
BP	15.75	23.97	48.63	73.29	84.25
SQ	19.18	30.82	63.70	84.25	93.84
velocities during submaximal session with 50% 1RM [$m \cdot s^{-1}$]					
+/-	**≤ 0.01**	**≤ 0.02**	**≤ 0.05**	**≤ 0.1**	**≤ 0.2**
BP	23.97	39.73	67.12	78.77	89.04
SQ	18.49	32.19	67.12	89.04	96.58
velocities during submaximal session with 70% 1RM [$m \cdot s^{-1}$]					
+/-	**≤ 0.01**	**≤ 0.02**	**≤ 0.05**	**≤ 0.1**	**≤ 0.2**
BP	34.46	56.76	82.43	95.27	98.65
SQ	28.38	45.95	79.73	91.22	97.97
velocities during submaximal session with 90% 1RM [$m \cdot s^{-1}$]					
+/-	**≤ 0.01**	**≤ 0.02**	**≤ 0.05**	**≤ 0.1**	**≤ 0.2**
BP	53.57	68.57	86.43	98.57	100.00
SQ	37.86	58.57	83.57	92.14	97.86
L_0 [kg]					
+/-	**≤ 1**	**≤ 3**	**≤ 5**	**≤ 7**	**≤ 10**
BP	22.00	44.00	70.00	86.00	88.00
SQ	10.00	22.00	32.00	42.00	54.00
v_0 [$m \cdot s^{-1}$]					
+/-	**≤ 0.01**	**≤ 0.02**	**≤ 0.05**	**≤ 0.1**	**≤ 0.2**
BP	12.00	18.00	40.00	62.00	88.00
SQ	10.00	16.00	38.00	72.00	90.00
A_{line} [$m \cdot s^{-1} \cdot kg$]					
+/-	**≤ 0.5**	**≤ 1**	**≤ 2**	**≤ 5**	**≤ 10**
BP	22.00	30.00	64.00	88.00	98.00
SQ	10.00	16.00	30.00	54.00	74.00
1RM [kg]					
+/-	**≤ 1**	**≤ 3**	**≤ 5**	**≤ 7**	**≤ 10**
BP	22.00	52.00	78.00	88.00	90.00
SQ	12.00	30.00	48.00	50.00	66.00

RESULTS

Validity – incremental 1RM test

For BP and SQ, 170 out of 197 repetitions (85.9%) and 197 out of 208 repetitions (94.7%), respectively, were assessed by Vmaxpro and hence included in the validity analysis. The distribution of missing data in relation to different MVs is illustrated in Figure S1. The mean bias of the MVs assessed by the Vmaxpro and MoCap was 0.02 $m \cdot s^{-1}$ (standard deviation [SD]: 0.11 $m \cdot s^{-1}$; limits of agreement [LoA]: 0.21 $m \cdot s^{-1}$) and 0.01 $m \cdot s^{-1}$ (SD: 0.11 $m \cdot s^{-1}$; LoA: 0.21 $m \cdot s^{-1}$) for BP and SQ, respectively (Figure 3). The Pearson product-moment correlation coefficient r was 0.935 and 0.900 (both $p \leq 0.01$) for BP and SQ, respectively. Regression analyses revealed

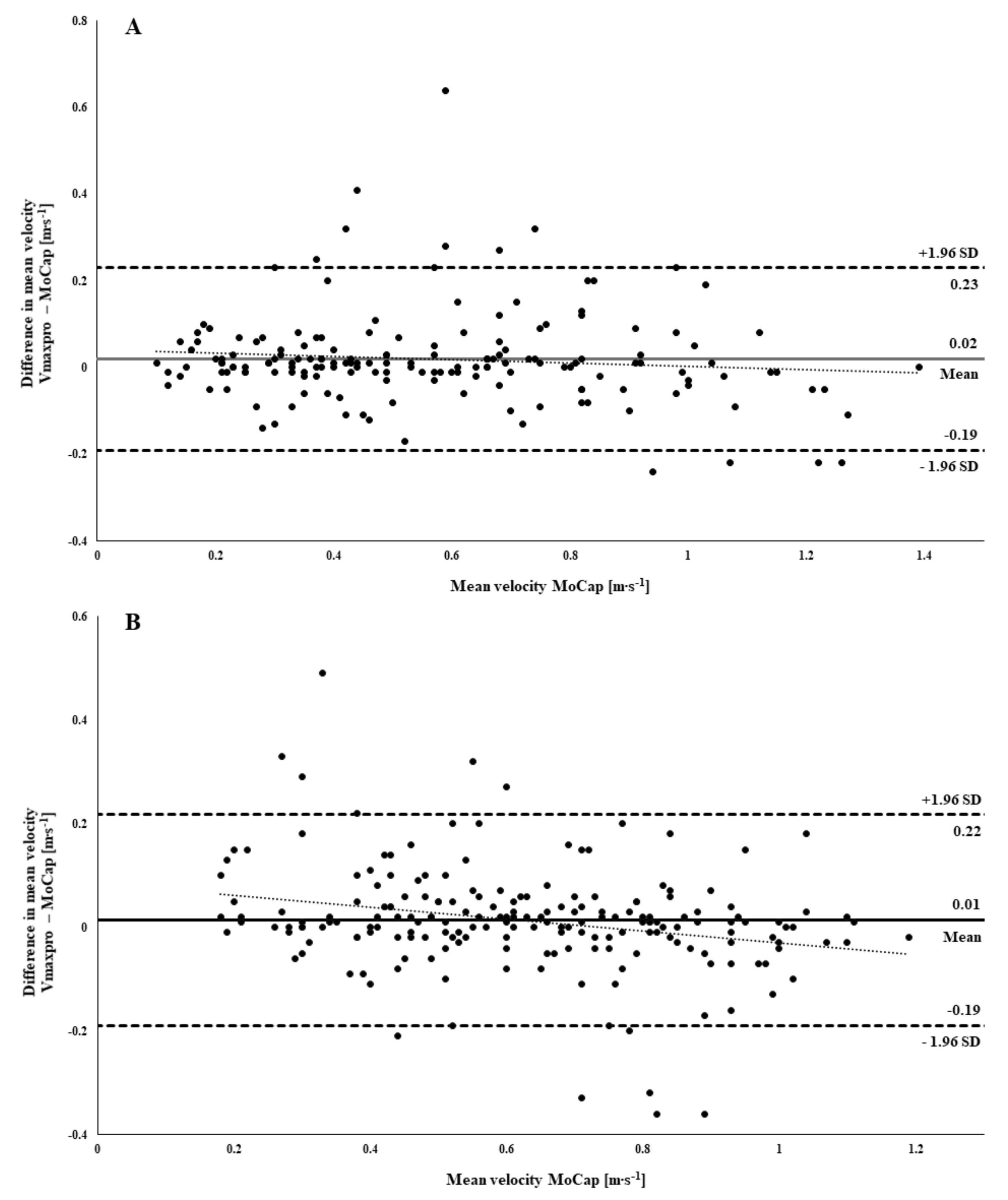

FIG. 3. Bland-Altman analysis with limits of agreement for bench press (A) and squat (B) data (± 1.96 SD).

a statistically significant linear relation between the Vmaxpro and the MoCap BP (F(1, 171) = 1175.52; $p \leq 0.01$; $R^2 = 0.874$) and SQ (F(1, 197) = 835.82; $p \leq 0.01$; $R^2 = 0.810$). When comparing the differences of the criterion and index (i.e., Vmaxpro vs. MoCap) with the MV of the criterion, regression analyses showed a statistically significant linear association for BP (F(1, 153) = 11.81; $p = 0.001$; $R^2 = 0.072$) with f(ΔVmaxpro - MoCap) = -0.0389x + 0.042 and SQ (F(1, 197) = 7.31; $p = 0.007$; $R^2 = 0.031$) with

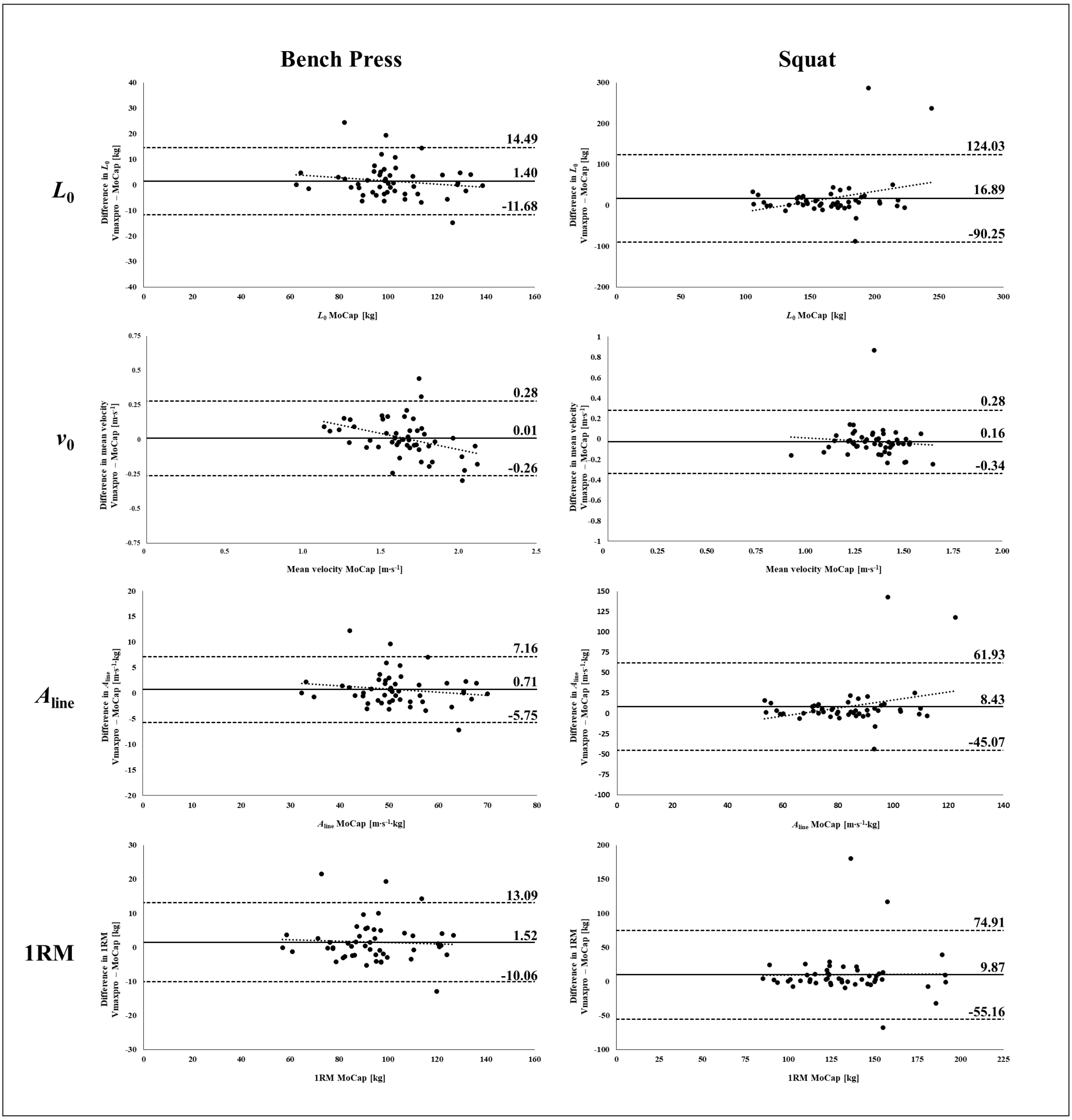

FIG. 4. Bland-Altman analysis with limits of agreement (± 1.96 SD) for both bench press and squat *L-V* variables and 1RM.

f(ΔVmaxpro - MoCap) = -0.1142x + 0.085 (Figure 3). The mean MAPE across all loads for Vmaxpro compared with the MoCap was 12.32 ± 15.03% and 11.94 ± 15.91% for BP and SQ, respectively. The proportion of Vmax data obtained from the 1RM test within fixed absolute differences compared to the MoCap is displayed in Table 1.

Validity – L-V variables and 1RM

The mean bias and the LoA for the calculated 1RM and *L-V* variables by the index and criterion are displayed in Figure 4. The Pearson product-moment correlation coefficients *r* for the calculated *L-V* variables and the 1RM between the index and criterion ranged from 0.808 to 0.942 (all $p \leq 0.01$) and from 0.615 to 0.741 (all $p \leq 0.01$)

for BP and SQ, respectively (Table 2). The R^2 ranged from 0.652 to 0.887 (all $p \leq 0.001$) and from 0.378 to 0.548 (all $p \leq 0.001$) for BP and SQ, respectively. The proportion of the calculated *L-V* variables and the 1RM based on the Vmax data within fixed absolute differences compared to the MoCap is displayed in Table 1.

Reliability – submaximal experimental session

The results of the intra-day and inter-day reliability analysis for both exercises are displayed in Tables 3 and 4, respectively. Mean intra-day CVs ranged from 2.4% to 9.7% and 3.7% to 8.6% for BP and SQ, respectively. Mean inter-day CVs ranged from 3.5% to 5.9% and 3.2% to 6.7% for BP and SQ, respectively.

DISCUSSION

The aim of the study was to assess the ecological validity, as well as intra-day and inter-day reliability, of the Vmaxpro sensor during a 1RM test and at submaximal loads (i.e., 30, 50, 70 and 90% of the 1RM) using free weights in both BP and SQ. Additionally, to gain a better understanding of how the possible deviation of the Vmaxpro influences training practice, we examined the validity of the Vmaxpro to predict *L-V* relationship variables (i.e., L_0, v_0, A_{line}) and the 1RM in both exercises. The validity analysis revealed a nearly perfect correlation between data derived from the Vmaxpro and MoCap for both exercises. However, compared to the MoCap, the Vmaxpro showed a systematic overestimation of the MV across all loads that is decreasing with higher MVs in BP and SQ. The comparison between the *L-V* variables and the 1RM derived from Vmaxpro and the MoCap showed a very high to nearly perfect and a high to very high validity for BP and SQ with a systematic overestimation for all variables. The Bland-Altman analysis, however, indicated high LoA, particularly for the SQ *L-V* variables and the 1RM. The CVs for the intra-day and inter-day reliability of the Vmaxpro were within an acceptable range for all loads in both exercises.

TABLE 2. Mean values of the *L-V* variables and the predicted 1RM with the respective r, R^2 and mean absolute percentage error (MAPE) for Vmax and the MoCap. BP = bench press, SQ = squat.

BP	Vmax	MoCap	*r*	R^2	MAPE [%]
L_0 [kg]	102.98 ± 17.38	101.58 ± 17.18	0.925 (≤ *0.001***)	0.856 (≤ *0.001***)	4.46 ± 4.40
v_0 [m·s^{-1}]	1.66 ± 0.22	1.65 ± 0.23	0.808 (≤ *0.001***)	0.652 (≤ *0.001***)	6.01 ± 5.07
A_{line} [m·s^{-1}·kg]	52.32 ± 8.66	51.61 ± 8.56	0.927 (≤ *0.001***)	0.859 (≤ *0.001***)	4.30 ± 4.30
1RM [kg]	95.12 ± 17.58	93.60 ± 16.90	0.942 (≤ *0.001***)	0.887 (≤ *0.001***)	4.06 ± 4.31
SQ	**Vmax**	**MoCap**	***r***	R^2	**MAPE [%]**
L_0 [kg]	182.76 ± 70.71	165.87 ± 31.69	0.740 (≤ *0.001***)	0.548 (≤ *0.001***)	10.65 ± 16.18
v_0 [m·s^{-1}]	1.32 ± 0.20	1.35 ± 0.14	0.615 (≤ *0.001***)	0.378 (≤ *0.001***)	7.00 ± 7.18
A_{line} [m·s^{-1}·kg]	92.04 ± 35.30	83.61 ± 15.84	0.741 (≤ *0.001***)	0.549 (≤ *0.001***)	10.51 ± 15.86
1RM [kg]	142.96 ± 42.59	133.09 ± 26.25	0.627 (≤ *0.001***)	0.393 (≤ *0.001***)	9.48 ± 14.30

TABLE 3. Mean MV and intra-day coefficient of variance (CV) of repetitions 1–3 in sessions 2–4 separated by the different intensities and exercises. BP = bench press, SQ = squat.

	Session 2		Session 3		Session 4	
Vmax BP	**MV [m·s^{-1}]**	**CV [%]**	**MV [m·s^{-1}]**	**CV [%]**	**MV [m·s^{-1}]**	**CV [%]**
30%	1.12 ± 0.16	8.7 ± 9.9	1.10 ± 0.21	7.3 ± 7.4	1.10 ± 0.23	9.7 ± 15.5
50%	0.80 ± 0.13	8.7 ± 8.9	0.84 ± 0.11	6.2 ± 7.2	0.82 ± 0.11	5.6 ± 5.8
70%	0.58 ± 0.11	3.7 ± 4.3	0.57 ± 0.09	5.4 ± 6.9	0.57 ± 0.09	4.3 ± 5.2
90%	0.34 ± 0.14	2.4 ± 1.7	0.32 ± 0.07	4.5 ± 5.8	0.30 ± 0.07	5.6 ± 7.5
Vmax SQ	**MV [m·s^{-1}]**	**CV [%]**	**MV [m·s^{-1}]**	**CV [%]**	**MV [m·s^{-1}]**	**CV [%]**
30%	0.95 ± 0.18	7.8 ± 13.4	0.95 ± 0.17	8.6 ± 13.8	1.00 ± 0.15	6.3 ± 9.7
50%	0.79 ± 0.14	3.9 ± 4.5	0.78 ± 0.15	4.8 ± 7.1	0.81 ± 0.10	4.6 ± 8.8
70%	0.64 ± 0.07	3.7 ± 3.4	0.64 ± 0.08	3.9 ± 4.8	0.64 ± 0.14	4.7 ± 7.4
90%	0.45 ± 0.09	4.4 ± 5.4	0.45 ± 0.08	4.8 ± 5.9	0.44 ± 0.13	5.5 ± 7.8

TABLE 4. Mean MV and inter-day coefficient of variance (CV) between sessions 2–4 separated by the different intensities and exercises. BP = bench press, SQ = squat.

	Mean velocity [$m \cdot s^{-1}$]			CV [%]
Vmax BP	**Session 2**	**Session 3**	**Session 4**	
30%	1.12 ± 0.13	1.10 ± 0.15	1.10 ± 0.17	5.9 ± 7.5
50%	0.80 ± 0.11	0.86 ± 0.11	0.82 ± 0.10	5.6 ± 6.9
70%	0.58 ± 0.10	0.57 ± 0.07	0.56 ± 0.09	3.5 ± 3.1
90%	0.45 ± 0.08	0.44 ± 0.07	0.44 ± 0.12	5.6 ± 9.0
Vmax SQ	**Session 2**	**Session 3**	**Session 4**	
30%	0.95 ± 0.12	0.95 ± 0.14	0.99 ± 0.11	3.7 ± 5.7
50%	0.81 ± 0.06	0.79 ± 0.08	0.81 ± 0.08	3.2 ± 3.0
70%	0.64 ± 0.06	0.64 ± 0.07	0.66 ± 0.10	3.2 ± 4.6
90%	0.45 ± 0.08	0.44 ± 0.07	0.44 ± 0.12	6.7 ± 10.8

Compared with our previous data on the Vmaxpro to assess the MV validity during a guided barbell SQ [10], our present data indicate lower validity when using free weights ($R^2 = 0.935$ vs. 0.810). This, however, can at least partially be explained by the degrees of freedom (3 axes vs. 1 axis). It appears that the Vmaxpro is not able to detect the changes in movement trajectory during free weight exercises with sufficient accuracy. In contrast to our findings, a recent study examining the validity of the Vmaxpro for the assessment of the MV during a free-weight SQ and hip thrusts reported good to excellent validity, indicated by low LoA (0.1 $m \cdot s^{-1}$ and 0.12 $m \cdot s^{-1}$ for SQ and hip thrusts, respectively) [18]. However, it needs to be considered that this study used a linear position transducer but not the gold standard (optical 3D motion capture system) as the criterion. Therefore, these results should be interpreted with caution. When comparing the validity of the Vmaxpro to assess the MV in both exercises, the LoA during the 1RM test in our study show comparable validity for BP and SQ (0.21 $m \cdot s^{-1}$ vs. 0.20 $m \cdot s^{-1}$). To the best of our knowledge, there are no existing data on the validity of the Vmaxpro to assess the MV in free weight BP exercise. However, when compared to another IMU (i.e., PUSH Band), the Vmaxpro showed a lower mean bias, but higher LoA (mean bias: 0.10 ± 0.06 $m \cdot s^{-1}$, LoA: 0.13 (extracted with the WebPlotDigitizer, Pacifica, California, USA, Version: 4.4) [19]) for assessing MV during a 1RM test [20]. When compared to data on the validity to the Beast sensor [20, 21], the Vmaxpro demonstrated higher validity in both BP and SQ. Regardless of the exercise, the validity of the Vmaxpro is comparable or higher, when compared to other commercially available IMUs [9].

In line with a previous study [10], we found a slight overestimation of the MV compared with the MoCap for both BP and SQ during the 1RM test. However, contrarily to our previous results, the systematic bias decreased with higher MVs, indicating higher validity at higher MVs (i.e., lower loads). A potential explanation for poorer validity at lower MVs remains speculative at this point but could be related to a larger variance in the movement trajectory during slower repetitions. These conflicting results do, however, reinforce the arbitrariness regarding the systematic over/underestimation at different MVs within the same IMU that we described previously [10]. Furthermore, it was intriguing that a high proportion of repetitions (14.1% and 5.3% for BP and SQ, respectively) during the 1RM test was not assessed by the Vmaxpro. As indicated by Figure S1, this appeared to be mostly the case at low MVs during BP. Obviously, a justification for this cannot be given but it needs to be noted that the manufacturer's user manual specifies that only MVs > 0.15 $m \cdot s^{-1}$ are detected by the sensor. In our data, however, this was only the case for 9 of the 36 non-acquired data points. This high proportion of missing data, especially for BP, is a major limitation of the sensor and should be considered when using the sensor in practice.

In order to provide valuable information on how the possible deviation of the Vmaxpro influences training practice, the proportion of Vmax data within fixed absolute differences to the MoCap was calculated. For example, during velocity-based training (VBT) with the fastest repetition at 0.5 $m \cdot s^{-1}$ and a typically used velocity threshold of 20% [22], an underestimation of the MV of 0.1 $m \cdot s^{-1}$ could already lead to a termination of the set, even without an actual loss in MV. In our study, MVs around 0.5 $m \cdot s^{-1}$ were reached at loads of 70% and 90% of the 1RM. The majority of MVs (~ 80%) assessed by the Vmaxpro at these loads are, however, within an acceptable absolute difference (≤ 0.05 $m \cdot s^{-1}$) to the MoCap. Thus, it seems that the Vmaxpro could be a valid IMU for assessing the MVs during VBT for recreational purposes. However, whether the accuracy of the sensor is sufficient for individual requirements has to be judged in a case-specific manner. Especially when using VBT for the development of explosive strength determinants, an exact estimation of the MV is necessary to avoid undesired fatigue caused by an overestimation of the MV. Therefore, practitioners should consider the absolute deviation in MV between the Vmaxpro and the gold standard (displayed in Table 1) to estimate whether this deviation could negatively influence the chronic development of the desired strength training parameter and based on that to evaluate whether use of the Vmaxpro is helpful in training practice.

For BP and SQ, the correlation between the *L-V* variables and the 1RM derived from Vmaxpro and the MoCap was very high to nearly perfect and high to very high, respectively. However, the Bland-Altman analysis indicated high LoA for the SQ *L-V* variables and the 1RM (e.g. 55.16 to 74.91 kg for the 1RM) with a systematic overestimation (e.g. 9.87 kg for the 1RM). This overestimation can be explained, to some extent, by a limited number of extreme outliers in the Bland-Altman plots (Figure 4). In turn, it needs to be considered that the biological inter-day variance of the MV for submaximal loads [23] affects the predicted *L-V* variables and the 1RM. This high inter-day variance may exceed the displayed differences between the data derived by the Vmaxpro and the MoCap. Thus, a high proportion of predicted *L-V* variables and the 1RM, especially for the BP, appears to be within an acceptable absolute difference for monitoring these variables. However, practitioners and athletes should be aware of the deviation in both *L-V* variables and the 1RM derived from the Vmaxpro, because in some elite sports a more precise estimation of the 1RM is essential. Furthermore, it needs to be addressed that the *L-V* variables and the 1RM were calculated based on the highest MV of 3 repetitions at each intensity, reducing the influence of possible outliers. Therefore, when aiming to calculate *L-V* variables and the 1RM based on the MVs assessed by the Vmaxpro, practitioners are advised to use more than one repetition for each load.

Regarding the reliability of the Vmaxpro, our study revealed acceptable (< 10%) intra-day and inter-day CVs for all loadings. Therefore, the reliability of the Vmaxpro can be classified as higher compared to the Beast sensor and comparable to the PUSH band [20]. However, the high standard deviation (up to 15.47%), especially for low load intra-day CVs, indicates large variations of the reliability between different measurements/individuals. Whether this can be explained by interindividual differences in the execution of the exercises needs to be addressed in future studies.

When interpreting our data, some limitations need to be considered. Firstly, we used only one Vmaxpro device; therefore, it cannot be ruled out that the observed error was device-specific. Furthermore, we did not use two sensors at the same time; thus, we did not assess the intra-device agreement (i.e. Vmaxpro1 vs. Vmaxpro2). Furthermore, factors such as the strength training experience, anthropometric data and, thus, the range of motion could influence the validity. Future studies should address possible differences in validity, for example in a heterogenous sample including different strength levels and anthropometrics.

CONCLUSIONS

Taking our findings together, the Vmaxpro seems to have acceptable validity for most recreational purposes. However, the lower validity at higher loads (i.e., lower velocities) may be of concern when using nearly maximal loads and/or using low velocity loss thresholds during VBT. Moreover, it was intriguing that a relatively high number of repetitions during the 1RM test (i.e., 14.1% and 5.3% for bench press and squat, respectively) were not assessed by the Vmaxpro in the present study. Whether this is a common observation specific to the device needs to be assessed in future studies. Also, the wide limits of agreement for the 1RM prediction may be sufficient for recreational purposes but not for elite sport settings where already small deviations may lead to undesired training results. In terms of the reliability, our data indicate the sensor to be suitable for monitoring changes in performance within the same individual in different settings of VBT (i.e., using velocity loss thresholds for training monitoring or assessing chronic changes in movement velocity).

Conflict of interest declaration

The authors declare no conflict of interest.

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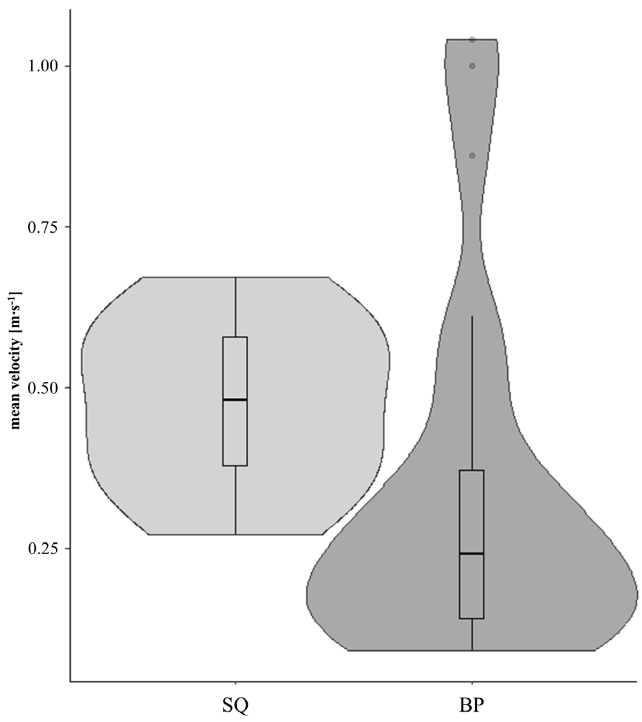
Supplemental figure

FIG. S1. Distribution of missing SQ and BP data in relation to different MVs, indicating a high proportion of missing data at low MVs, particularly in the BP exercise.



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The effects of training type and area size variations on the physiological and session rating of perceived exertion responses during male judo matches

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ABSTRACT: Modified exercise prescription in judo is commonly used to activate the energy systems in different magnitudes. In order to study the physiological and rating of perceived exertion (RPE) responses according to area sizes (i.e., 4 m × 4 m, 6 m × 6 m and 8 m × 8 m) and training mode variations (i.e., groundwork, ne-waza; standing combat only, tachi-waza; and free combat, free randori), eighteen male judo athletes (age: 22.6 ± 1.8 years) were randomly assigned, on separate days, to 9 experimental conditions (3 area sizes × 3 training modes) with each condition lasting 4 min. Delta lactate [La] was calculated based on the blood lactate values measured before and after every condition. Heart rate (HR) was measured during and after each bout and RPE recorded at the end of each combat. The results showed that mean and peak HR, percentage of maximum HR (% HR_{max}), delta [La] values and RPE scores were lower in 4 m × 4 m compared to 6 m × 6 m and 8 m × 8 m, and in groundwork training mode compared to standing combat and free randori (all $p < 0.001$). Furthermore, the 6 m × 6 m condition induced lower delta [La] values than 8 m × 8 m ($p < 0.001$) and free randori resulted in higher RPE scores than standing combat ($p = 0.001$). In conclusion, different training variables can be easily manipulated in a variety of different ways to specifically activate the energetic systems. Focusing on groundwork, the 6 m × 6 m area size was found to be the most suitable condition to induce a higher cardiovascular response, while the standing combat and free randori in 6 m × 6 m resulted in increased glycolytic activation compared to the groundwork condition.

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INTRODUCTION

Judo competition is physiologically demanding; therefore, a high level of aerobic and anaerobic fitness is required [1]. Exercise is prescribed in such a manner as to activate and thus train different physiological systems, thereby enhancing judo athletes' abilities to cope with, prepare for and recover from training and competition [1]. In support of this, several previous studies in judo were conducted to improve training programmes aiming for competition success by developing the physical fitness as well as the technical-tactical skills [1, 2, 3]. It is relevant to note that physiological and perceptive responses were studied in various judo-specific exercises. It was reported that continuous uchi-komi exercises (i.e., technique repetition without throwing) induced low glycolytic demands while the intermittent protocols resulted in higher demands, suggesting therefore that the uchi-komi training modality may improve aerobic and anaerobic fitness [1, 2, 4]. When the technique repetition training modality was performed by throwing the partner (i.e., nage-komi), different physiological responses were recorded based on the technique used [1]. Specifically, when seoi-nage (i.e., an arm technique) was used during nage-komi, the oxidative demand was higher compared to o-uchi-gari (i.e., a leg technique) [5]. Regarding training mode, it has been previously shown that continuous randori (i.e., combat or fight practice; sparring) elicited higher cardiovascular strain compared to the intermittent randori [6]. Additionally, ne-waza sessions (i.e., groundwork combat) have been reported to be less demanding in terms of glycolytic activation (inferred from blood lactate concentration) compared with standing combat, which can be a more appropriate mode for aerobic fitness development for judo athletes [7].

Recently, Ouergui et al. [3] investigated the physiological responses and rating of perceived exertion (RPE) during different judo combat conditions in female judo athletes. They found that RPE scores were higher in 4 m × 4 m compared with 8 m × 8 m area size. The post-combat lactate [La] values were higher in 4 m × 4 m compared to 6 m × 6 m and 8 m × 8 m area size, and in free randori compared with the 3:1 ratio condition. However, no changes were reported for heart rate (HR) values. It is known that there are several differences regarding a judo match's time-motion characteristics between male and female judo practitioners (e.g., male judo athletes spend longer time in standing combat than female judo athletes) [8], which may be related to hormonal [9], cardiovascular and anaerobic capacity [10], as well as technical-tactical [10, 11] aspects. Thus, based on these male-female differences [8, 9, 10, 11, 12], it seemed unlikely that the outcomes obtained with female judo athletes [3] would be replicated in male judo athletes. To the authors' knowledge, no studies have investigated the physiological responses and perceived exertion in male judo combat when altering area size and varying the training mode.

Therefore, the aim of this study was to examine the effect of altering area sizes (4 m × 4 m, 6 m × 6 m and 8 m × 8 m) and training mode variation (groundwork, standing combat and free randori) on physiological (i.e., [La] and HR responses) and RPE responses in male judo athletes. It was hypothesized that physiological and perceptive responses would be higher in 4 m × 4 m compared to other area sizes [3], while lower responses would be attributed to groundwork in comparison to standing combat due to its high energetic demand (most of the throwing techniques used are with the maximum physical lever) [13]. When considering both area size and training mode, the main hypothesis was that 4 m × 4 m in standing combat would induce the largest responses.

MATERIALS AND METHODS

Participants

A priori power analysis was calculated using the G*Power software (Version 3.1.9.4, University of Kiel, Kiel, Germany) using the F test family (ANOVA: repeated measures, within-between interaction). The analysis revealed that a total sample size of 12 subjects would be sufficient to find significant differences (effect size f = 0.25, $\alpha = 0.05$) with an actual power of 83.16%. Eighteen male judo athletes volunteered to participate in this study (mean ± SD, age: 22.6 ± 1.8 years; height: 174.6 ± 2.6 cm; body mass: 73.3 ± 4.4 kg; and judo experience: 9.8 ± 1.5 years). All athletes were grouped according to their weight divisions [lightweight (-73 kg) and half-middleweight (-81 kg) categories] and had participated regularly in judo tournaments for more than 2 years. They were also undertaking a similar training regime (3–5 times a week, 2 hours per session). The athletes did not present any medical restrictions during the experimental period and refrained from any strenuous exercises 48 hours before each experimental session. This study was conducted according to the Declaration of Helsinki for human experimentation and approved by a local research ethics committee. Written informed consent was obtained after a detailed explanation about the aims and risks involved in the investigation.

PROCEDURES

Study design

Based on variation in area size (4 m × 4 m, 6 m × 6 m and 8 m × 8 m) and training mode (groundwork, standing combat and free randori), 9 experimental conditions were randomly performed during a maximum period of 30 days with recovery duration of at least 48 h (but not more than 72 h) between 2 successive sessions [3]. Before each condition, the athletes were assigned to a standardized warm-up session (i.e., 15 minutes of jogging and dynamic stretching). The baseline measures were determined after 3 minutes of passive rest. The sessions were always conducted at the same time of the day (10 am to 12 pm) and took place at the training centre with daily controlled temperature (~20°C). All athletes competed against each other, were exposed to the same match duration and were instructed to continue the combat even when an ippon was scored [3]. The experimental protocol was directed by 2 investigators ensuring the athletes' safety. One week before the beginning of the investigation, the judo athletes were familiarized with the tests and the randori sessions order. They accomplished the 20 multistage shuttle run test [14] to determine their maximal HR (HR_{max}).

Study measures

Blood samples were taken 10 min before and immediately after each condition from the fingertip, after which [La] was measured using the Lactate Pro2 Analyzer (Arkray, Tokyo, Japan). Blood lactate concentration at pre- and post-conditions was determined and delta lactate (Δ) was calculated for the main analyses. Heart rate was measured continuously with a 5-second interval using a telemetric system (Polar Team2 Pro System, Polar Electro OY, Kempele, Finland). A transmitter belt worn by each judo athlete communicated via Bluetooth to sideline software for display of multiple players' HR. The Polar Pro sensor was handed out to all judo athletes before the start and was then collected at the end of the experimental conditions. After the completion of each condition, data were uploaded, and HR was analysed through Polar Flow (Polar Electro Oy, Kempele, Finland). For each data collection, the athletes wore the same transmitter belt to prevent recording differences. HRpre, mean (HRmean) and peak (HRpeak) values were used for the analysis. After being familiarized with the scale, athletes reported their RPE scores using a CR-10 scale [15] 30 min after each combat session.

Statistical analysis

The statistical analysis was performed using SPSS 20.0 statistical software (SPSS Inc, Chicago, IL, USA). Univariate normality was checked and confirmed using the Kolmogorov-Smirnov test. Data were analysed using a two-way analysis of variance (area size [4 m × 4 m, 6 m × 6 m, and 8 m × 8 m], training mode [groundwork, standing combat and free randori]) with repeated measurements to compare HRmin, HRmean, HRpeak, $\%HR_{max}$, delta lactate and RPE. The sphericity was tested and confirmed using the Mauchly test. The Bonferroni test was used as a post-hoc procedure. Standardized effect size (Cohen's d) analysis was used to interpret the magnitude of differences between variables and classified according to Hopkins [16]: < 0.20 (trivial); 0.20–0.60 (small); 0.60–1.20 (moderate); 1.20–2.0 (large); 2.0–4.0 (very large); and > 4.0 (extremely large). Moreover, upper and lower 95% confidence intervals of the difference (95% CIds) were calculated for corresponding variation. The statistical significance level was set at $p < 0.05$.

RESULTS

The mean value of HR_{max} recorded during the multistage 20-m shuttle run test was 199 ± 4 beats·min^{-1}. Figure 2 presents heart rate, delta lactate concentration [La] and session rating of perceived exertion (RPE) responses to different experimental conditions resulting from the interaction between area size and training mode.

For HRmin values, there was no area size, no training mean and no interaction effects ($p > 0.05$).

For HRmean, HRpeak and $\%HR_{max}$ there was an area size effect ($F_{2,153} = 29.769$, $F_{2,153} = 9.747$ and $F_{2,153} = 31.050$, respectively; all $p < 0.001$), with 4 m × 4 m resulting in lower values than 6 m × 6 m and 8 m × 8 m (HRmean: 95%CId= -15;-7 and -12;-4; d=-1.24 and -0.81 (large and moderate); HRpeak: 95%CId= -6;-1 and -6;-1; d=-0.46 and -0.48 (moderate for both comparisons); %HRmax : 95%CId= -7;-4 and -6;-2; d=-1.28 and -0.81 (large and moderate); all p<0.001).. Moreover, a training mode main effect was detected for the same HR parameters ($F_{2,153} = 34.048$, $F_{2,153} = 118.058$ and $F_{2,153} = 35.597$, respectively; all $p < 0.001$), with groundwork eliciting lower values in comparison to free randori and standing combat (HRmean: 95%CId= -15;-8 and -12;-5; d=-1.42 and -0.87 (large and moderate); HRpeak: 95%CId= -16;-11 and -16;-11; d=-2.31 and -2,23 (very large for both comparisons); %HRmax: 95%CId= -8;-4 and -6;-3; d=-0.87 and -1.5 (moderate and large); all p<0.001). For delta lactate, there was an area size effect ($F_{2,153} = 31.050$; $p < 0.001$), with 4 m × 4 m producing lower values than 6 m × 6 m and 8 × 8 m ((95%CId= -2;-0.13 and -3;-2; d=-0.47 and -1.44 (moderate and large); p=0.29 and p<0.001, respectively) and 6 m × 6 m resulting in lower

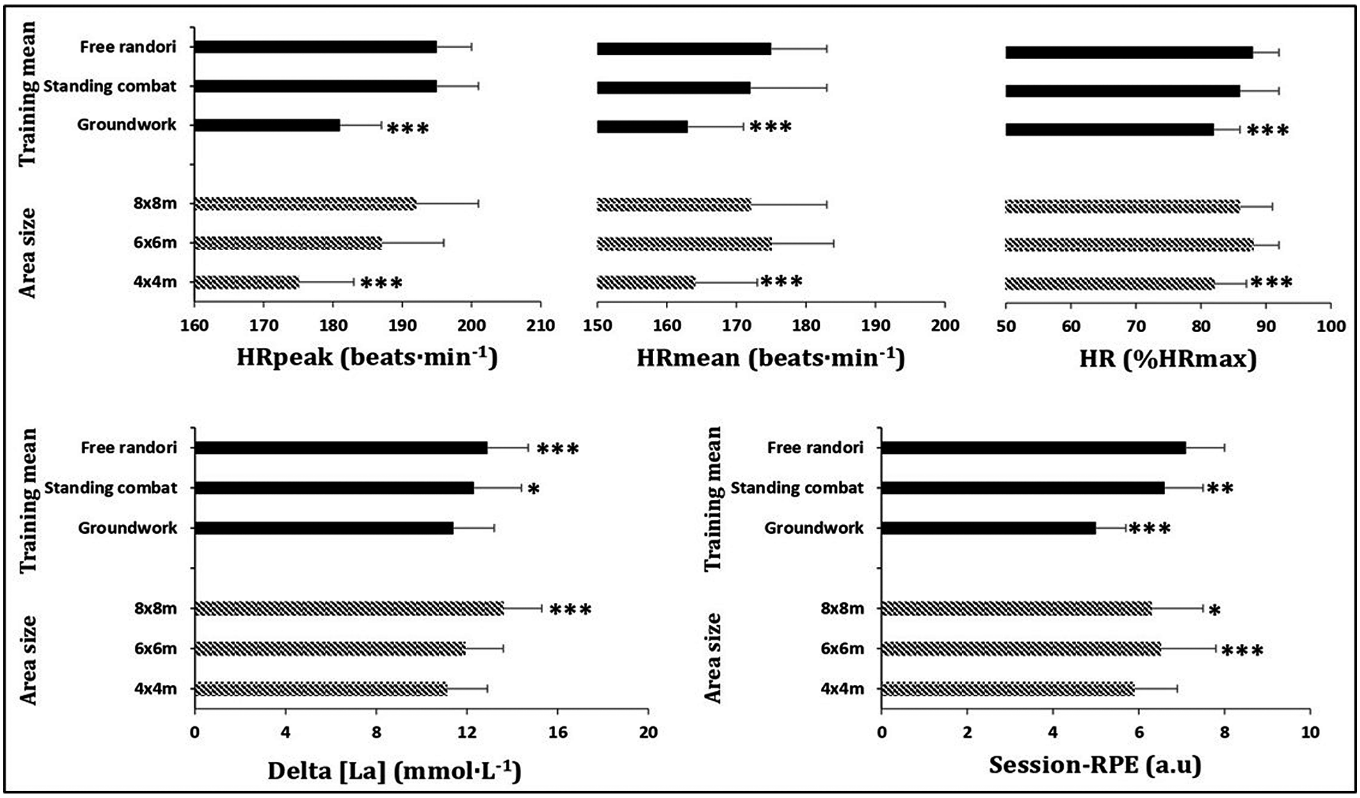

FIG. 1. Area size and training mode main effects on heart rate, delta lactate concentration [La] and session rating of perceived exertion responses during different experimental conditions. * different at $p < 0.05$: Delta lactate was higher in standing combat compared to groundwork; Session RPE was higher in 8 m × 8 m in comparison to 4 m × 4 m. ** different at $p < 0.01$: Session RPE was lower in standing combat compared to free randori. *** different at $p < 0.001$: HRmean, HRpeak and $\%HR_{max}$ were lower in 4 m × 4 m compared to 6 m × 6 m and 8 m × 8 m; HRmean, HRpeak, $\%HR_{max}$ and session RPE were lower in groundwork compared to standing combat and free randori; session RPE was higher in 6 m × 6 m compared to 4 m × 4 m; delta lactate was higher in 8 m × 8 m in comparison to 4 m × 4 m and 6 m × 6 m; delta lactate was higher in free randori compared to groundwork. a.u. arbitrary unit; RPE: rating of perceived exertion; HRpeak: peak heart rate; HRmean: mean heart rate; $\%HR_{max}$: percentage of maximum heart rate.

values than 8 m × 8 m (95%CId= -2;-1; d=-1.01 (moderate); p<0.001). Moreover, a training mode main effect was detected ($F_{2,153}$ = 35.597; p < 0.001), with groundwork resulting in lower values in comparison to free randori and standing combat (95%CId= -2;-1 and -2;0; d=-0.83 and -0.4 (moderate and small); p<0.001 and =0.015, respectively). Finally, for session-RPE there was an area size effect ($F_{2,153}$ = 9.574; p < 0.001), with 4 m × 4 m resulting in lower values than 6 m × 6 m and 8 m × 8 m (95%CId= -1;-0.16 and -1;-0.13; d=-0.51 and -0.37 (small for both comparisons); p<0.001 and p=0.014, respectively). Moreover, a training mode main effect was detected ($F_{2,153}$ = 119.034; p < 0.001), with groundwork resulting in lower values in comparison to free randori and standing combat (95%CId=-2;-2 and -2;-1; d=-3.08 and -2.29 (very large for both comparisons); p<0.001, for both comparisons) and standing combat resulting in lower values compared to free randori (95%CId=-1;-0.16; d=-0.63 (moderate); p=0.001) (Figure 1).

When considering both area size and training mode, an interaction effect was found in HRmean ($F_{4,153}$ = 34.048; p = 0.001), with groundwork in 4 m × 4 m eliciting lower values in comparison to 6 m × 6 m (95%CId = -16; -3; d = -1.45, large; p = 0.001) and lower values during the standing combat in 4 m × 4 m compared to 6 m × 6 m and 8 m × 8 m (95%CId = -26; -13 and -20; -7; d = -3.12 and -1.74, very large and large; p < 0.001, for all comparisons), and higher values in the standing combat in 6 m × 6 m compared to 8 m × 8 m (95%CId = 0;13; d = 0.79, moderate; p = 0.045). For HRpeak, there was an interaction effect ($F_{4,153}$ = 5.493; p < 0.001), with free combat in 8 m × 8 m generating higher values

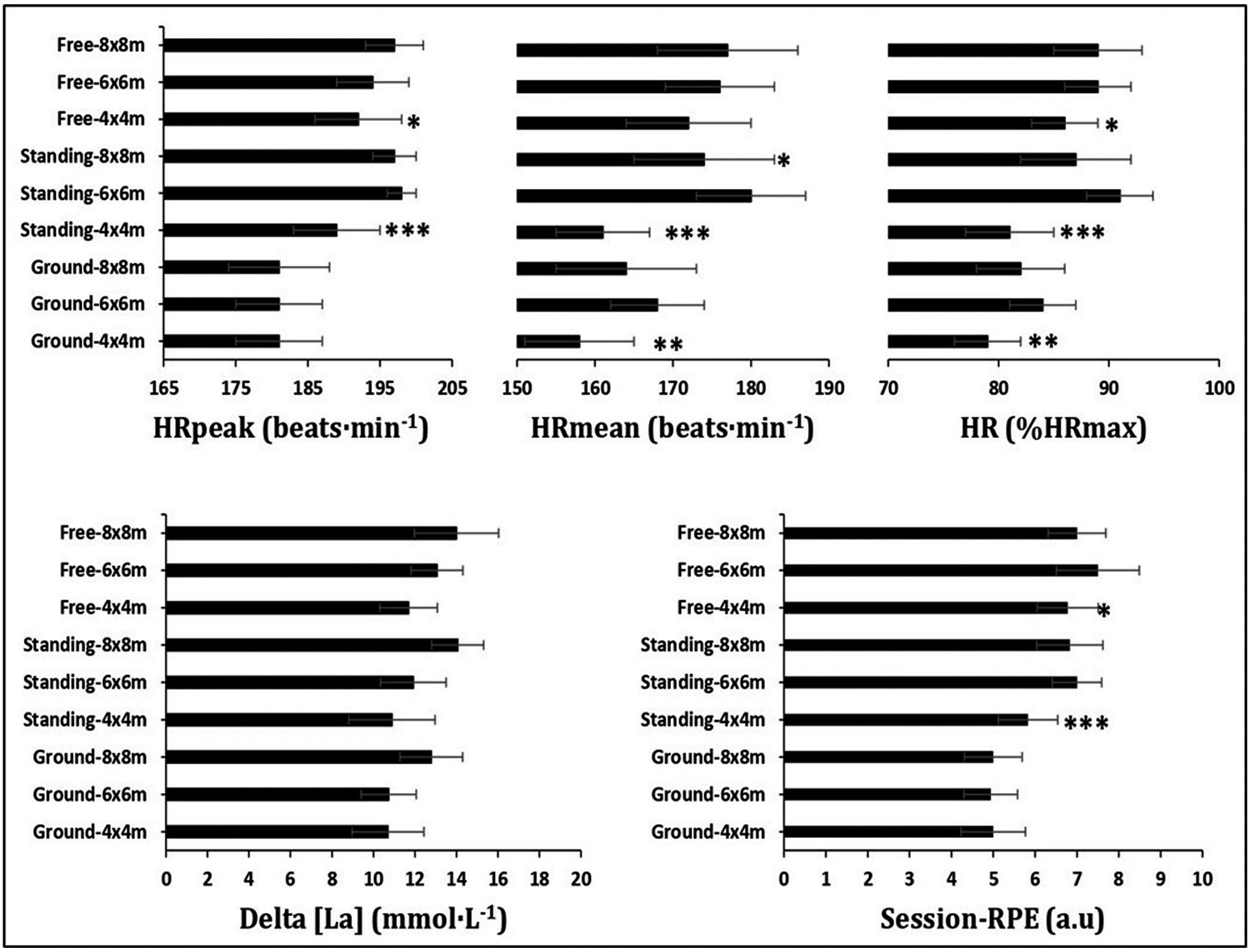

FIG. 2. Heart rate, delta lactate concentration [La] and session rating of perceived exertion (RPE) responses during different experimental conditions resulting from the interaction between area size and training mode. * different at p < 0.05: HRmean was lower during standing combat in 8 m × 8 m compared to 6 m × 6 m; HRpeak was lower during free combat in 4 m × 4 m compared to 8 m × 8 m; $\%HR_{max}$ was lower during standing combat in 8 m × 8 m compared to 6 m × 6 m; Session RPE was lower during free combat in 4 m × 4 m compared to 6 m × 6 m. ** different at p < 0.01: HRmean and $\%HR_{max}$ were lower during groundwork in 4 m × 4 m compared to 6 m × 6 m and 8 m × 8 m. *** different at p < 0.001 HRmean, HRpeak, $\%HR_{max}$ and session RPE were lower during standing combat in 4 m × 4 m compared to 6 m × 6 m and 8 m × 8 m. a.u. arbitrary unit; RPE: rating of perceived exertion; HRpeak: peak heart rate; HRmean: mean heart rate; $\%HR_{max}$: percentage of maximum heart rate.

in comparison to 4 m × 4 m (95%CId =1;8; d=0.86, moderate; $p = 0.03$) and lower values during the standing combat in 4 m × 4 m compared to 6 m × 6 m and 8 m × 8 m (95%CId = -14; -5 and -13; -4; d = -2.11 and -1.77, very large and large; $p < 0.001$, for all comparisons). Additionally, for $\%HR_{max}$ an interaction effect was detected ($F_{4,153} = 5.049$; $p = 0.001$), with higher values in 6 m × 6 m area size during groundwork compared to 4 m × 4 m in the same condition (95%CId = 2;8; d=1.47, large; $p = 0.001$), lower values during the standing combat in 4 m × 4 m in comparison to 6 m × 6 m and 8 m × 8 m in the same condition (95%CId = -13; -7 and -10; -4; d = -2.96 and -1.53, very large and large; $p < 0.001$, for all comparisons), and higher values in the standing combat in 6 m × 6 m compared to 8 m × 8 m in the same condition (95%CId = 1;6; d = 0.79, moderate; $p = 0.041$). Finally, an interaction effect was revealed for session RPE ($F_{4,153} = 4.047$; $p = 0.004$), with free randori in 4 m × 4 m producing lower values in comparison to 6 m × 6 m in the same condition (95%CId = -1; -0.13; d = -0.99, moderate; $p = 0.012$), lower values during the standing combat in 4 m × 4 m compared to 6 m × 6 m and 8 m × 8 m in the same condition (95%CId = -2; -1 and -2; -0.49; d = -1.65 and -1.42, large for both comparisons; $p < 0.001$, for both comparisons).

DISCUSSION

The present study showed that 4 m × 4 m induced lower HR mean, HR peak, $\%HR_{max}$, delta lactate and session-RPE values in comparison to 6 m × 6 m and 8 m × 8 m areas as well as lower values in groundwork in comparison to standing combat and free randori. Higher RPE scores were recorded in free randori compared to standing combat and lower delta lactate values in 6 m × 6 m compared to 8 m × 8 m.

Regarding the interaction between area size and training mode, the 4 m × 4 m in groundwork condition elicited lower HR mean and $\%HR_{max}$ values in comparison to the 6 m × 6 m in the same condition. As it was reported that male judo athletes used more immobilization, arm-locks, and choke techniques [17], the transition between these different ne-waza techniques needs larger spaces to apply than the 4 m × 4 m area, which can interrupt the transition's continuity. However, specific time-motion analysis studies need to be conducted comparing these area sizes to check whether this explanation can be confirmed. Additionally, in the present study, lower HRmean and $\%HR_{max}$ values were recorded in the 4 m × 4 m area size compared to 6 m × 6 m and 8 m × 8 m in the standing combat. This result suggests that performing standing techniques in 4 m × 4 m is an irrelevant combination to stress the cardiovascular system compared to larger areas such as 6 m × 6 m and 8 m × 8 m. This may be explained by the fact that male judo athletes spend more time on performing standing techniques with high frequency of sacrifice techniques [8]. Suitable execution of such techniques requires a large space; therefore, 6 m × 6 m and 8 m × 8 m would be the ideal areas to execute these techniques. Conversely, the 4 m × 4 m area was not suitable for these techniques as it limits the offensive attempts of judo athletes via the execution of these techniques, which is confirmed by lower HR values in this area size. Furthermore, a 6 m × 6 m area in the standing condition elicited higher HR mean values (180 ± 7 beats·min^{-1}, corresponding to 91% of HR_{max}) than in 8 m × 8 m with the same training mode. This result was similar to what was previously reported in other investigations [18, 19, 20], suggesting, therefore, that this condition may stimulate as close as possible the competition's physiological demands. This result can be supported by the fact that standing combat in 6 m × 6 m may provide athletes opportunities to spend more time in gripping disputes, to execute more attacks and use complex combinations [21], resulting in higher physiological demands [22]. However, the 8 m × 8 m area size may result in additional wasted time in displacement without contact [23], which may lower the physiological responses. It is relevant to note that the highest HRpeak values were recorded in the 8 m × 8 m free randori condition compared to 4 m × 4 m. Recently, it was observed that male judo athletes prefer to perform a variety of gripping [24], combined with arm technique [17] followed by groundwork attacks [24], that cannot be easily executed in reduced areas (i.e., 4 m × 4 m) but are well conducted in larger ones, such as 8 m × 8 m. It has been suggested that arm techniques result in increased cardiovascular responses compared to leg and hip techniques [5]. The findings cited above may explain our results regarding differences in HR peak responses between area sizes in free randori condition unless a technical analysis of these conditions disproves it. Thus, to obtain cardiovascular responses that mimic those observed during official judo combats (i.e., HR peak ranging from 190 to 200 beats·min^{-1} [20]), the free randori condition in 8 m × 8 m (HRpeak = 197 ± 4 beats·min^{-1}) can be the most appropriate training combination. Likewise, HRpeak values recorded in the present investigation are contradictory to those previously reported by Ouergui et al. [3] in the 8 m × 8 m free randori executed by female judo athletes. These differences in physiological responses between sexes can be explained by a difference in the physical fitness and the expertise level (i.e., elite versus non-elite) [22, 25, 26] between male and female judo athletes investigated in our study and by Ouergui et al. [3].

Session RPE scores in the present study showed an interaction between conditions, while no interaction for delta lactate was found. The lowest scores recorded were in 4 m × 4 m compared to 8 m × 8 m during standing combat condition. It is well known that the gripping phase (i.e., holding the judogi) is one of the components of standing techniques [27]. Also, senior male judo athletes tend to hold the judogi for a long time [19, 28]. However, the grip duration seems shorter in the smaller area as the match is interrupted when the athletes leave the combat area, which is more likely to happen in a smaller area (4 m × 4 m) and may affect the judo athlete's engagement and their RPE scores. Therefore, this may explain our results such as lower session RPE scores in 4 m × 4 m during standing combat. In addition, 4 m × 4 m in standing combat and free randori training modes resulted in lower session RPE values compared to when athletes performed in 6 m × 6 m area. This may be explained by the fact that the 4 m × 4 m area can result in a lower attack volume, while the larger area would be more appropriate to perform attacks without interruption. Indeed, senior middleweight male judo athletes' (similar weight category in the present study) total combat time (233 ± 78 s) was longer compared to other weight categories, which may result in a higher attack volume [23].

It is known that judo attack phases are characterized by high-intensity actions stimulating the glycolytic system [4, 29, 30, 31], which may reflect the RPE scores obtained within the standing and free combat conditions in 6 m × 6 m. To highlight that, HR outcomes in the present study were higher in the 6 m × 6 m condition. Therefore, this higher physiological strain may explain the RPE scores as RPE and HR are correlated [32]. Additionally, this result may be explained by the fact that standing techniques need a larger area to be performed, especially with expert level judo athletes [21], who use a larger range of movements, such as incorporating more frequently throwing opponents forwards and backwards [33]. However, our results are not in line with those reported by Ouergui et al. [3] in female judo combat, or with striking combat sports [34, 35], which may be explained by the sex difference concerning physical fitness [22] and technical actions involved [8, 33]. Furthermore, in striking combat sports, the distance control is different from grappling combat sports, with wider distance maintained throughout the match interspersed by powerful actions (e.g., kicks, punches, elbow, or knee attacks) [34, 35], whereas in grappling combat sports, the opponents stay in close contact to execute the throwing techniques [3]. Therefore, area and training mode affect these athletes differently. The lack of analysis of technical and tactical behaviours for each condition performed is a limitation of the present study. This analysis could provide relevant information to explain the changes in physiological responses in the different experimental conditions.

CONCLUSIONS

The study's findings indicated that different training variables (i.e., area size of combat and type of combat) can be manipulated to differentially stress the energetic systems among male judo athletes. Namely, standing combat and free randori training modes are more appropriate to induce higher glycolytic activation and the 6 m × 6 m standing combat condition is closer to mimicking the physiological demands of the competition. In addition, the 4 m × 4 m groundwork condition could be involved in the transition phase of periodization due its lower solicitation of the glycolytic system, or for technical and tactical purposes, resulting in lower training intensity. These outcomes would be useful for judo and fitness coaches when prescribing exercise regimes, although their long-term training effects need to be investigated.

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Conflict of interest

All authors declare having no conflict of interest.

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The validity of automatic methods for estimating skeletal age in young athletes: a comparison of the BAUSport ultrasound system and BoneXpert with the radiographic method of Fels

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ABSTRACT: This study examined the validity of two automated methods (BAUSport, BoneXpert software using Fels, Greulich-Pyle, Tanner-Whithouse III protocols) for estimating skeletal age (SA) in young athletes in comparison to a reference standard (Fels). 85 male and female athletes, nine to seventeen years of age, from multiple sports were assessed for SA as part of an annual medical and health screening programme. Intra-class correlations demonstrated high degrees of association between the automatic methods for estimating SA (BAUSport r = .98; BoneXpert r = .96–.99) and the discrepancy between SA and chronological age (SA-CA) (BAUSport r = .93; BoneXpert r = .88–.97), with the reference standard. Concordance analyses for the categorisation of participants as early, on-time and late maturing also demonstrated substantial levels of agreement for both methods (BAUSport Kappa = .71; BoneXpert Fels Kappa = .63) with the reference standard. Bland-Altman plots comparing the automatic methods with the reference standard identified statistically significant fixed biases, ranging in magnitude from small to large. Collectively, these results suggest that BoneXpert and BAUSport can provide comparable estimates of SA and SA-CA in young athletes relative to the Fels method. Biases in the estimation of SA should, however, be considered and the automatic methods should be implemented as part of a comprehensive growth and maturity screening protocol. The non-invasive nature of the BAUSport method affords particular advantages (no radiation exposure, portability) in contexts where the regular estimation of SA is recommended.

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Assessment
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Maturity
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INTRODUCTION

The optimal development of young athletes requires a sound understanding and awareness of child development [1]. It is advised that sport's national governing bodies implement practical and effective policies/procedures for assessing and monitoring growth and maturation in young athletes, and educate coaches, sports scientists, and medical practitioners on physical development in youth [1]. Individual differences in maturity status and timing impact athletic performance, athlete selection biases, training effects, and injury risk in young athletes. Information pertaining to the growth and maturation of young athletes can be used for several purposes. These include, (i) differentiating between athletes who are early, on-time, or delayed in maturation, (ii) more accurately evaluating physical fitness, athletic performance and future potential, (iii) identifying when athletes enter developmental stages where they may be at greater risk for injury (i.e., adolescent growth spurt), (iv) grouping athletes by maturity for training and/or competition (i.e., bio-banding), and/or (v) informing the design, implementation and evaluation of training and conditioning programmes [2, 3]. The effectiveness of these strategies is, however, dependent upon the validity and reliability of the methods used to estimate growth and/or maturation.

The processes of growth and maturation are related yet distinct [4]. Growth refers to changes in body size, composition, and/or physique; whereas maturation refers to the process of progress towards the adult or mature state [4]. Common measures of growth include height and weight, which can be assessed in terms of status (cm. or kg.) and/or velocity (e.g., gains in cm. or kg., per annum). Maturation occurs, and can be estimated, within multiple biological systems, including skeletal, dental, endocrine, sexual, and somatic characteristics.

Skeletal age (SA) is considered the most reliable and valid method for estimating maturation status and can be estimated from birth to late-adolescence [4]. Radiographs of the hand-wrist are generally used to estimate SA with several methods (protocols) available, including the Greulich-Pyle [5], Fels [6], and the Tanner-Whitehouse methods (TW1, TW2 & TW3) [7–9].

SA derived from radiographs of the hand-wrist provide valid and reliable estimates of biological maturation status in youth; however, this index is not without limitations [10]. Radiographs are expensive, time intensive, and require specialists trained in the use and interpretation of skeletal hand-wrist x-rays. Assessments of SA via x-ray also involves exposure to small radiation doses [11]. Although the dose presents minimal risk, decisions to request radiographs must provide evidence that the benefits of performing the procedure outweigh the potential health risks to the athlete. Consequently, the use of skeletal hand x-rays to estimate maturation status in young athletes is increasingly limited to cases where there are medical concerns regarding the growth/health/injury status of the child or when his/her chronological age is unknown.

Advances in digital imaging technologies and machine learning have led to the development of imaging software, such as BoneXpert, that automatically estimates SA from digitalised skeletal hand-wrist radiographs [12]. BoneXpert uses a three-layer imaging process to (i) reconstruct and validate the bone borders and architecture (ii) determine and validate SA, and (iii) average and adjust SA to the Greulich-Pyle method and/or transform these values to the TW3 or Fels stages and estimates of SA. BoneXpert provides a standardised, cost effective, and less time-intensive alternative for estimating SA, yet still requires the procurement of the hand-wrist x-ray.

Ultrasound has been proposed as an alternative, automatic, and non-invasive method for estimating SA in youth [13]. Ultrasound methods estimate SA by deducing the velocity at which sound waves pass through specific bones sites, generally the distal radius and/or ulna epiphysis [13]. As ultrasound does not involve ionizing radiation, it presents no risk to the child and can be used more frequently. Strong correlations have been reported between estimates of SA derived from sonography and skeletal hand-wrist x-rays using the Greulich-Pyle method [13, 14]. These studies have, however, included broad age ranges from early childhood to late adolescence [13, 14]. Associations between estimates of biological maturation are inflated when considering children across broad age ranges and the capacity of sonographic methods to differentiate between children of varying maturity status within narrower age bands remains unclear. Existing sonographic methods have also been criticised for relying upon single sites of assessment and over- and under-estimating SA in late and early maturing youth, respectively [15].

A particular limitation of existing sonographic methods for estimating SA is the reliance upon single or limited numbers of bone sites (i.e., radius and/or ulna). The epiphyses of the radius and ulna are ideal sites as they are present from early childhood and represent two of the last bones in the hand-wrist to attain full maturity [4, 10]. Nevertheless, there is substantial variance in the rates and ages at which the radius and ulna achieve maturity [11], introducing the potential for significant error and limiting their suitability as *exclusive* sites for estimating SA. The validity and reliability of sonographic methods could be improved by increasing the number of sites within the assessment procedure. Emerging evidence suggests that sonographic techniques (BAUSport) that utilise multiple assessment sites (e.g., radius, ulna, carpals, phalanges) may provide more reliable and valid estimates of SA [16]. Further research examining the validity and reliability of these new methods is, however, warranted.

Considering the preceding discussion, the purpose of this investigation was to examine the validity of two automatic methods for estimating SA in a combination of male and female athletes. Specifically, estimates of SA and SA-CA derived from invasive (BoneXpert) and non-invasive (BAUSport) automatic methods for estimating SA were compared against estimates of SA derived from the Fels protocol. The capacity of both automatic methods to correctly identify participants as early, on-time and late maturing relative to the Fels protocol was also investigated. Bland Altman analyses were also performed to examine the degrees of agreement between the estimates of SA provided by the automatic methods and the Fels protocol. The Fels method was selected as the *reference standard*, as it uses a comprehensive and diverse set of criteria for estimating SA and includes an accompanying standard error [17].

MATERIALS AND METHODS

Participants

The sample include 85 male and (n = 13) female soccer, volleyball, handball, and basketball players registered with a multisport academy in Catalonia, Spain. Participants were aged between 9 and 17 years (M = 13.0 years, SD = 1.6 years). A post-hoc power analysis for correlational analyses (G*Power version 3.1.9.6) [18] based upon current sample size, the lowest value for designating a large effect (r = 0.5), and a minimum probability value of .05, indicated sufficient statistical power (= .99). As all protocols for estimating skeletal age were sex specific, male and female participants were combined for all analyses. Further, there was not adequate statistical power to conduct the analyses for the female participants alone.

Ethical procedures

Data collection was approved by Clinical Research Ethics Committee of the Sports Administration of Catalonia. Participants and their parents and/or guardians were informed of the nature and purpose of the study in advance of data collection before providing both written consent and assent for participation. Ethical approval for the analysis of anonymised data was approved by the Research Ethics Approval Committee for Health at the lead author's host institution.

Measures

The data collection was conducted over a 10-month period. Maturity status assessments were conducted following standardised procedures for skeletal hand-wrist x-rays and use of the BAUSport system. All participant assessments were conducted on a single day by the Academy's Medical Service Department as part of the annual medical and health screening programme for registered athletes.

Skeletal Age: Radiographs

Dorso-palmar radiographs of the left hand-wrist were procured to estimate skeletal age (SA) using the Fels method [6]. The x-ray examinations were performed using standardised procedures by two medical doctors, each with over 15 years' experience in Paediatric Sports Medicine. Digital images (DICOM files) were then generated from each radiograph to estimate SA using the BoneXpert 3.0 imaging software [19]. The BoneXpert software provide estimates of SA in accordance with the Fels. Greulich-Pyle, and TW3 protocols. One participant's DICOM image was unable to be processed by BoneXpert. Accordingly, this participant was excluded from all analyses pertaining that required estimates of SA derived from BoneXpert. Participants presenting an SA equal or greater to, or equal lesser than, one year of their chronological age were categorised as early or late maturing, respectively. Participants with a SA falling within +- 1 years of their chronological age were categorised as 'on time'.

SA was estimated independently by a single Academy medical doctor specialising in paediatric sports medicine who was trained in the use of the Fels protocol and associated software (Felshw.com) as part of his professional and medical training. A subsample of 20 of radiographs were also assessed by the lead author. Both assessors were blinded to one another's SA estimates and the estimates derived from the BAUSport and BoneXpert systems. The intra-class correlation (ICCs) between the independent investigators' estimates of SA using the Fels protocol was positive, strong, and statistically significant ($r = .99$, $p < .001$). The absolute (A.TEM) and relative technical errors of measurement (R.TEM) between the independent assessors estimates of SA using the Fels protocol across the subsample was .42 years and 3.2 percent, respectively, with the lead author reporting a slightly lower mean estimate for SA (-0.23 years).

Skeletal Age: Ultrasound

The BAUSport instrument system with accompanying software, produced by SonicBone Medical Ltd., Rishon LeZion, Israel, was used to estimate SA based upon ultrasound assessment of three skeletal locations on the left hand-wrist. Assessments were conducted by three medical professionals in the academy's Medical Services Department who were trained in the use of the BAUSport system. These sites include the distal radius and ulna's secondary ossification centres on the epiphysis at the hand-wrist: the growth plate of metacarpal III and the shaft of the adjacent proximal phalange, and the distal metacarpal epiphysis. Information, based upon the speed at which high frequency waves of an ultrasound pulse propagate through bone and distance attenuation factors (i.e., decay rate), is fed into an integrated algorithm using the scoring method designed by Tanner and Whitehouse (TW2 method). The algorithm then provides the estimate of SA and future adult stature. The time durations for the scans at each of the various sites was 12 seconds for the radius and ulna, and four seconds for the proximal phalange and distal metacarpal. Total time for completing the assessment is approximately five-to-ten minutes per participant. The BAUSport system has previously demonstrated high levels of repeatability and validity in young athletes and the general population [16, 20–22].

Statistical Analyses

A series of statistical analyses were conducted to the investigate the degree to which the automatic estimates of SA agreed with the reference standard (Fels), including ICCs to examine associations between the estimates of SA and SA-CA; A.TEM and R.TEM to determine the magnitude of the differences between the automatic estimates of SA with the reference standard; Bland-Altman plots to examine the degree to which the automatic methods estimates of SA agreed with the estimates provided by the reference method; one-sample mean T-tests to identify the presence of fixed effect biases between automatic estimates of SA and the Fels standard; and cross tabulation analyses using Cohen's Kappa coefficient to determine the agreement amongst the methods in classifying participants as early, on-time, and late maturing.

Outliers

Prior to the main analyses, the data were investigated for outliers. Outliers represent data points that differ significantly from other observations and may occur due to chance or experimental error. A strategy whereby any participant presenting an estimate of SA that differed by more than three years from at least two of the four SA estimates derived from other methods, was used to identify, and remove outliers. One skeletal year approximates one standard deviation in skeletal age among youth of the same age. Two male participants, approximating two percent of the original sample, were removed based upon SA estimates derived from the BAUSport ($n = 1$) and BoneXpert ($n = 1$) protocols and the exclusion criteria.

RESULTS

Descriptive analyses

Descriptive statistics for age, SA and the discrepancy between skeletal and chronological age (SA-CA) are presented for the total sample and by sex in Table 1. For all the automatic estimates of SA, except the BAUSport system, the reference method (Fels Practitioner) produced a higher mean value. Of note, all the mean values for SA in the male participants were higher than the equivalent value for chronological age; whereas the mean values for SA in the female participants approximated, or fell below, the mean value for chronological age.

Intra-class correlations

ICCs (one-tailed) using mixed effects and absolute agreement were performed to examine the magnitude and direction of the associations

TABLE 1. Descriptive statistics for chronological age and estimated skeletal age (SA) across methods by sex and for the total sample.

	Males (n = 70, [a]69) M (SD)	Females (n = 13) M (SD)	Total (N = 83, [c]82) M (SD)
Chronological age	13.3 (1.5)	11.5 (1.3)	13.0 (1.6)
SA FELS Practitioner	14.3 (2.3)	11.2 (1.6)	13.8 (2.4)
SA BAUSport	14.5 (2.4)	11.6 (1.8)	14.0 (2.5)
SA FELS BoneXpert	14.0 (2.3)[a]	11.0 (1.5)	13.5 (2.4)[c]
SA GP BoneXpert	13.8 (2.3)[a]	10.7 (1.5)	13.3 (2.5)[c]
SA TW3 BoneXpert	13.4 (2.2)[a]	10.3 (1.4)	12.9 (2.4)[d]

TABLE 2. Comparison of methods for estimating skeletal age against the Fels method in male and female adolescent athletes aged 11 to 17 years.

	ICC SA	ICC SA-CA	A.TEM Years	R.TEM	Kappa
BAUSport	.98[c]	.93[c]	.49	3.49%	.71[c]
BoneXpert GP	.98[c]	.95[c]	.45	3.38%	.54[c]
BoneXpert TW3	.96[c]	.88[c]	.67	5.07%	.35[b]
BoneXpert Fels	.99[c]	.97[c]	.35	2.60%	.63[c]

Note: SA = skeletal age, CA = Chronological Age, ICC = Intraclass correlation, A.TEM = Absolute Technical Error of Measurement, R.TEM = Relative Technical Error of Measurement, [b] = $p < .01$, [c] = $p < .001$.

TABLE 3. Bland Altman analyses comparing methods for estimating skeletal age against the Fels method ($FELS_{PRACT}$-Comparison Method) in male and female adolescent athletes aged 11 to 17 years.

	Est. Bias (SD)	ULOA (95%)	LLOA (95%)	LOA Range	r
BAUSport	-.23 (.65)	1.05	-1.50	2.55	-.21
BoneXpert GP	.44 (.46)	1.35	-.46	1.81	-.12
BoneXpert TW3	.82 (.47)	1.74	-.09	1.83	.07
BoneXpert Fels	.22 (.45)	1.10	-.66	1.76	-.07

Note: ULOA = Upper Level of Agreement; LLOA = Lower Level of Agreement.

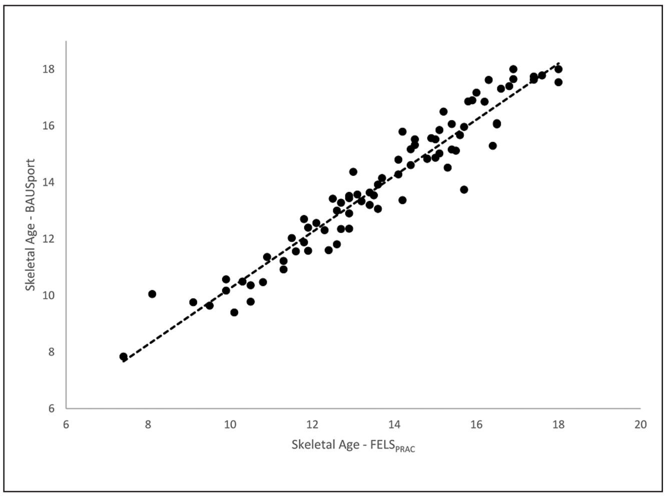

FIG. 1. Intraclass correlations and scatterplots for estimates of skeletal age derived from the BAUSport system and Fels protocol.

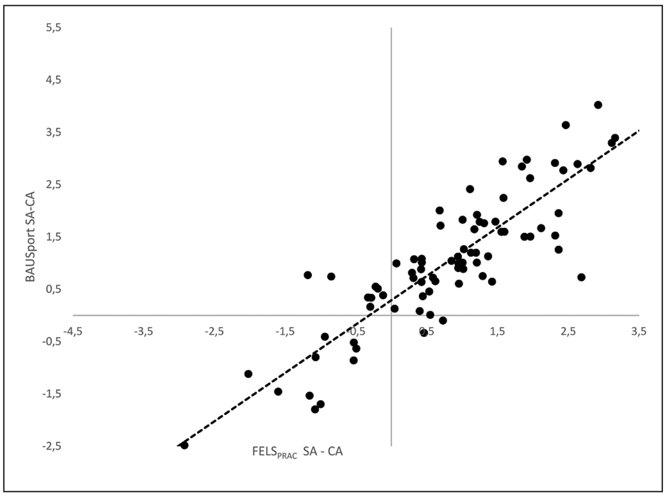

FIG. 2. Intraclass correlations and scatterplots for estimates of skeletal age and the discrepancy between skeletal and chronological age (SA-CA) as estimated by the BAUSport systems and Fels protocol.

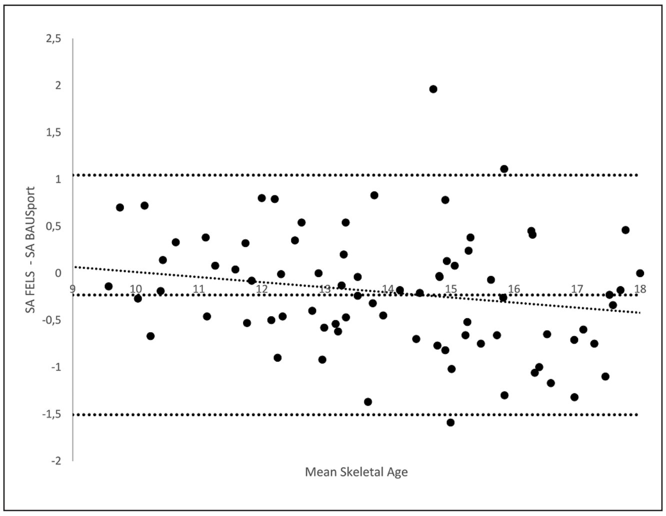

FIG. 3. Bland-Atlman plot illustrating the degree of agreement between estimates of skeletal age (SA) derived from the Fels and BAUSport protocols.

between the automatic estimates of SA and the reference method (Table 2). One-tailed analyses were selected on the basis that estimates of SA and SA-CA are expected to correlate positively across protocols. A separate series of equivalent analyses were conducted for the discrepancies between SA and chronological age (SA-CA) (Table 2). All estimates of SA and the SA-CA were positively and significantly correlated with the reference method. The correlations for SA were strong in magnitude ranging from .96 (BoneXpert TW3) to .99 (BoneXpert Fels). The correlations for SA-CA were also statistically significant and strong in magnitude yet presented a greater range of variation (BoneXpert TW3 r = .88; BoneXpert Fels r = .97). Accompanying scatterplots for the correlations between the non-invasive automatic method (BAUSport System) and the Fels method are presented in Figures 1 and 2 for SA and SA-CA, respectively.

A.TEMs and R.TEMs were calculated for all estimates of SA, relative to the reference standard, and are presented in Table 2. The A.TEM. values ranged from .35 (BoneXpert Fels) to .67 (BoneXpert TW3) years. The R.TEM. values ranged from 2.60% (BoneXpert Fels) to 5.07% (BoneXpert TW3).

Cross tabulation analyses using percentage of agreement values and Cohen's Kappa coefficients examined the degree of concordance between the automatic estimates of SA and the Fels reference protocol in classifying participants as early, on-time, and late maturing. All methods presented Kappa coefficient values that were statically significant, thereby indicating agreement between the automatic methods and the reference method (Table 2). The concordance value was highest for the BAUSport system, which presented a good level of agreement (Kappa = .71); and lowest for the BoneXpert TW3 method which demonstrated moderate agreement (Kappa = .35).

Bland-Altman analyses with accompanying linear regression analyses were conducted for each of the automatic estimates of SA and the reference standard. Mean differences (estimated bias) between the estimates of SA and the 95% upper and lower levels of agreement were calculated for each plot (Table 3). A regression line (two-way) was fitted to the scatter plots to identify systematic or proportional biases (Table 3). The estimated mean differences between the automatic estimates of SA and the reference method were all statistically significant (one sample means t-tests), indicating the presence of fixed biases. The estimated biases range from -.23 (BAUSport) to .82 (BoneXpert TW3). The range between the 95% upper and lower levels of agreement resulting from the Bland-Altman analyses varied across methods from 1.76 years (BoneXpert Fels) to 2.55 years (BAUSport). None of the methods (presented statically significant associations between the mean estimate of SA and degree of agreement between the estimates of SA. The Bland-Altman plot for the BAUSport estimate of SA and the Fels reference standard is presented in Figure 3.

DISCUSSION

This study investigated the validity of two automatic methods for estimating skeletal age in athletes aged 9 to 17 years. The ICCs indicated a series of strong and positive associations between the automatic estimates of SA and the Fels reference method. These findings are consistent with previous research using the BAUSport and BoneXpert systems [16]. Highly positive ICCs are desirable when comparing estimates of SA in validation studies and suggest a high degree of association between the estimates. They do not, however, reflect the extent to which the estimates of SA agree and/are equivalent to one another. Two methods can be strongly correlated yet produce markedly different estimates of SA. The TW3 method, for example, correlates strongly with other estimates of SA, yet produces lower estimates of SA [11]; as occurred in the current study. Equally, the broad age range of the current sample (9 to 17 years) likely inflated the magnitude of the observed correlations between the estimates of SA. That is, correlations among estimates of SA tend to be smaller when considered in restricted age samples [23]. Thus, these results, although promising, should be interpreted with caution.

The ICCs for the SA-CA discrepancy provided a more rigorous test of validity, as age-associated variance in maturation was controlled for. All the automatic estimates of SA-CA demonstrated positive and statistically significant associations with the reference method. The magnitude of the correlations was strong, varying from .88 (BoneXpert TW3) to.97 (BoneXpert Fels), suggesting that the automatic methods can provide valid estimates of SA-CA discrepancies. This observation is promising as the capacity of sonographic methods to effectively differentiate between children of similar ages, yet varying maturity status, has been questioned [15]. The more fixed geometrical position in which the hand-wrist is positioned when using the BAUSport system and greater number of assessment sites may afford greater validity and reliability when estimating SA via ultrasound.

For the BoneXpert software, the A.TEM and R.TEM values varied from -.35 to -.67 years and 2.60 to 5.07%, respectively, with all three protocols underestimating SA relative to the reference. The A.TEM and R.TEM values were greatest for the BoneXpert TW3 method, which is consistent with previous research [10]. The A.TEM and R.TEM for SA derived via the BAUSport system were comparable to, and fell between, the equivalent values for the BoneXpert estimates. The A.TEM and R.TEM values that are considered acceptable in anthropometry vary relative to the skill of the practitioner, complexity of the assessment, and opportunity for error [24]. Whereas an inter-investigator Relative TEMs of below 7.55% are considered acceptable for less precise measures, such as skinfolds, values below 1.5% are considered acceptable for more precise measures (e.g., height, weight) [24]. As the methods for estimating SA employ separate protocols, one might posit a R.TEM of below 5% to be acceptable in comparing levels of agreement between methods [24]. Applying this criterion, all methods, except for the BoneXpert TW3 protocol, presented R.TEM. values that would be considered acceptable.

The automatic methods for estimating SA all demonstrated statistically significant degrees of agreement with the reference methods in categorizing participants as early, on-time, and late maturing. The non-invasive BAUSport system demonstrated the highest degree of concordance, achieving a good level of agreement, strong enough to be considered clinically significant. The degree of concordance between the BoneXpert and Fels methods varied across protocols, ranging from to moderate (TW3) to good (Fels). Accordingly, both the BAUSport and BoneXpert systems appear to be appropriate methods for identifying youth as early, on time and late maturing.

Although all of methods presented statistically significant fixed biases when compared against the standard; only the BAUSport system presented a negative bias, which is consistent with previous research [16]. None of the methods identified a proportional bias with the Fels refence standard, suggesting no systematic errors associated greater or lesser estimates of SA. The difference between the 95% upper and lower levels of agreement varied across methods, ranging from 1.76 years (BoneXpert Fels) to 2.55 years (BAUSport). The latter finding is worthy of further consideration. Although the BAUSport system presented the smallest fixed bias and demonstrated the highest level of agreement in categorising participants as early, on-time, and late, it also produced the widest limits of agreement. A closer inspection of the participants that presented the greatest discrepancies between the BAUSport and Fels estimates of SA failed to reveal any influence of participant age and/or maturity status. A potential explanation for the wider levels of agreement is inconsistent use of the BAUSport system. Variance in the positioning of the hand or marking of anatomical sites when using the BAUSport system may have contributed to greater discrepancies in the estimation of SA across cases. More rigorous training on the use of the BAUSport system and its protocols may be important in terms of determining the degree of training required to optimally ensure methodological fidelity and reduce any extreme errors in estimation of SA.

Practical implications of the current study should be considered. Collectively, the results support the use of the BoneXpert software and BAUSport system as automatic methods for estimating SA in young athletes. The BAUSport system demonstrated the highest level of agreement with the reference method when classifying youth as early, on-time and late maturing. BoneXpert performed best when employing Fels protocol, however, the observation of positive fixed biases across all three protocols indicated a tendency for all three protocols to underestimate SA. Accordingly, estimates of SA derived from the BoneXpert software should be interpreted with caution and not treated as directly interchangeable with values derived from the reference method.

As the BAUSport system does not require exposure to radiation it provides a particular advantage when estimating maturation status in youth; especially in contexts where regular screening and monitoring of growth and maturation status may be advised (e.g., clinical cases, youth sports). In terms of estimating SA and SA-CA the BAUSport method performed as well as the BoneXpert software, although it produced marginally higher estimates of SA than the reference method. Thus, SA estimates derived from the BAUSport system cannot be considered as directly interchangeable with those derived from the reference method. As with all methods, caution is required when interpreting BAUSport estimate of SA at the individual level. The cost-effective, non-invasive, and time-efficient nature of the BAUSport system increases the opportunities for researchers and practitioners performing estimates of SA in countries where specialised equipment or personnel may not be readily available. Ideally all estimates of SA should be considered and interpreted in parallel with other indices of growth and maturation status, such as height/weight velocity, percentage of predicted adult stature, and/or changes in physique, appearance, and/or secondary sex characteristics [10]. The Premier League's Growth and Maturity Screening Programme, for example, considers multiple sources of information to assess the growth and maturational status of registered academy players every three-to-four months [25]. Combined with non-invasive estimates of SA, such information could provide greater insight as to the physical development of young athletes, optimising their training, athletic development, health, and safety.

Limitations of the current investigation must be noted. First, the results are limited to a small sample of Spanish academy athletes aged 9 to 17 years, the majority of whom were male. It is difficulty to generalise these findings across the sexes or other sports and future studies with larger samples of male and female athletes are required. Male athletes are also more likely to present limited variance in maturity due to inherent selection biases towards early maturers. As maturity selection biases are less common in female sports, female samples may provide more rigorous and representative tests of the validity and reliability of these methods. In contrast, clinical samples tend to demonstrate negative SA-CA discrepancies. The magnitude of the correlations between estimates of SA may also have been artificially inflated relatively broad age range. That said, the strong correlations remained strong for the SA-CA discrepancy, where age associated variance in maturity was effectively controlled for.

CONCLUSIONS

In conclusion, the current findings support the use of BAUSport as an alternative, practical and non-invasive methods for the estimation of SA in young athletes. In comparison to the established methods for estimating SA in youth, the BAUSport and BoneXpert systems both performed well and especially in relation to the categorization of youth as early, on-time, and delayed in maturation.

Author Contributions

Conceptualization, FD and SC.; methodology, FD and SC; logistics FD and GR; validation FD and SC; formal analysis, SC.; resources, FD and SC; data acquisition FD and RP; data curation, FD and SC; writing – original draft preparation, SC and AR; writing – review and editing, SC, FD, RP, and AR; supervision, AR and GR; project administration, FD and SC.; funding acquisition, SC. All authors have read and agreed to the published version of the manuscript.

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Conflic of interest declaration

The authors declared no conflict of interest.

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Disentangling the dynamic interplay between muscle damage and energetics in male boxers during a short training block

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ABSTRACT: Boxing is a combat sport linked to muscle damage (e.g., soreness, rising creatine kinase [CK]) and energetic biomarkers (e.g., urea, glucose). These factors have not, however, been examined dynamically in terms of day-to-day, lagged and reciprocal effects during normal training. This study investigated the dynamic interplay between muscle damage and energetics in male boxers during a short training block. Thirteen amateur boxers were monitored over 16 consecutive days during early-season training. The participants were assessed each morning for plasma CK, urea, glucose, and creatinine (days 1 and 16 only) concentrations, before self-reporting muscle soreness (1–10 scale). Within-person contemporaneous (lag-0) and temporal (lag-1) networks were estimated using multilevel vector autoregression. Muscle soreness, CK, urea, and glucose presented different trajectories with training, but with some heterogeneity reflecting within-person variances (47% to 78%). The contemporaneous network yielded a significant positive edge (or correlation) between CK and soreness (r = 0.44), along with negative CK-glucose and glucose-urea edges. More significant edges emerged in the temporal network, with soreness linked to CK (r = 0.19), glucose (*r* = -0.28) and urea (*r* = 0.22), whilst the CK-glucose edge sign switched. In summary, daily fluctuations in muscle damage and energetic activity, which presented in a normal physiological range, were highly variable among boxers during early-season training. Within-person networks indicated some interrelatedness between CK, soreness, urea, and glucose, although the nature and presence of these relationships were contingent on temporal ordering. These inconsistences reflect the pleiotropy of energetic biomarkers in training and recovery.

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INTRODUCTION

Boxing is a combat sport characterized by short duration, high-intensity bursts of physical activity and impact [1, 2, 3]. Physiologically, boxing matches and sparring are associated with high-energy turnover, leading to activation of energetic biomarkers (e.g., glucose, cortisol, lactate) and micro-injuries that provoke an inflammatory response [2, 3, 4, 5]. Many factors can influence these parameters (at rest or after exercise) among boxers, like age and training status [1], whether the activity is traumatic (i.e., real boxing) or simply muscular work (i.e., shadow boxing) [6], dietary factors (e.g., protein supplementation) [7], and any post-exercise recovery strategies used [8]. Whilst this work is informative, little is known about the training response of boxers [9, 10]. In particular, how these factors interact on day-to-day basis, including lagged and reciprocal effects, in an ecological training environment.

This research sought to disentangle the daily interplay between muscle damage (i.e., muscle soreness, CK) and energetic activity (i.e., urea, glucose) in male boxers during a short training block. Measurements were collected over 16 consecutive days. We first examined the group and individual trajectories over time, before simultaneously modeling the entire dataset using multivariate network analyses. By taking a network approach, we view the muscle damage-recovery process as a "dynamical system" in which the factors described affect, and are affected by, each other on different time scales. Within-person networks were emphasized to accommodate individual-specific responses to exercise-induced muscle damage (EIMD) [4, 11, 12]. As an exploratory study, no firm hypotheses were generated.

MATERIALS AND METHODS

Participants

Thirteen amateur male boxers were recruited for this study, with a mean (± SD) age and body mass of 25.1 ± 1.5 years and 67.1 ± 13.2 kg, respectively. The athletes were classified as elite performers, who were competing at a national and/or international level, with an average training experience of 11.1 ± 1.5 years. The participants did not report taking any drugs, doping agents or special supplements at the time of this study (or prior to), nor did they report any injuries or medical problems that would affect the study results or their ability to train. Ethical approval was obtained from the Institute of Sport – National Research Institute, Poland, with full adherence to ethical standards in sport and exercise research [13]. For example, each athlete received a full briefing on the study aims, experimental procedures, and potential benefits, before providing written and verbal informed consent. Participation was completely voluntary, so they could leave the study at any time without prejudice.

Study design

A longitudinal, observational study was undertaken involving the daily assessment of male boxers for muscle damage and energetic activity over 16 consecutive days. Data were collected across an early-season training block, which represented the first training camp in February (Polish winter months) following a 1-month detraining period. All athletes were housed together where they completed the same training regime, followed a similar sleep-wake schedule, and consumed a similar diet via a set daily menu. Individual dietary intake was not strictly monitored during this study, but we anticipated that typical macronutrient needs for athletes (e.g., 50–60% carbohydrates, 10–20% protein, 20–30% fat) would be naturally adhered to. We assumed high calorie intake by these athletes without energy restriction, as required for preparatory training, and adequate hydration throughout. The modality, intensity and format of training was the same for all athletes during this preparatory period; see below for more specific details.

Athlete training comprised of moderate- to high-intensity exercise that included a combination of; (1) general physical conditioning (e.g., shuttle runs, push-ups, pull-ups, skipping) in both interval and continuous formats, (2) heavy bag work in interval format to simulate a boxing contest (3–5 x 3-min rounds, 1-min recovery), (3) one-on-one boxing drills involving pad work with a trainer, (4) full-contact sparring (3 x 3-min rounds, 1-min recovery) with both participants wearing gloves and head protection. The sparring workouts were preceded by shadow boxing and some bag work, as a warm-up procedure. The boxers completed 1–2 training sessions a day, each lasting ~1 hour, with exercise intensity gradually increasing (i.e., greater work to recovery ratio) from day 1 up to day 16. Exercise intensity was subjectively assessed by the coach and training staff using visual / verbal cues of perceived effort, movement quality, and fatigue. The study participants were scheduled to train on Monday to Saturday of each week with Sundays free of any physical activity.

Assessments

Capillary blood samples (~200 μL) were collected from the earlobe into heparinized tubes. The tubes were centrifuged and the plasma portion was extracted into another tube for storage in a -80° C freezer. Each sample was tested for creatinine (in μmol/L), CK (in U/L), urea (in mmol/L), and glucose (in mmol/L) concentrations using a biochemical analyzer (Biotecnica Instruments, Italy) and reagents supplied by the manufacturer. Note that plasma creatinine was assessed on days 1 and 16 only. Capillary-based measurements of CK, urea, and glucose [14, 15, 16] are reliable and also valid, compared with venous blood collections, although the measured concentrations are not always interchangeable between blood compartments.

General muscle soreness was assessed daily by self-report and anchored on a 1 (= no pain) to 10 (= extremely painful) Likert scale [12, 17]. These data were collected with a time-framed question (i.e., how sore are your major muscle groups right now?), after which the participant was shown a card with all possible ratings and explanations. Body mass was measured to the nearest 0.1 kg on days 1 and 16 using electronic scales (Seca, Germany), with subjects wearing training shorts and a shirt, but without shoes.

Statistical analyses

Data were analyzed in the R programming environment [18]. First, descriptive means and SDs were calculated for all variables, based on averages of all within-person results. Intraclass correlation coefficients (ICC) were also calculated for selected variables (i.e., soreness, CK, urea, glucose) to extract the variance components. In other words, is the observed variability due to within-person (e.g., CK changes over time for all subjects) or between-person (e.g., CK differences among subjects) sources. Next, a visual inspection of the variable trajectories was conducted to identify group patterns and individual differences from the group mean. To do this, we plotted the smoothed means of the study population using a generalized additive model, overlaying all individual data points.

Two within-person networks were estimated using multilevel vector autoregression (VAR) in the mlVAR package [19]. The first is a *temporal network* reflecting within-person partial correlations of the average person at lag-1 (1-day), and second is a *contemporaneous network* reflecting within-person partial correlations of the average person at the same measurement occasion (lag-0). In networking parlance, correlations between variables are termed edges and variables are termed nodes [20]. Prior to analysis, checks for VAR assumptions of stationarity, multivariate normality, and linearity were performed. To meet these assumptions, the glucose data were regressed onto time and the residuals saved as the new variable. The study design ensured that the VAR assumption of equidistant intervals was met. In line with recent studies using different dynamical-system modeling approaches [21, 22, 23], all time-series data were standardized within a person prior to network estimation. The ensuing network edges were thresholded at $p < 0.05$. No edge adjustments were made for multiple comparisons, as we wanted to err on the side of discovery.

RESULTS

The descriptive and stability results are presented in Table 1. Athlete ratings of muscle soreness, although stimulus and timing dependent, are similar to other EIMD studies on untrained adults [12, 17] and male boxers [7]. The concentration measures of plasma creatinine,

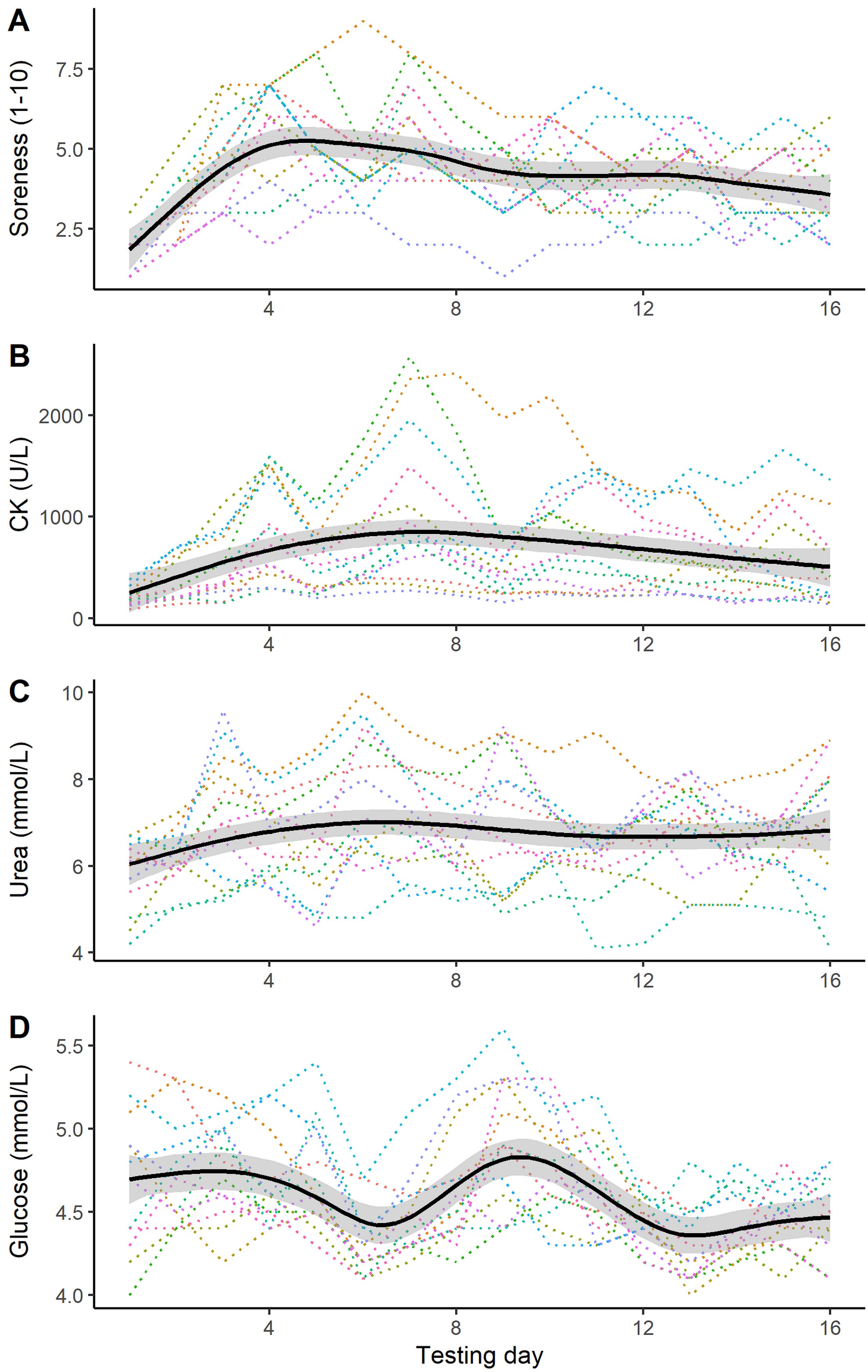

FIG. 1. Time-series plots for the muscle damage and energetic variables in male boxers. The solid black line represents the smoothed trajectory, with the shaded region indicating the 95% CI. The dotted lines represent the individual time series. Key: CK = creatine kinase.

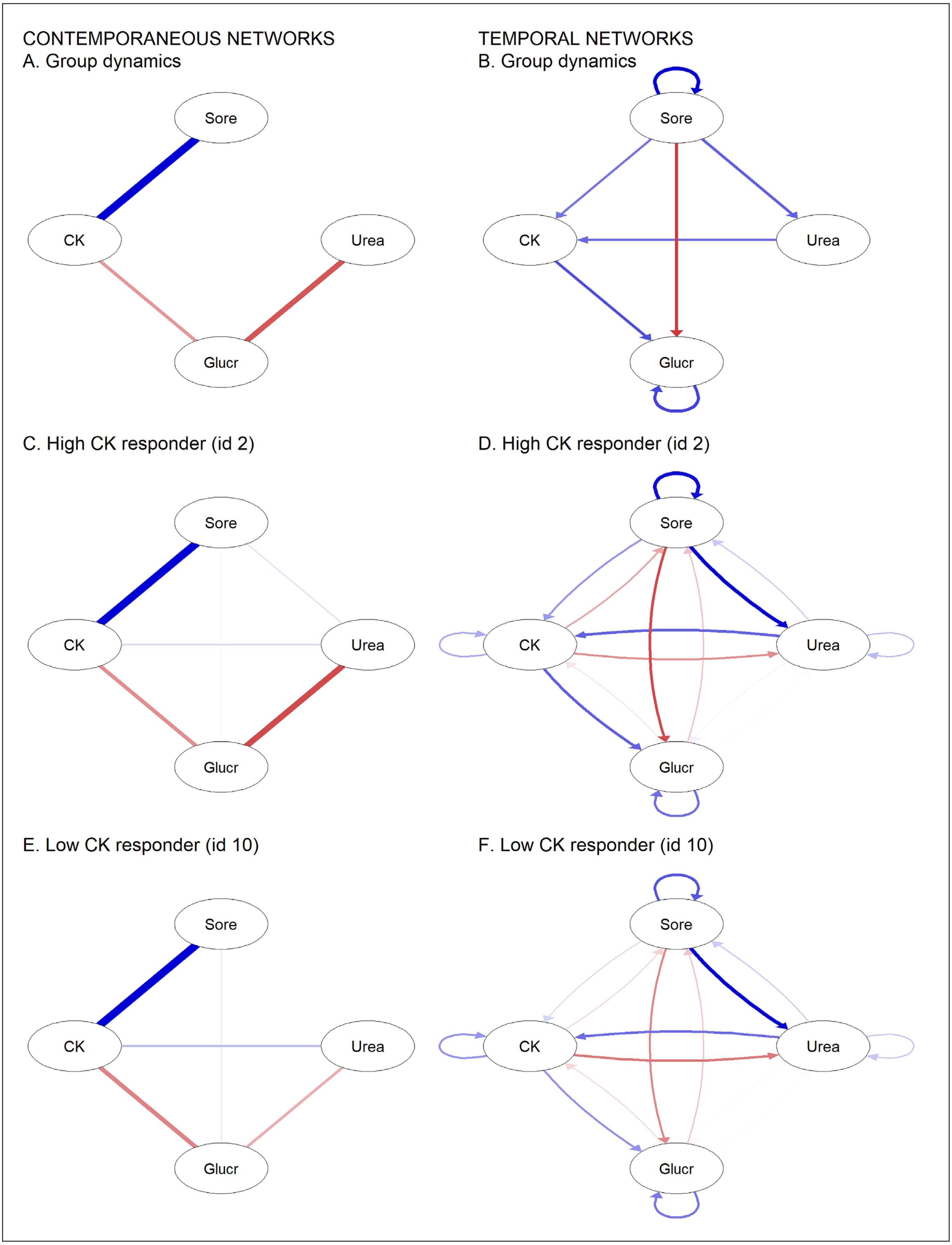

FIG. 2. Within-person contemporaneous and temporal networks between the muscle damage and energetic variables in male boxers. Blue edges represent positive correlations and red edges indicate negative correlations. The mlVAR software hides non-significant edges in the group network, but cannot hide the same edges in subject networks. Key: CK = creatine kinase, Glucr = glucose residuals, Sore = muscle soreness.

TABLE 1. Descriptive and reliability statistics for the muscle damage and energetic variables in male boxers across a short training block.

Variables	Mean	SD	ICC	Sample range (min – max)
Soreness (1–10)	4.17	1.37	0.22	1–9
Creatinine (μmol/L)*	84.7	3.64	na	54–118
CK (U/L)	650	297	0.52	88–2573
Urea (mmol/L)	6.72	0.82	0.53	4.1–10.0
Glucose (mmol/L)	4.59	0.28	0.25	4.0–5.6

Key: CK = creatine kinase. *Assessed on days 1 and 16 only.

CK, urea, and glucose all lie within a normal physiological range, and overlap reported values in other boxing studies [1, 2, 4, 5, 6, 7, 9, 10, 24]. All ICCs were small to moderate for muscle soreness and the plasma biomarkers, varying between 0.22 and 0.53, which means that 22% to 53% of the variances originated at the between-person level. Thus, the remaining variances (47% to 78%) can be attributed to within-person sources.

Regarding the group response, muscle soreness rose immediately after study inception, peaking on days 4–5 before declining slowly over the remaining days (Figure 1A). For plasma CK (Figure 1B), we saw a more gradual concentration increase up to day 7, followed by a slow decline over time. A relatively flat trajectory was observed for plasma urea concentration (Figure 1C), whereas plasma glucose activity (Figure 1D) was undulating over the 16-day period. Importantly, all variable measurements were characterized by large individual variability. T-test analyses (day 1 vs. day 16) revealed a non-significant decrease in body size (-0.4%, $p = 0.118$), but a significant increase in creatinine concentration (3.8%, $p = 0.040$).

Three significant edges emerged in the within-person contemporaneous network (Figure 2A), between the soreness and CK ($r = 0.44$), CK and glucose ($r = -0.18$), and glucose and urea nodes ($r = -0.29$). More significant connections were identified in the within-person temporal network (Figure 2B), with soreness exhibiting positive edges with CK (r = 0.19) and urea ($r = 0.22$), and a negative edge with glucose ($r = -0.28$). A positive urea and CK edge also emerged ($r = 0.28$) and the negative CK-glucose edge in the contemporaneous network was now positive ($r = 0.25$). To establish whether individuals differed in system dynamics, we explored the corresponding networks for boxers displaying the highest CK (id 2, Figure 2C and Figure 2D) and lowest CK means (id 10, Figure 2E and Figure 2F). For both participants, the contemporaneous and temporal networks were largely similar to the group response and each other.

The mlVAR package [19] can disaggregate time-series data to additionally estimate a between-person network, although the edges between nodes are biased when N is low. Consequently, we have not presented the between-person network in this study.

DISCUSSION

This study sought to disentangle the day-to-day dynamics between muscle damage and energetics in male boxers within an ecological training environment. As a group, the muscle soreness, CK, urea, and glucose trajectories revealed different training patterns, but with a large degree of heterogeneity that arguably reflects within-person variances (from 47% up to 78%) from the mean. Within-person network analyses revealed some interrelatedness between these outcomes in the contemporaneous network, with more (but not always consistent) edges emerging in the temporal network.

Across different sports and levels of eliteness, initial return to structured training after the off-season period results in elevated concentrations of EIMD biomarkers [25]. The muscle soreness and CK profiles of our boxing sample concur with this evidence, increasing over the first few days of early-season training and remaining somewhat elevated thereafter. Among boxing populations, the induction of EIMD is likely due to mechanical, metabolic, and oxidative stressors arising from repeated and initially unaccustomed exercise, combined with the physical trauma of full-contact sparring, heavy bag work, and related boxing drills [4, 6, 9, 10]. Other potential moderators of EIMD include training intensity [9], the number and locality of punches received when competing (or sparring) [5], dietary intake (e.g., soy protein) [7], and use of any post-sparring recovery intervention [8]. We further demonstrated a positive within-person edge between soreness and CK in both networks; a finding that supports evidence from untrained adults [11, 12, 17] and male boxers [7] that muscle soreness and CK concentration tend to rise and fall in parallel or with a short lag.

Other results generated by the network models were contradictory. In the temporal network, greater muscle soreness correlated with higher urea and lower glucose levels 1-day later, whereas the same edges were absent based on time-matched (contemporaneous) comparisons. Daily fluctuations in urea and glucose concentrations were also related in the latter, but not the former, network. Finally, a CK and glucose edge emerged in both networks, but was differently expressed in the contemporaneous (negative) and temporal (positive) models. The pleiotropic role of energy biomarkers in muscle contractions, glycemic control, the inflammatory insult, and muscle recovery, could explain this diversity. Hence, it is problematic to limit these results to the silo of EIMD, especially when athletes are performing multiple training sessions each day and week to achieve different physiological responses. Rather, they should be interpreted from the broader prism of training and recovery, with muscle damage as a secondary outcome. Adding to these difficulties, upstream signals like pro-inflammatory cytokines (e.g., IFNγ, TNF) and glucocorticoids (e.g., cortisol) can affect glucose homeostasis [26, 27], and notwithstanding the direct effect of dietary intake on energetic biomarkers like glucose.

Our data indicate a high degree of individual variability in muscle damage and energetics, as seen in boxers [4, 5, 9], rugby players [28, 29], and untrained adults [11, 12, 17]. Physical impacts in a sporting contest can affect CK release [28, 29] and thus, drive this individuality, but sparring impacts from boxing were not measured. Others have highlighted the role of genetic factors. As an example, the highly variable CK response to exercise was attributed to polymorphisms in genes that encode proteins involved in CK release [11]. On the other hand, the network profiles of the highest CK (mean 1353 U/L) and lowest CK (mean 212 U/L) responder indicate similar dynamical interplay. This raises the intriguing possibility of adaptive mechanisms that synergize the training response to compensate for differences in baseline and reactive physiology, or it could reflect a predisposition that favors natural selection to the inherent demands of boxing. To test the uniformity and strength of these networks, one could take a case-study approach over several weeks and months of data collection [23, 30], thereby ensuring a more detailed and personalized inspection of EIMD to address questions around different training phase and/or workload effects [25].

On a practical level, the selected EMID and energetic biomarkers appear to be indicative of training responsivity and/or functional connectivity and thus, should form part of a standing testing battery in boxers. Researchers, coaches, and practitioners could also benefit from the creation of within-person networks, either for a training squad or individual athletes. One could explore the structure of a multivariate dataset, as we have, with network representations helping to communicate intricate patterns of interrelatedness [20]. For instance, we identified more edges in the temporal network, which suggests that a daily testing schedule and investigation of lagged effects can extract more meaningful results for boxers. Further possibilities exist to generate causal hypotheses for testing [20], such as our observation of coherent network patterns (across all boxers and high and low CK responders) reflecting training synergy or natural selection. The network approach further aligns to contemporary perspectives of sport processes that encompass complex systems principles (e.g., interdependence, temporal nestedness, circular causality) [23, 31, 32]. This conceptual shift from traditional models (e.g., univariate and non-lagged analyses, pre and post design) can better capture when, how, and why, different biomarkers interact in a sports environment, allowing a more targeted approach to athlete training, assessment and evaluation.

Caution should still be exercised when interpreting the current findings. Only a limited number of variables were collected and we did not quantify the training stressors, in particular sparring impact, each day. Moreover, the networks were estimated from sparse sampling and we fixed the temporal network at lag-1, which precludes detection of correlations that exist within, or beyond, the 1-day sampling interval. As a delimitation, any inferences are specific to male boxers of a similar age and amateur status, as well as the specific phase of training. The lack of a body-fat assessment is another limitation. Rapid weight loss can also affect CK and other energetic biomarkers in combat-sport athletes [33]. However, this work was conducted early in the boxing season and weight cutting for competition was not a goal, and prior weight cutting (> 1 month earlier) was not deemed relevant. Future work on boxers would benefit from study replication over a longer time period, with added biochemical (e.g., cytokines, neutrophils), endocrine (e.g., cortisol, testosterone) and/or performance (e.g., muscle power, fatigue) measures [3], alongside a detailed anthropometric assessment (via bioimpedance or dual x-ray absorptiometry) to determine how changes in body composition affect blood biochemistry. Combining this information with daily exercising loads, including sparring impacts and their location (e.g., head vs. body), would help construct a more comprehensive ontology of training, EIMD, and recovery processes.

CONCLUSIONS

To summarize, day-to-day fluctuations in muscle damage and energetic activity, which occurred in a normal physiological range among male boxers, were found to be highly variable during early-season training. Within-person network analyses identified some interrelatedness between the study outcomes, although the strength, direction, and even presence, of these relationships were contingent on temporal (lag-0 vs. lag-1) ordering. We attribute these inconsistences to the pleiotropy of energy biomarkers in training and recovery.

Conflict of interest

The authors declared no conflict of interest.

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Are EFI data valuable? Evidence from the 2022 FIFA World Cup group stage

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ABSTRACT: The 2022 World Cup used new Enhanced Football Intelligence (EFI) data, stoppage time calculation methods and substitution rules that were introduced by FIFA. The aim of this study is to explore the effectiveness of EFI in match analysis and to identify the key indicators that influence the match and provide a reference for coaches' tactical design and training. Data were derived from the FIFA website, including EFI data for 48 matches at the group stage of the Qatar World Cup. A total of 46 indicators were used for analysis and the average values of the corresponding indicators for the different competition results were used in the analysis to identify the key index that determines the outcome of the competition. Apart from scoring more goals and having more assists, winning teams had significantly more attempts on target than drawing and losing teams ($p < 0.05$); Winning teams had significantly more attempts inside the penalty area, completed defensive line breaks and receptions behind the defensive line than losing teams ($p < 0.05$). There is no difference in possession between matches with different results ($p > 0.05$). Goals were significantly correlated with completed defensive line breaks and receptions behind the defensive line ($r = 0.27–0.30$, $p < 0.01$). Attempts on target was significantly positively correlated with receptions, final third entries and line breaks ($r = 0.31–0.67$, $p < 0.01$) and negatively correlated with defensive pressures applied ($r = -0.35$, $p < 0.01$). The efficiency of the offense is more important. Teams need to have more receptions, final third entries and line breaks to get more shots on target rather than possession. This study may help coaches to interpret the game from a multi-dimensional perspective and coaches can use EFI to help their teams improve their match performance.

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Goal
Metrics

INTRODUCTION

Football technical indicators reflect a team's athletic performance and influence the outcome of a match, and therefore receive a great deal of attention from practitioners [1–3]. The FIFA World Cup, as the highest-level soccer tournament at the international level for national teams, has received particular attention from researchers for its influence and competitive nature [1, 4–9].

For example, Castellano et al. [5] combined the 2002, 2006, and 2010 World Cups and found that the number of shots, shots on goal, and possession were the most influential factors in the game, consistent with the results of subsequent analyses of 2014 and 2018 [1, 4]. Liu et al. [1] found in 2014 World Cup that possession and short passing increased winning possibilities by 11% and 24%, respectively, while crosses and dribbles decreased the probability of winning by 29% and 12%, respectively. Yi et al. [10] found accordingly a higher probability of winning for teams with a possession style in the 2018 World Cup. An analysis of possession by high level teams at the 2010–2018 World Cup found that possession in one's own defensive zone increases the likelihood of goals through multiple passes in short periods of time [9].

However, there is some dispute in the research about the simple use of higher or lower possession. In some tournaments, superior possession does not lead to higher win rates [11], and distinguishing the main areas when in possession is more critical [12]. In addition, recent studies found that crosses have a positive impact on the outcome of matches [13, 14], contrary to previous findings [1, 15]. More precisely, the 2018 World Cup data show a higher probability of scoring from out-swinging crosses and the losing teams prefer to take middle crosses and late crosses [16]. Moreover, 69.9% of goals were scored from short passes, 13.6% from long passes and 16.5% from mixed passes [17].

To sum up, the notational analysis of the World Cup has produced some results, but the indicators are relatively conventional. Conclusions such as more shots on target help teams win are difficult for teams to apply in practice. There is a need to find more nuanced technical indicators that can help teams improve their performance.

Based on this, FIFA has launched Enhanced Football Intelligence (EFI) to provide a more intelligent and refined reference for match analysis. In the 2022 World Cup, FIFA assembled a data analysis team and started to use this indicator for relevant statistics. Each game will have its unique analytical data during and after the live broadcast. As new data to be used from 2022, the EFI has different characteristics from the previous data. For example, defensive height can distinguish a team's defensive starting position; possession in contest adds an insightful third dimension to possession statistics, which cannot be clearly calculated at the moment of scramble in previous data. EFI has several times more data points in the competition than previous data counting methods. The factual data in the match can be processed in 2 seconds with its high-speed algorithm and fed back to the officials quickly. It can provide both factual data during the match and during the post-match evaluation. If EFI data are combined with video and other metrics such as running patterns, it will provide practitioners with a clearer understanding of the game. In fact, EFI is already being used in the Women's U20 World Cup in August 2022, providing a powerful aid for match analysts.

Considering that EFI has just been used in the competition, it is necessary to study its effectiveness in analysing the match. Therefore, the aim of this study is to compare the differences in technical indicators between the results of different matches and the relationship between EFI and attempts on target.

MATERIALS AND METHODS

Sample and variable

The data are taken from the official FIFA website (https://www.fifa.com/fifaplus/en/tournaments/mens/worldcup/qatar2022), which is freely available. Another four success rate figures (line breaks, defensive line breaks, passes and crosses) were calculated from FIFA data for analysis. During matches in the knockout rounds more goals were scored than during matches group stage (3.1 vs 2.5 goals). Since almost one third of the knockout games went into extra time, and the data provided by FIFA are inclusive of extra time data and not for the 90 minutes separate, only matches in the group stage (48 games, 96 cases (38 won, 20 drew, 38 lost)) were selected as the object of study. The definition of the EFI data is provided on the official FIFA website (https://www.fifatrainingcentre.com/en/fwc2022/efi-metrics/efi-metrics-pdfs.php) and Table 1 shows the variables analysed in this paper. Since this study is an observational study without any intervention on the subjects, no ethical proof is required.

Statistical analysis

Data were processed using SPSS 26.0 (IBM, Armonk, NY, USA), and data were expressed as mean ± standard deviation. Normality was checked by Kolmogorov-Smirnov tests. To compare the difference between win, draw and loss figures, one-way ANOVA was used for normal data, the Levene test was used for the homogeneity-of-variance test, the least significant difference (LSD) test was used for post-hoc tests when the variance was homoscedastic, and Tamhane's T2 test was used when the variance was not homoscedastic. The chi-square test was used to determine the difference between teams with different possession rates, passing success rates, and line breaking success rate. K-sample independent tests were used for non-normal data. A non-parametric correlation test was performed using Spearman correlation. The criteria for correlation are as follows: r = 0.1–0.29 = small, 0.3–0.49 = medium, 0.5–0.69 = large, 0.7–0.89 = very large, 0.9–0.99 = almost perfect, and 1 = perfect [18]. The significance level was defined as $p < 0.05$.

RESULTS

In the group stage, there was a total of 120 goals, of which 36% were scored in the first half. Among all the indexes provided by FIFA, only goals, goals conceded, goals inside the penalty area, goals outside the penalty area, assists and attempts on target were significantly different between winning, drawing and losing teams ($p < 0.05$). Winning teams had significantly more goals, goals inside the penalty area, assists, and attempts on target than drawing and losing teams ($p < 0.05$). Winning teams scored significantly more goals outside the penalty area, had more attempts inside the penalty area, more receptions behind the defensive line, completed more defensive line breaks, had a higher success rate of defensive line breaks, and more forced turnovers than losing teams ($p < 0.05$). Drawing teams had significant fewer yellow cards than losing teams ($p < 0.05$). No significant difference was found in other data (Tables 2 and 3).

The number of goals was correlated with completed defensive line breaks and receptions behind the defensive line ($p < 0.01$) with no other EFI data correlated with number of goals (Table 4). Attempts on target were significantly positively correlated with attempted line breaks, completed line breaks, attempted defensive line breaks, completed defensive line breaks, receptions between midfield and defensive lines, receptions behind the defensive line and all the area of final third entries ($r = 0.31–0.67$, $p < 0.01$), and negatively correlate with defensive pressures applied ($r = -0.35$, $p < 0.01$) (Table 4). A two-factor linear regression model was constructed on the attempts on target and receiver data, as these indicators are particularly important for technical and tactical purposes and have the highest correlation coefficient (Figures 1 and 2). The R^2 for the attempts on target was 0.40 for receptions between midfield and defensive lines and 0.48 for receptions behind the defensive line.

TABLE 1. Selected technical match variables.

Variable		Measurements
Goal	Goal (n)	A team succeeds in scoring a goal
	Conceded (n)	Goal scored by opponent
	Goal Inside the Penalty Area (n)	The shot before the goal took place in the penalty area
	Goal Outside the Penalty Area (n)	The shot before the goal took place outside the penalty area
	Assists (n)	A pass that gets converted into a goal by another player
Attempts	Attempts (n)	An attempt to score a goal
	Attempts On Target (n)	Shots where the target is within the range of the goal
	Attempts Off Target (n)	Shots where the target is outside the range of the goal
	Attempts Inside the Penalty Area (n)	Shots that occur inside the penalty area
	Attempts Outside the Penalty Area (n)	Shots that occur outside the penalty area
Possession	Total (%)	Percentage of total time that a team has been in full control of the ball
	In Contest (%)	The ball was not always fully controlled by both sides of the game and the percentage of the total game time that was spent with contested possessions.
Final Third Entries	Left Channel (n)	The ball is successfully distributed or carried into the last third of the left channel of the final third, which consists of the left sideline, the extension of the left penalty area line and the offensive third of the field.
	Left Inside Channel (n)	The ball is successfully distributed or carried into the last third of the left inside channel of the final third, which consists of the extended area of the left goal area line, the extended area of the left penalty area line and the offensive third of the pitch.
	Central Channel (n)	The ball is successfully distributed or carried into the last third of the central channel of the final third, which consists of the extended area of the left goal area line, the extended area of the right goal area line, and the offensive third of the pitch.
	Right Inside Channel (n)	The ball is successfully distributed or carried into the last third of the right inside channel of the final third, which consists of the extended area of the right goal area line, the extended area of the right penalty area line and the offensive third of the pitch.
	Right Channel (n)	The ball is successfully distributed or carried into the last third of the right channel of the final third, which consists of the right sideline, the extension of the right penalty area and the offensive third of the field.
Offers to Receive	Total (n)	A clear and deliberate action performed in an attempt to receive the ball
	Offers to Receive In Behind (n)	A clear and deliberate action performed in an attempt to receive the ball behind the defensive line of the opponent
	Offers to Receive In Between (n)	A clear and deliberate action performed in an attempt to receive the ball between the first line and the defensive line of the opponent
	Offers to Receive In Front (n)	A clear and deliberate action performed in an attempt to receive the ball in front of the first line of the opponent
Receptions	Receptions Between Midfield and Defensive Lines (n)	The ball has been received between the opponents' midfield and defensive line
	Receptions Behind the Defensive Line (n)	The ball has been received behind the opponents' defensive line

TABLE 1. Continue.

Variable		Measurements
Line Breaks	Attempted Line Breaks (n)	The team attempts to pass/cross or carry the ball past the last player in one of the lines of the defending team
	Completed Line Breaks (n)	The team successfully passes/crosses or carries the ball past the last player in one of the lines of the defending team
	Success Rate of Line Breaks (%)	Successful line breaks as a percentage of attempted line breaks
	Attempted Defensive Line Breaks (n)	The team attempts to pass/cross or carry the ball past the last player in the defensive line of the defending team
	Completed Defensive Line Breaks (n)	The team successfully passes/crosses or carries the ball past the last player in the defensive line of the defending team
	Success Rate of Defensive Line Breaks (%)	Successful defensive line breaks as a percentage of attempted defensive line breaks
Fouls	Yellow Cards (n)	Player shown yellow card by referee for foul and other offences
	Red Cards (n)	Player shown red card by referee for foul and other offences
	Fouls Against (n)	Any infringement that is penalised as foul play by a referee
	Offsides (n)	Appeared in an offside position, which was called by the referee
Pass/Cross	Passes (n)	Short passes aimed at teammates
	Passes Completed (n)	Successful pass to a teammate
	Success Rate of Passes (%)	Successful passes as a proportion of total passes
	Crosses (n)	Long passes aimed at teammates
	Crosses Completed (n)	Successful crosses to a teammate
	Success Rate of Crosses (%)	Successful crosses as a proportion of total crosses
Others index	Switches of Play Completed (n)	Successfully completed the attack through switches
	Corners (n)	The ball passes over the goal line, on the ground or in the air, having last touched a player of the defending team, and a goal is not scored
	Free Kicks (n)	The ball is given to a member of one side to kick because a member of the other side has broken a rule
	Penalties Scored (n)	Goal scored by penalties
	Goal Preventions (n)	Actions a goalkeeper takes when attempting to prevent the concession of a goal
	Own Goal (n)	A goal scored by the defending team
	Forced Turnovers (n)	The attacking team loses position of the ball due to pressure being applied by the defending team
	Defensive Pressures Applied (n)	Defensive pressure applied towards an attacker in possession of the ball

TABLE 2. FIFA EFI metrics for winning, drawing and losing teams (mean ± SD)

Index	Win	Draw	Lose	F	K	p
Goal	2.2 ± 1.4* ^	0.6 ± 0.9	0.6 ± 0.8		40.767	0.000#
Conceded	0.6 ± 0.8*	0.6 ± 0.9&	2.2 ± 1.4		40.767	0.000#
Goal Inside the Penalty Area	2.0 ± 1.4* ^	0.5 ± 0.8	0.5 ± 0.7		36.953	0.000#
Goal Outside the Penalty Area	0.2 ± 0.4*	0.1 ± 0.3	0.0 ± 0.2		7.762	0.021#
Assists	1.6 ± 1.3* ^	0.5 ± 1.0	0.4 ± 0.4		31.326	0.000#
Attempts	12.2 ± 6.6	9.6 ± 3.5	10.3 ± 5.7		2.075	0.354
Attempts On Target	5.0 ± 2.9* ^	2.1 ± 2.1	3.1 ± 2.1		10.781	0.005#
Attempts Off Target	4.8 ± 3.1	4.4 ± 2.1	5.0 ± 2.9		0.310	0.856
Attempts Inside the Penalty Area	7.8 ± 4.7*	6.2 ± 3.1	5.9 ± 4.2		4.548	0.103
Attempts Outside the Penalty Area	4.4 ± 3.6	3.4 ± 1.3	4.5 ± 2.7		2.194	0.334
Final Third Entries						
Left Channel	13.5 ± 7.8	12.3 ± 5.3	13.4 ± 7.0		0.037	0.982
Left Inside Channel	4.7 ± 3.2	3.7 ± 2.2	4.8 ± 2.8		2.006	0.367
Central Channel	5.0 ± 3.1	4.7 ± 3.3	4.5 ± 2.6		0.375	0.829
Right Inside Channel	5.0 ± 3.5	3.8 ± 1.6	4.3 ± 2.4		0.908	0.635
Right Channel	12.2 ± 5.3	11.4 ± 5.4	11.4 ± 6.8	0.224		0.800
Offers to Receive	568.5 ± 204.2	554.9 ± 105.1	553.5 ± 177.7	0.078		0.925
Offers to Receive In Behind	126.9 ± 40.7	116.0 ± 23.2	121.5 ± 39.5	0.579		0.562
Offers to Receive In Between	218.1 ± 76.2	225.6 ± 63.1	213.5 ± 59.7	0.210		0.811
Offers to Receive In Front	223.6 ± 103.7	213.3 ± 51.6	218.5 ± 109.6		0.132	0.936
Receptions Between Midfield and Defensive Lines	99.0 ± 30.8	92.5 ± 20.5	94.1 ± 29.1	0.451		0.638
Receptions Behind the Defensive Line	12.6 ± 7.0*	10.1 ± 4.8	9.4 ± 6.1		5.560	0.062
Attempted Line Breaks	167.2 ± 32.6	172.5 ± 20.5	164.6 ± 34.9	0.404		0.669
Completed Line Breaks	111.9 ± 34.6	109.4 ± 26.4	104.3 ± 32.1		0.514	0.773
Attempted Defensive Line Breaks	18.9 ± 7.0	19.1 ± 5.5	16.9 ± 7.0	1.109		0.334
Completed Defensive Line Breaks	10.8 ± 5.6*	9.7 ± 4.6	8.6 ± 6.0		4.585	0.101
Yellow Cards	1.6 ± 1.5	1.3 ± 1.1&	2.1 ± 1.6		4.344	0.114
Red Cards	0.1 ± 0.2	0	0			
Fouls Against	11.8 ± 3.7	11.6 ± 3.1	12.6 ± 5.0	0.550		0.579
Offsides	1.8 ± 1.4	1.5 ± 1.6	2.2 ± 2.1		1.688	0.430
Passes	484.8 ± 192.7	485.5 ± 104.9	484.4 ± 159.0		0.467	0.792
Passes Completed	419.8 ± 192.3	411.8 ± 108.4	411.0 ± 159.1		0.225	0.893
Crosses	18.1 ± 7.9	18.3 ± 7.2	18.2 ± 8.3		0.014	0.993
Crosses Completed	4.7 ± 3.3	3.9 ± 2.6	4.5 ± 3.0		1.089	0.580
Switches of Play Completed	6.3 ± 3.3	6.5 ± 4.2	5.9 ± 4.0		0.635	0.728
Corners	4.9 ± 3.1	4.6 ± 2.5	4.1 ± 3.0		2.047	0.359
Free Kicks	14.1 ± 5.1	13.0 ± 3.2	13.1 ± 4.7		1.411	0.494
Penalties Scored	0.1 ± 0.3	0.1 ± 0.2	0.1 ± 0.3		1.176	0.555
Goal Preventions	10.6 ± 5.8	9.9 ± 3.7	12.5 ± 6.6		1.890	0.389
Own Goal	0.1 ± 0.2	0	0			
Forced Turnovers	72.3 ± 11.1	71.0 ± 13.6	65.9 ± 13.5		4.087	0.130
Defensive Pressures Applied	288.1 ± 92.4	280.7 ± 55.5	282.2 ± 87.7	0.069		0.933

*: Significant difference between win and lose; ^: Significant difference between win and draw; &:Significant difference between draw and lose. #: significant difference between groups

TABLE 3. Chi-square test of different match results

Index	Win	Draw	lose	χ^2	p
Possession (%)	43.8 ± 13.9	43.1 ± 9.8	44.3 ± 13.3	84.653	0.460
Success Rate of Line Breaks (%)	66.0 ± 10.2	62.8 ± 9.4	62.5 ± 9.1	183.579	0.453
Success Rate of Defensive Line Breaks (%)	55.2 ± 15.4	48.7 ± 13.1	46.4 ± 20.8	107.865	0.816
Success Rate of Passes (%)	85.0 ± 8.7	83.9 ± 4.9	83.3 ± 6.1	192.000	0.446
Success Rate of Crosses (%)	26.1 ± 13.4	20.1 ± 10.4	23.9 ± 9.6	98.311	0.639

TABLE 4. Correlation Between EFI Indicator and Goals/Attempts On Target

	Line Breaks				Receptions		Final Third Entries					FT	DPA
	ALB	CLB	ADLB	CDLB	BMDL	BDL	LC	LIC	CC	RIC	RC		
Goals	0.037	0.104	0.137	0.265**	0.191	0.298**	-0.041	0.097	0.064	0.083	0.021	0.161	-0.054
AOT	0.417**	0.486**	0.480**	0.605**	0.621**	0.667**	0.373**	0.466**	0.395**	0.335**	0.308**	-0.036	-0.347**

** represents $P < 0.01$. AOT = Attempts On Target, ALB = Attempted Line Breaks, CLB = Completed Line Breaks, ADLB = Attempted Defensive Line Breaks, CDLB = Completed Defensive Line Breaks, BMDL = Between Midfield and Defensive Lines, BDL = Behind the Defensive Line, LC = Left Channel, LIC = Left Inside Channel, CC = Central Channel, RIC = Right Inside Channel, RC = Right Channel, FT = Forced Turnovers, DPA = Defensive Pressures Applied.

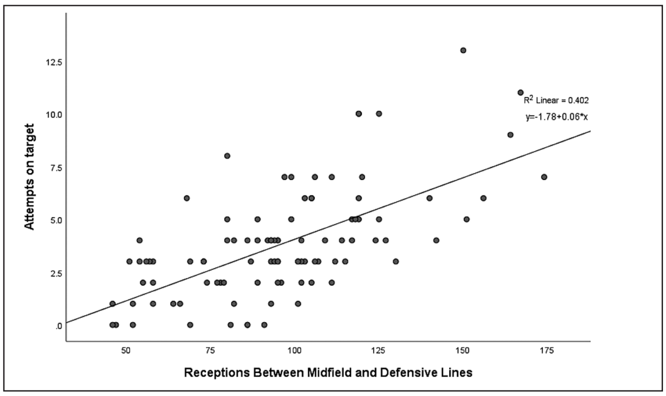

FIG. 1. Regression analysis of Attempts and Receptions Between Midfield and Defensive Lines

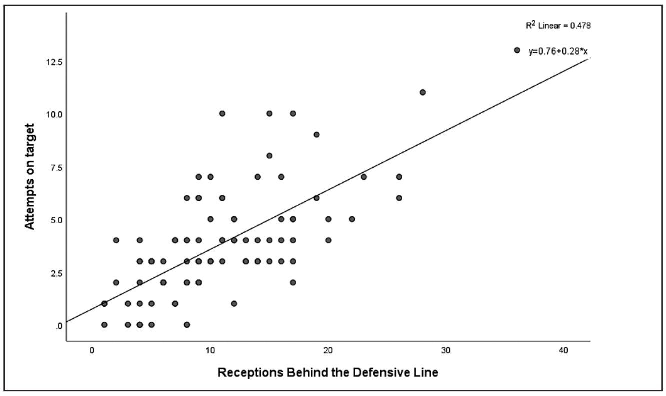

FIG. 2. Regression Analysis of Attempts and Receptions Behind the Defensive Line

DISCUSSION

This study is the first to examine the validity of EFI for analysing matches, and this study compares the differences in technical indicators for different match outcomes at the 2022 World Cup group stage.

We found that most goals and attempts related indicators can distinguish the outcome of a match, in line with previous studies [1, 5, 6]. However, there is no difference in the total number of attempts between winning, drawing and losing, in contrast to previous studies in both the male and female FIFA World Cup [1, 5, 19]. This suggests that the efficiency of attempts was even more important in determining the outcome of the game. Also, no significant difference ($p > 0.05$) in the number of corners and free kicks was found between winning, drawing and losing, in contrast to the study of the LaLiga [20] and Women's World Cup [19]. This may be due to increasing prevalence of intensive defending making set pieces become more and more crucial, and successful teams are more efficient at scoring from set pieces than their less successful opponents [21]. In addition, drawing teams but not winning teams had significantly fewer yellow cards compared to losing teams, which is partially different from previous studies [6, 22]. The main reason may be that most of the draws in the 2022 World Cup occurred in the last match of the group. With the group's advancing form clear, both sides deliberately adopted a low-aggressive strategy to prevent players from being injured and banned from the next stage, thus resulting in a significant drop in the number of yellow cards. For the possession after the new calculation method based on EFI, no differences were found between the different results of the match ($p > 0.05$), in contrast to previous studies [4, 5, 10]. The reason for this is, on the one hand, that the possession rates of both sides are closer after the inclusion of the "in contest" moments. On the other hand, it is difficult to convert possession into an offensive advantage with the strategy of counterattack being more prevalent due to the increased intensity of the game and the density of player coverage [23]. For intensive and high density defence, it will not only put high pressure on the possession team but also increase the success rate of counterattack of the opponents [24]. Thus, many teams will voluntarily give up possession, especially against strong teams [25]. The number of passes and success rate of passes are considered to be among the most important signs of ball control [7, 26], but the indicator was not found to be associated with differences between the results of different matches, further supporting the conclusion that possession plays a limited role.

In addition, we found that receptions behind the defensive line and completed defensive line breaks made a difference between winning and losing teams ($p < 0.05$). Higher rates of these mean that the team has more chances to get into the penalty area and attempts, and therefore will have more chances to score and win the game. Although other EFI data did not account for differences in results across matches, this does not mean that other EFI data are not meaningful, as match performance and results are also influenced by other factors such as opponents and judgements of referees [27–29]. We found that almost all post-match EFI indicators are correlated with attempts on target ($p < 0.01$), except for forced turnovers. However, the difference between forced turnovers in winning and losing teams approached the significance level ($p = 0.05$), consistent with the findings in LaLiga teams [20]. The reasons for this are manifold; marker, location, individual errors, pressure, conditioning [30], etc. all affect the forced turnover result of teams, especially in a knockout tournament like the World Cup where matches are played at short intervals. Moreover, as the Qatar World Cup is held in December, the league became more congested before the World Cup 2022 than previous World Cups, which increased the physical burden of the players [31, 32]. Therefore, fewer teams may be adopting an aggressive high-pressure strategy, leading to forced turnovers in the group stage being not too decisive.

Finally, line break, reception in the key area and final third entry all have a medium to large positive correlation with attempts on target, indicating that performing these actions as much as possible will help the team get more attempts on target to a greater extent. Studies of high-level players have shown that penetrating performances and exploiting gaps in the defensive line can increase a team's chances of scoring goals [33, 34], supporting our results. In fact, the results show that receptions between midfield and defensive lines and behind the defensive line explain 40% and 47% of the variance in shots on target, respectively. A relatively high figure considering that there are other events after the reception that can affect the likelihood of a shot. Additionally, more entries into final third area mean that the team has more chances to threaten the goal and therefore correlates moderately with the number of attempts on target. This may also be the reason why the percentage of possession in this area was found to be more critical compared to total possession [12].

In general, this study provides evidence for practitioners to improve their match performance. Possession does not determine the outcome of a game, and teams need to be efficient in attack and give up possession appropriately. At the same time, the efficiency of the shot is more important than the number of shots. This study also indicates that the coach needs to improve the tactics of players in the game, opting to receive the ball between the lines whenever possible, to enhance the team's shooting opportunities. Meanwhile, this study also provides ideas for athlete development, i.e., developing more awareness and ability to catch the ball at the line of defence in training.

One of the limitations of this study is that it did not incorporate physical fitness data. However, technical indicators are more likely to predict a team's success than physical indicators [35, 36], and thus this study can still provide an important reference for practitioners. The inability to compare the group stage with the knockout stage is another limitation of this study. Future research can integrate technical indicators with physical and other contextual information such as opponent level, weather, and altitude. It is also possible to use video analysis to find out which technical indicators at specific moments of the game can help the team gain a greater advantage. This will provide more detailed guidance on team tactical options.

CONCLUSIONS

There were significant differences in goal-related variables between match outcomes. In addition, the winning team had more defensive line breaks and receptions at the group stage of the 2022 World Cup. Receptions, final third entries and line breaks have a medium to high correlation with attempts on target and can provide important information for practitioners. Coaches need to identify the key indicators that affect the outcome of a match, rather than focusing on indicators such as possession that do not give a clear advantage. To conclude, the EFI provides a new reference for match analysis, which practitioners can use to better improve their team's match performance.

Author Contributions

Concept and design: Xiaobin Wei and Chong Chen; Data collection and analysis: Xiaobin Wei and Yifan Zhao; Drafting the article: Xiaobin Wei and Hui Chen; Critical revision of the article for important intellectual content: Peter Krustrup and Morten B Randers; Study Supervision: Chen Chong and Peter Krustrup. All authors approved the final version of the article.

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Conflict of interest disclosure

The authors report there are no competing interests to declare.

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Effectiveness of short vs. long-distance sprint training on sprinting and agility performance in young soccer players

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ABSTRACT: The purpose of this study was to examine the effects of short sprint-distance training (SST) compared with long sprint-distance training (LST), matched for the total session training volume, on short-, medium- and long-distance sprint performance and agility in young soccer players. Eighteen U19 male players (age: 17.1 ± 0.7 years; height: 178.0 ± 6.3 cm, body mass: 69.4 ± 6.6 kg) were randomly assigned to SST ($n = 9$) or LST ($n = 9$) group. The intervention programs were performed 2 times a week over 6 weeks. Before and after training period, 5 m, 10 m, 20 m, 30 m and 40 m sprint, and agility were assessed. Within-group analysis showed significant improvements ($p \leq 0.001$) in 5 m, 10 m, 20 m, 30 m and 40 m sprint from pretest to posttest in SST (9.2%, 6.6%, 5.3%, 2.9%, and 2.5%, respectively) and LST (10.5%, 8.5%, 6.5%, 5.1%, and 4.7%, respectively). Players in both SST and LST also showed significant enhancements in agility from pretest to posttest. In the between-groups analysis, there were no differences between the sprint training groups (SST vs. LST) in any variable ($p > 0.05$). In conclusion, the findings of this study indicate that both sprint training distances used seem to be effective to improve soccer-specific performance measures. However, due to the better percentage changes obtained by LST group in all fitness variables, this method could be considered as preferred method.

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INTRODUCTION

Soccer is characterized as an acyclical and intermittent high-intensity team sport in which short bouts of very intense activity are interspersed with lower intensity movements [1]. Time motion analyses have indicated that sprint account for ~4% and ~3% of the total distance covered during matches in adult and youth soccer players, respectively [2–4], and these actions are the most common and decisive movements during goal-scoring opportunities, that could determine the outcome of the game [5, 6]. Moreover, sprint ability can discriminate players from different standards of play [7]. In addition, professional soccer players have increased the peak sprint velocity, the total sprinting distance, and the number of sprints performed in match play over time [8]. Consequently, specific conditioning programs aimed to develop sprint should be considered paramount for physical performance in soccer [9, 10].

The importance of short-distance sprint in soccer, with the most common sprint during soccer matches varying between 2 to 4 s or 10 to 30 m, indicates that there is a large demand on acceleration speed [11]. However, sprint performance over medium- or longer-distances should also be developed as it is important for defensive and offensive success and injury prevention and differentiate between playing standards and age categories [12–15]. Thus, strength and conditioning coaches should use distance-specific training stimuli for their players to generate positive adaptations when attempting to enhance speed [16].

Sprint performance in soccer and other team sports can be improved through primary (e.g., sprint technique, sprinting), secondary (e.g., resisted or assisted sprinting), tertiary (e.g., non-specific methods including resistance training and plyometrics), or combined training methods [14, 17]. In this respect, primary training methods (e.g., sprint technique drills and un-resisted sprint) constitute the most used drills to develop sprint performance in elite football code athletes [9]. However, two recent systematic reviews and meta-analyses concluded that primary methods are insufficient to enhance performance in football code players [14, 17]. On the other hand, an early meta-analysis conducted on male youth team sport athletes, with 80% of the included studies focusing on soccer players, found that sprint training (which was the primary method) was an effective way to improve sprint performance. Furthermore, the study revealed that the effectiveness of sprint training increased progressively as the athletes matured. [18]. Thus, the training response to primary sprint training methods may be affected by mediator variables such as age or maturation status [14, 17].

To optimize training adaptations with sprint training in soccer, different principles of training (e.g., specificity, progression) and loading factors (e.g., intensity, recovery, frequency) may be followed and manipulated, respectively [4, 19]. Specifically, in soccer, several scientific protocols have been conducted to test the effect of manipulating different sprint training variables such as frequency (1 vs 2 days per week) [20], regime (linear vs. change-of-direction) [21], or intensity (maximal vs submaximal) [22, 23]. However, the distance covered per repetition in sprint training has not been explored in the literature. Despite the vast amount of scientific evidence on primary training methods in soccer, it is unclear what effects manipulating this variable under volume-equated conditions would have.

Considering the principle of specificity, short-sprint training should improve short-sprint performance, while longer sprints should improve medium- and/or long-sprint ability [4]. However, a scientific comparison between short and long sprint-training regimes remains unknown. Therefore, the aim of this study was to examine the effects of short sprint-distance training (SST) compared with long sprint-distance training (LST), matched for the total session training volume, on short-, medium- and long-distance sprint performance and agility in young soccer players. Considering the training specificity principle, it is hypothesized that SST would induce greater improvement in short sprint distances whereas LST would induce greater improvement in long sprint distances and agility.

MATERIALS AND METHODS

Design

This study used a two–group, randomized controlled trial design to compare the effects of different sprint training distances (SST vs. LSD). The intervention program of each group was added to the athletes' daily training routine. The study was conducted over a 6-week competitive period (October–December) during the 2021–2022 season. During this period, the training regimen was designed to include a range of different drills and exercises, with a particular emphasis on technical and tactical development. These included technical drills, tactical drills, small-sided games, and game-based exercises. To compare the effects of sprint training, the following tests were selected: (a) 5 m sprint, (b) 10 m sprint, (c) 20 m sprint, (d) 30 m sprint, (e) 40 m sprint, and (f) T-test. To reduce the influence of confounding variables, all subjects were instructed to maintain their usual lifestyle and normal dietary intake before and during the course of the study.

Subjects

A priori power analysis [24] (G*Power, version 3.1.9.7, Universität Kiel, Düsseldorf, Germany) with an assumed type I error of 0.05 and a type II error rate of 0.20 (80% statistical power) was conducted for sprint performance. It revealed that eight subjects per group would be sufficient to observe medium group × time interaction effects. Eighteen U19 male soccer players were recruited for the current study. Exclusion criteria were injuries resulting in the loss of one or more soccer matches/ training sessions in the three months prior to study initiation. Only outfield players were included (i.e., the goalkeepers were excluded). The participants in systematic soccer training had a mean experience of 9.08 ± 3.27 years. The players regularly performed 4–5 weekly soccer sessions with their team on average exercising 8.1 ± 2.2 $h \cdot wk^{-1}$ in their normal training cycle. Likewise, the team usually competed in one official match per week. Players were randomly assigned by an investigator not directly involved in testing or the training intervention into 1 of 2 groups, SST (n = 9; age: 17.1 ± 0.7 years; height: 177.4 ± 5.9 cm, body mass: 71.5 ± 7.11 kg) or LST (n = 9 age: 17.1 ± 0.8 years; height: 178.6 ± 7.1 cm, body mass: 66.5 ± 5.2 kg). The intervention program was added to the usual training routines. In all other respects, all subjects completed identical training activities. Only players who participated in at least 80% of all training sessions were included in the statistical analysis. Written informed consent indicating their voluntary participation was obtained from participants and legal representatives after explanation of the experimental protocol and its potential benefits and risks. The research protocol was approved by the Local Ethics Committee (University of Vigo; 20–0320), in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Training Programs

After pretesting, subjects began one of the six-week sprint training protocols presented in Table 1 in addition to the usual soccer training. The intervention program was performed 2 times a week (total of 12 sessions), on non-consecutive days (4 days and 2 days before match). This schedule remained consistent throughout the entire 6-week period. The training sessions were conducted on an artificial pitch turf, which was the same surface used for the testing sessions. Both groups completed the same amount of total distance per session (Table 1). The only difference between the 2 interventions was that the SST group performed all the maximal straight-line sprints in a distance of 20 m and the LST group in 40 m. The players were instructed to provide maximal effort in each training session. Before each session, participants completed a standardized warm-up (same as pre- and post-testing), as prescribed by a certified strength and conditioning specialist. A certified strength and conditioning specialist supervised all training sessions to ensure that all warm-up activities and sprints were completed with correct technique and with maximum effort. Foster's 0–10 scale was recorded to quantify the intensity of the training sessions using rating of perceived exertion (RPE) [25]. All participants were familiarized with the use of this RPE scale, as they had used it throughout the season in their teams' training sessions.

TABLE 1. Summary of training load progression.

Week	Group	Distance (m)	Recovery (s)	Repetition	Distance per session (m)	Distance per week (m)
1	SST	20	60	12	240	480
	LST	40	120	6	240	480
2	SST	20	60	12	240	480
	LST	40	120	6	240	480
3	SST	20	60	14	280	560
	LST	40	120	7	280	560
4	SST	20	60	14	280	560
	LST	40	120	7	280	560
5	SST	20	60	16	320	640
	LST	40	120	8	320	640
6	SST	20	60	16	320	640
	LST	40	120	8	320	640

SST = short-sprint training; LST = long-sprint training

Procedures

During testing sessions, the players were required to wear the same athletic equipment and measurements were conducted at the same time of the day to minimize the effect of diurnal variations on the selected parameters during two experimental sessions. All data collection and test sessions were performed on the same pitch. Each player was instructed and verbally encouraged to make a maximal effort during all tests. All tests were performed after 72 hrs of rest and at the same venue under identical conditions and supervised by the same investigators. The players complied with the following pre-test guidelines: (a) to not consume any caffeinated beverages or supplements 48 hrs prior to testing; (b) to not consume food at least 2 hours prior to testing. Before testing, all participants performed 10 min of standardized warm-up involving 2 min of light dynamic stretching (10 repetitions for hamstrings, quadriceps, and calf muscles) and 5 min of jogging, followed by short distance accelerations (3 submaximal sprints, progressing to 90% of their maximal velocity for the shuttle distance [30 + 30 m]). This routine was supervised by the team's coach before the tests. During testing sessions, players performed the following tests:

5 m, 10 m, 20 m, 30 m, and 40 m sprint tests. Sprint time was measured using a dual infrared reflex photoelectric cell system (Witty, Microgate, Bolzano, Italy). To capture data, five pairs of wireless photoelectric cells were mounted on tripods at a height of 0.9 m and spaced at intervals of 0, 5, 10, 20, 30, and 40 m. All players began with a standing start, with the front foot positioned 0.5 m from the first timing gate. They were instructed to perform all the sprints with a maximal effort. To ensure reliable and consistent data, each participant was given three attempts, with a 3-minute recovery period allowed between each trial.

T-test. Photoelectric cells (Witty, Microgate, Bolzano, Italy), placed on the starting line, were used to measure the soccer players' performance and to increase test reliability. A T-test was administered using the protocol outlined by Munro and Herrington [26]. Participants performed three trials, and the fastest time was used as the T-test score. When ready, players sprinted forward 9.14 m to touch the first cone. They then side-shuffled 4.57 m to the left and touched the second cone. Next, they side-shuffled 9.14 m to the right and touched a third cone, and then 4.57 m to the left, back to the point where the first cone was, touching it again. Finally, participants back-pedaled 9.14 m, passing through the finish line.

Statistical Analysis

All variables were normally distributed (Shapiro-Wilk test). Data are presented as means and standard deviation (SD). All statistical analyses were conducted using the statistical package SPSS for Macintosh (version 25.0, Chicago, IL, USA). A 2 (group: SST and LST) × 2 (time: pre, post) mixed factorial analysis of variance (ANOVA) was calculated for each parameter. Additionally, Cohen's *d* was computed for comparing effect sizes (ES). ES were classified as trivial ($d < 0.2$), small ($0.2 \le d < 0.5$), moderate ($0.5 \le d < 0.8$), and large (≥ 0.8) [27]. Moreover, pre- to-post change percentage was calculated for corresponding variation. Relative and absolute reliability of the variables analyzed in this study were assessed using the intraclass correlation coefficient (ICC) and the coefficient of variation (CV), respectively. Significance was established at the $P \le 0.05$ level.

RESULTS

Reliability results are shown on Table 2. The relative reliability as depicted by ICC was very high for all the tests, exceeding 0.80

TABLE 2. Relative and absolute reliability measures for the assessed variables.

Variables	ICC	CV (%)
5 m	0.90	1.8
10 m	0.92	1.1
20 m	0.94	0.8
30 m	0.98	0.5
40 m	0.97	0.5
T-test	0.86	2.9

ICC = intraclass correlation coefficient; CV = coefficient of variation.

(ranging from 0.86 to 0.98). The absolute reliability also showed very high levels for all the test with CV ranged from 2.93 to 0.49%. RPE scores collected at each training session during the whole training period were not different between the two groups ($p > 0.05$; 2.5 and 2.6 for SST and LST, respectively).

Mean values and SD, percentage changes from pre- to post-training for 5 m, 10 m, 20 m, 30 m, 40 m sprint tests, and T-test performance indices are reported on Table 3.

There were no significant group time × group interactions observed in any of the sprint and agility tests ($p > 0.05$). A significant time effect was found in the 5 m, 10 m, 20 m, 30 m, and 40 m sprint tests for SST and LST. The statistical analysis also revealed main effect for time in the T-test for SST and LST.

The percentage change for SST and LST groups in the sprint tests is shown in Table 3 and Figure 1.

DISCUSSION

The aim of this study was to analyze the effect of a sprint training protocol with short and long distances in youth soccer players during the in-season period. To our knowledge, this is the first sprint-training study that has been conducted in soccer players comparing the effects of different sprint training distances on physical fitness. Based on the analyses, the main findings of this study were that: (a) both sprint training interventions were equally effective in developing 5 m, 10 m, 20 m, 30 m, and 40 m sprint performance; (b) both SST and LST induced significant changes in T-test performance.

Sprinting speed is one of the most essential fitness components for playing soccer [5, 6]. Moreover, sprint ability can discriminate youth players from different standards of play [7]. Therefore, training interventions aimed at improving sprinting speed may be a priority for youth soccer coaches. In contrast to the main research hypothesis, both the SST and LST training programs induced similar significant and positive changes in all sprint distances, without significant differences between both sprint training programs. The rationale for this hypothesis was based on the training specificity principle as short sprints would be more effective in developing acceleration in short distances (e.g., 5 m, 10 m, and 20 m sprint) than the long repetitions, despite the matched total distance of both training programs.

Haugen and Buchheit [28] stated that the smallest worthwhile change (SWC) for team sport players is ~1.5% for 5 m sprints and ~1% for 10 to 40 m sprints. Since the performance changes observed in the present study were clearly greater (ranged between 2.5% to 10.5%) than the measurement noise observed (ranged between 0.5 to 1.8% CV for sprint time) and the SWC described in the scientific literature for team sport players [28, 29], the usefulness of the SST and LST protocols performed was reasonably high (Figure 1).

This is the first study that compared the effects of different sprint training distances on short, medium, and long sprint performance, therefore, direct comparisons with other studies are not possible. Nevertheless, the main results of the present study are consistent with previous investigations that examined the effects of primary sprint training method on sprint performance in soccer players with similar age group cohort. For example, Pavillon et al. [21] compared the effect of two different sprint training regimes (i.e., linear sprints vs. change-of-direction sprints) on short-distance sprint performance in youth soccer players over 30 weeks. The results showed significant improvements in 5 m and 10 m sprint performance. Likewise, Marzouki et al. [20] reported one or two sprint training sessions per week of equal volume produce similar improvements in 10 m, 20 m, and 30 m sprint performance in youth soccer players. In addition, the present study observed performance changes across different sprint distances in both the SST and LST groups, ranging between 2.5% to 9.2% and 4.7% to 10.5%, respectively. These findings are consistent with previous studies in professional, who experienced similar improvements in sprint performance after a 6-week training program involving a combination of resisted (2.7% to 6.9%) and unresisted (2.1% to 8.4%) methods such as squat jumps, linear sprints, and change-of-direction drills [30]. Additionally, similar changes were observed in youth soccer players who completed a 5-week high-intensity interval training (5.0% to 7.3%) and small-sided games (5.9% to 7.9%) programs [31].

The present findings are in line with the pattern of sprint trainability described by Moran et al. [18] in their meta-analysis regarding the effects of sprint training on sprinting performance across peak height velocity groups (PHV) in young male athletes. As an outcome of this article, the authors stated that sprint training becomes progressively more effective with increasing maturation showing the post-PHV group the greatest trainability effects, which corresponds with the participants of the present study in terms of chronological age (16–18 years). Thus, large effects observed in SST and LST could be explained by the greater muscular size, hormonal activity and development, greater muscular size, increased limb length, changes to musculotendinous tissue, enhanced neural and motor development and better movement quality and coordination [18, 32].

TABLE 3. Changes in physical fitness after six weeks of sprint-training in youth soccer players.

Variables	SST				LST				ANOVA		
	Pre	Post	∆ (%)	ES	Pre	Post	∆ (%)	ES	Time	Group	Time × group
5 m (s)	1.08 ± 0.04	0.98 ± 0.06	-9.2	1.96	1.09 ± 0.02	0.98 ± 0.03	-10.5	4.31	< 0.001	0.657	0.437
10 m (s)	1.82 ± 0.07	1.70 ± 0.08	-6.6	1.59	1.85 ± 0.05	1.70 ± 0.03	-8.5	3.63	< 0.001	0.536	0.055
20 m (s)	3.14 ± 0.12	2.98 ± 0.14	-5.3	1.22	3.19 ± 0.07	2.98 ± 0.08	-6.5	2.79	< 0.001	0.656	0.129
30 m (s)	4.42 ± 0.23	4.28 ± 0.22	-2.9	0.62	4.45 ± 0.13	4.23 ± 0.10	-5.1	1.89	< 0.001	0.933	0.216
40 m (s)	5.66 ± 0.33	5.51 ± 0.28	-2.5	0.49	5.71 ± 0.18	5.43 ± 0.11	-4.7	1.87	0.001	0.910	0.217
T-test (s)	9.64 ± 0.49	9.17 ± 0.27	-4.7	1.18	9.53 ± 0.33	9.00 ± 0.55	-5.5	1.16	< 0.001	0.469	0.731

SST = short-sprint training; LST = long-sprint training; ES = effect size.

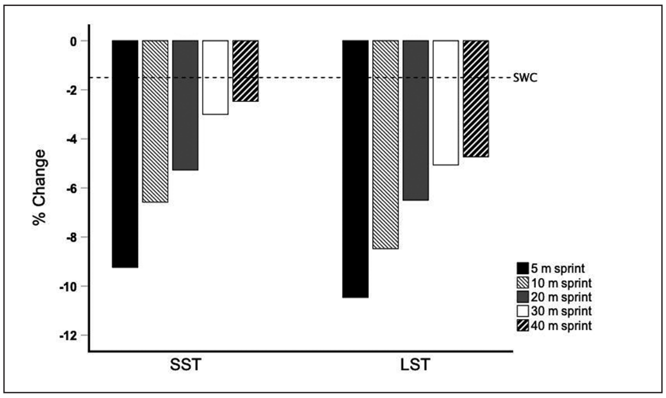

FIG. 1. Percentage change in sprint performance in response to short (SST) and long-sprint training (LST). Horizontal line represents the smallest worthwhile change (SWC) for team sports athletes.

Agility is considered an important quality required by team sports players [33]. According to previous literature, training programs designed to improve agility should be specific and independent from sprint training programs [34]. However, in the present study SST and LST groups induced improvements of 4.7 and 5.5% in the T-test, respectively, similar to the effect observed in sprint performance. However, no significant difference was observed between the two experimental groups, suggesting that agility improvements are not dependent on sprint training distance when players perform the same training volume. These findings are in accordance with the results of Marzouki et al. [20], who reported a significant reduction of 4.2 and 2.4% in T-test performance after 10-week training including on or two sessions a week, respectively. Furthermore, the current study's results are consistent with those of Bianchi et al. [35] who demonstrated a significant decrease in the 505 change-of-direction test time after implementing a 6-week combined training method involving both plyometrics and sprinting drills. Several factors could explain the agility improvements observed in this study after training period. However, the most plausible factor could be related to increments in lower limb strength [21].

The results of the present study suggest that sprint training programs with short or long distances were both useful for improving sprint performances over distances between 5 and 40 m. Indeed, present results demonstrated the prescription of SST or LST during in-season period contributed to improving agility performance among youth soccer players. These results reinforce previous evidence indicating usual sprint training modality is an approach to be recommended to increase sprint performance in male youth athletes [18].

The interpretation and broader implications of the current findings must be understood within the limits of the specific data collection undertaken. Although the study had many unique aspects, there are some limitations that should be considered. First, even though the number of participants in this study was similar to other sprint training studies in youth soccer players. Another limitation to be considered in this study is the duration of the training intervention, which was only six weeks. Third, the absence of a control group without participating in any of the experimental protocols limits conclusions from this study. Future studies considering a larger sample size, longer training periods, and using control group may provide more conclusive results.

CONCLUSIONS

This study showed that six weeks of short- and long-distance sprint training, matched for the total session training volume, seem to represent a time-efficient stimulus for a simultaneous improvement of short, medium, and long sprint performance, as well as agility during in-season period in youth soccer players. However, although there were no statistically significant differences between the two training programs, LST group showed better percentage changes in all fitness variables evaluated. Thus, from a practical perspective, because even small changes can be the difference between winning and losing decisive 1-on-1 duels or create goal-scoring opportunities in soccer by having body or shoulder in front of the opposing player, LST seems to be a preferred training method for these variables. These training-specific adaptations offer coaches and strength and conditioning professionals the possibility to individualize training content specific to the athletic qualities in soccer.

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Conflict of interest declaration

The authors declare no conflict of interest.

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Do small-sided games prepare players for the worst-case scenarios of match play in elite young soccer players?

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ABSTRACT: The aim of the study was to determine whether the physical performance of young soccer player during various small sided games (SSGs) underloads, replicates or overloads the requirements of the worst-case scenarios (WCS) during match play. A total of 521 SSGs' individual observations and 15 different formats of SSGs with different areas per player (ApP) (ApP100: < 100; ApP200: ranged from 101 to 200; ApP300: > 201, all in $m^2 \cdot player^{-1}$) were taken into consideration. Whole (90-min average; OM) and 15-, 5- and 1-min worst-case scenarios (WCS15, WCS5 and WCS1, respectively) were analysed. Total distance covered relative ($m \cdot min^{-1}$) (TDCR), high-speed distance relative ($m \cdot min^{-1}$) (HSDR), very high-speed distance relative ($m \cdot min^{-1}$) (VHSDR) and sprint distance relative ($m \cdot min^{-1}$) (SDR), player load relative (PLR) and both total (ACCR) and high intensity relative accelerations ($n \cdot min^{-1}$) (ACCHR) were collected. All external load measures analysed were significantly higher in WCS1 compared to WCS of longer duration and SSGs with different ApP ($p < 0.001$). The analysis demonstrated interactions between game type and player positions ($p < 0.001$) for TDCR, VHSDR, PLR and ACCHR. The SSG formats did not sufficiently stimulate the WCS for locomotor demands (VHSDR and SDR). SSGs played on an ApP100 overestimated the mechanical values compared to WCS15 and WCS5. The analysed SSG formats did not sufficiently stimulate players to cope with all external load demands that occurred during WCS1. This study provides useful information for practitioners on the heightened impact of different SSG formats on external load in relation to the WCS of competitive match play.

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INTRODUCTION

Small sided games (SSGs) are currently one of the most common tasks used to enhance players' soccer-specific technical, tactical, and physical skills [1]. In fact, SSGs allow players to replicate specific physical, technical, and tactical defensive and offensive behaviours without having to repeat mechanical movements [2]. According to previous scientific literature, the physical performance and the development of fatigue in SSGs vary depending upon several variables [1, 2]. Two of the most often used constraints in designing SSGs are the number of players and the pitch size [3]. When both variables are combined, the area per player (ApP) is obtained. It is a key concept during this type of task and it is defined as the theoretical pitch area that corresponds to each player; it is determined as the total pitch area divided by the number of players on the pitch [4]. From a practical perspective, previous research revealed that large areas lead to an increase in total distance, total distance per minute, distance at different intensities, and sprint frequency [4, 5]. However, controversy exists regarding accelerations and decelerations. It seems that with smaller ApP increases in acceleration and deceleration are reported [6].

Monitoring training and match load can provide a scientific explanation for changes in performance. Load monitoring could be fundamental to reducing the risk of injury, optimizing performance, and avoiding non-functional overtraining [7, 8]. In addition, professional soccer players have increased the high-speed distance (HSD) and sprint distance (SD) performed in match play over time, highlighting the importance of monitoring these factors during training, specifically during training tasks [9]. Hence quantifying training load (TL) is important to obtain overall knowledge of how the training sessions or tasks such as SSGs differ from the official match (OM) demands [10]. Previous research analysed the differences between SSGs and friendly matches [11]; these authors concluded that high-intensity distance during friendly matches was greater than during SSGs. However, the global indicator of workload (work ratio and player load) was higher during SSGs than in friendly matches. More recently, Pinheiro et al. [12] stated that with professional soccer players the total distance per minute was higher during friendly matches than during different formats of SSGs. Additionally, no differences were found between friendly matches and SSGs considering mechanical values (number and average distance of accelerations). Another group of authors compared different SSGs with OMs [13] and found that only large-sided games (9vs9; 194 $m^2 \cdot player^{-1}$) simulated the official full match more accurately than other sided games in terms of sprinting. Medium and SSGs were more intense than full matches considering mechanical values. However, these studies took into account physical performance variables for whole matches. Whilst reporting half or whole-match activities is useful to help understand overall physical loading, such data do not reflect the stochastic nature of soccer match-play [14]. Therefore, considering the most intense periods of the competition could be valuable when managing the TL.

The worst-case scenarios (WCS) are defined as the periods of maximum physical output throughout the match [14]. If the objective of training is to replicate or overload the movement demands reported during the competition, the use of WCS could be key to optimizing performance and adequately preparing the player for the matches. Hence, elucidating the demands associated with the WCS and comparing them with one of the most used tasks in training sessions (i.e., SSGs) may be useful when developing and scheduling specific training sessions. Although there are studies analysing the differences between SSGs and official competitions [6, 13], to the authors' knowledge there is a gap in the literature examining the differences between SSGs and WCS during soccer competitions. Previous research [15, 16, 17] analysed the differences between SSGs and WCS. Nevertheless, only one previous study reported these differences considering young soccer players [17]. This information may be useful for developing soccer-specific training programmes designed to condition youth players to cope with potentially decisive periods of matches. The first group of authors with senior Norwegian professional players indicated that HSD during 4vs4 and 6vs6 was 78% and 86% lower than in the peak period of match play, showing that this type of SSGs could underestimate high-intensity activities reported during the WCS. It seems that the distance, HSD and distance covered when sprinting are the variables that have the lowest percentage of most demanding passages while performing the game formats studied, especially in the smallest formats of training games [16]. Meanwhile, with elite young players, Sydney et al. [17] mentioned that no SSGs of different sizes were found to replicate the peak of total distance and HSD during match-play. However, these authors only considered two locomotor variables (total distance and HSD). In agreement with Martin-Garcia et al. [16] we believe that using more time windows (e.g., 1, 5, and 15 minutes) would have made it possible to explore in greater depth how the values relating to the competition percentage vary. In consequence, more research in young players using more WCS time windows and considering more variables is needed.

Hence, the objective of this study was to determine whether the physical performance of young soccer players during various SSGs underloads, replicates or overloads the requirements of the worst-case scenarios during match play. The conclusions of the present study would make it possible to manage the ApP used during SSG to underload, replicate or overload the requirements of the worst-case scenarios during match play and plan the whole-session training load during practice.

MATERIALS AND METHODS

Subjects

The data for this study were collected from players belonging to an elite Spanish soccer academy ($n = 31$; age = 17.0 ± 1.3 years; height = 173.7 ± 6.0 cm; body mass = 66.9 ± 7.1 kg and body fat percentage = 10.6 ± 1.0%). Goalkeepers were excluded from the data collection. The club's medical staff certified the health status of each player. Injured players diagnosed by medical services or

TABLE 1. Number of observations of each SSGs, OM and WCS according to player positions.

Position	ApP100	ApP200	ApP300	OM	WCS15	WCS5	WCS1	Total
CD	62	27	53	18	22	22	21	225
FB	37	18	33	14	19	19	19	159
MF	32	13	16	11	14	14	14	114
WM	39	26	56	21	25	25	25	217
FW	18	9	21	9	14	14	14	99
Total	188	93	179	73	94	94	93	814

Note: WCS15 (worst case scenario of 15 minute of duration); WCS5 (worst case scenario of 5 minute of duration); WCS1 (worst case scenario of 1 minute of duration); ApP100 (Area per player < 100 $m^2 \cdot player^{-1}$); ApP200 (Area per player between 100 and 200 $m^2 \cdot player^{-1}$); ApP300 (Area per player > 200 $m^2 \cdot player^{-1}$); OM (official match); CD (Central Defender); FB (Fullback); MF (Midfielders); WM (Wide Midfielder); FW (Forward).

players involved in rehabilitation training sessions were also excluded from data collection. Participants were categorized according to playing positions as directed by the head coach. Playing positions were CD = Central Defender (n = 11 and 225 observations), FB = Fullback (n = 5 and 159 observations), MD = Midfielder (n = 3 and 114 observations), WM = Wide Midfielder (n = 8 and 217 observations) and FW = Forward (n = 4 and 99 observations) (Table 1). A consent letter was obtained from the club agreeing with the procedures. The local Ethics Committee (E1621871) approved the study and it was performed in accordance with the principles of the Declaration of Helsinki. Since data used in the present study were acquired as part of players' routine monitoring, informed consent was not required [18].

Training contents and matches

A total of 521 SSGs' individual observations were undertaken (average per player: 26.3 (± 17.5) and all SSGs were grouped according to the ApP. SSGs ranged from 10 vs 10 to 3 vs 3 and ApP ranged from 60 to 332 $m^2 \cdot player^{-1}$ (with 24 different ApP). The SSGs' training formats are described in Table 2. The ApP was obtained as the total pitch area divided by the number of players on the pitch [19]. Goalkeepers were present for each game type although they were excluded in the calculations when determining the relative pitch area per player (m^2). Small, medium and large-sided games were all abbreviated as SSGs and specified by ApP (ApP100: < 100 $m^2 \cdot player^{-1}$; ApP200: ranged from 101 to 200 $m^2 \cdot player^{-1}$; ApP300: ranged from 201 to 350 $m^2 \cdot player^{-1}$). The ApP was used as a discrete variable to compare the physical demands of SSGs with different ApP with those of WCS during OM. The SSGs were performed under the supervision and motivation of several coaches to maintain a high work ratio. In addition, a ball was immediately made available by replacement when it went out of play. In SSGs, the corners were replaced by a ball in game from the goalkeeper (except for 10 vs 10, where corners were performed). Coach feedback was present during each SSG and players were instructed to pressure the opposition as much as possible [17].

A total of 11 OM and 752 records (CD = 176, FB = 152, MF = 112, WM = 200 and FW = 112) were considered to analyse the WCS of match play. Only players who started the match and completed the whole OM were included. Each match was ninety minutes in duration, separated by two forty-five-minute halves, with any additional time determined by the match referee. All matches were played under the same competition rules, limiting each team to three substitutions and a fifteen-minute break for half-time. Matches were preceded by a twenty-minute standardized warm-up consisting of dynamic stretching, 20 m and 30 m maximal sprint efforts, short

TABLE 2. Pitch size during small sided games.

Nº players	length:width (m)	width:length ratio	m^2	$m^2 \cdot player^{-1}$	Goalkeeper	Floater	Duration Range (min)	Bouts Range
	104 × 62	0.59	6448	322				
	75 × 62	0.86	4650	232				
	70 × 62	0.88	4340	217				
10 vs 10	67 × 62	0.92	4154	208	Yes	0	8-30 min	2-4
	62 × 65	1.04	4030	202				
	60 × 62	1.03	3720	186				
	58 × 64	1.10	3712	185				
9 vs 9	62 × 55	0.88	3410	179	No	1	8-15 min	1-2
	60 × 40	0.66	2400	126				
	61 × 62	1.01	3782	236	Yes	0		
8 vs 8	54 × 50	0.92	2700	168			10-11 min	1-2
	65 × 62	0.95	4030	237	Yes	1		
6 vs 6	35 × 32	0.91	1120	93	Yes	0	4-6 min	2-4
	30 × 32	1.06	960	96				
5 vs 5	30 × 26	0.86	780	78	Yes	0	2-5 min	2-4
	27 × 25	0.92	675	68				
4 vs 4	30 × 26	0.86	780	98	Yes	0	3-4 min	2-4
3 vs 3	18 × 22	1.22	396	66	Yes	0	2-3 min	3
	21 × 18	0.85	378	54	Yes	1		

and long passing, and possession play (4 vs 4 plus 2 floaters). Matches were played on official fields (104 × 62 m, length × width, respectively). Both mean values and peak 15-, 5-, and 1-minute values were calculated. Hence, for each player and for each variable, the most intense phases of 15-, 5-, and 1-minute duration were calculated using rolling average methods [20].

External load variables

The running variables were obtained from the Global Positioning System (GPS). All external load measures were normalized as relative distance covered in one minute ($m \cdot min^{-1}$) or the number of accelerations in one minute ($n \cdot min^{-1}$) [21]. Consistent with a previous study [22] that utilised similar thresholds, the movement demands were reported as total distance covered relative ($m \cdot min^{-1}$) (TDCR), high-speed distance relative (HSDR) (> 18 $km \cdot h^{-1}$), very high-speed distance ($m \cdot min^{-1}$) relative (VHSDR) (> 21 $km \cdot h^{-1}$) and sprint (> 25 $km \cdot h^{-1}$) distance m) relative (SDR). The total number (per minute) of accelerations (ACCR) and the total number of high-intensity accelerations (ACCHR) (> 3 $m \cdot s^{-2}$) were also gathered [5, 20]. Moreover, a global load indicator was included as a variable: player load per minute (PLR), which is a measure based on the tri-axial accelerometer measures and may serve as a complementary tool for measuring the load from activities misrepresented by time-motion analysis [15].

TABLE 3. Physical performance variables (mean, standard deviation, and range) for three worst case scenarios (WCS15, WCS5 and WCS1), OM and different types of small-sided games (ApP100, ApP200 and ApP300).

	TDCR	HSDR	VHSDR	SDR	ACCR	ACCHR	PLR
WCS15	129.5 ± 13.0 (126.8–132.2)	18.4 ± 5.1 (17.3–19.4)	10.3 ± 4.0 (9.4–11.1)	4.2 ± 2.5 (3.7–4.7)	7.0 ± 1.1 (6.8–7.2)	1.6 ± 0.4 (1.5–1.7)	5.5 ± 0.6 (5.4–5.7)
WCS5	143.3 ± 10.4 (141.2–145.5)	27.3 ± 6.9 (25.8–28.6)	16.8 ± 5.7 (15.7–18.0)	8.4 ± 4.2 (7.5–9.2)	8.3 ± 1.1 (8.1–8.5)	2.2 ± 0.4 (2.1–2.3)	6.1 ± 0.5 (6.0–6.2)
WCS1	194.1 ± 14.1 (191.2–197.1)	70.7 ± 17.3 (67.2–74.3)	50.2 ± 15.3 (47.0–53.3)	30.5 ± 14.4 (27.5–33.4)	12.9 ± 1.4 (12.6–13.2)	4.9 ± 0.9 (4.7–5.1)	8.1 ± 0.6 (7.9–8.2)
OM	116.0 ± 9.5 (113.5–117.9)	12.9 ± 4.0 (11.9–13.8)	6.4 ± 2.7 (5.7–7.0)	2.1 ± 1.3 (1.7–2.4)	5.9 ± 0.8 (5.7–6.1)	1.2 ± 0.3 (1.2–1.3)	4.9 ± 0.5 (4.8–5.1)
ApP100	103.6 ± 19.6 (100.7–106.4)	4.3 ± 3.7 (3.8–4.9)	1.1 ± 1.7 (0.8–1.3)	0.1 ± 0.6 (0.1–0.2)	10.0 ± 2.7 (9.6–10.4)	2.8 ± 1.2 (2.6–2.9)	5.3 ± 0.9 (5.2–5.5)
ApP200	111.2 ± 18.3 (107.4–115.0)	8.8 ± 4.5 (7.8–9.7)	3.2 ± 2.5 (2.7–3.7)	0.6 ± 1.0 (0.4–0.8)	7.2 ± 1.5 (6.9–7.5)	1.5 ± 0.4 (1.4–1.6)	5.0 ± 0.8 (4.8–5.1)
ApP300	115.4 ± 18.3 (112.7–118.1)	11.6 ± 4.9 (10.9–12.3)	5.3 ± 2.9 (4.8–5.7)	1.3 ± 1.5 (1.1–1.5)	6.6 ± 1.2 (6.4–6.7)	1.3 ± 0.4 (1.3–1.4)	4.9 ± 0.8 (4.8–5.1)
Statistical differences ($p < 0.05$)	WCS1 > WCS5, WCS15, OM, ApP100, ApP200, ApP300 WCS5 > WCS15, OM, ApP100, ApP200, ApP300 WCS15 > OM, ApP100, ApP200, ApP300 OM, ApP300, ApP200 > ApP100	WCS1 > WCS5, WCS15, OM, ApP100, ApP200, ApP300 WCS5 > WCS15, OM, ApP100, ApP200, ApP300 WCS15 > OM, ApP100, ApP200, ApP300 OM, ApP300 > ApP100, ApP200 ApP200 > ApP100	WCS1 > WCS5, WCS15, OM, ApP100 ApP200; ApP300 WCS5 > WCS15, OM, ApP100, ApP200, ApP300 WCS15 > OM, ApP100, ApP200, ApP300 OM > ApP200, ApP100 ApP300 > ApP100	WCS1 > WCS5, WCS15, OM, ApP100, ApP200, ApP300 WCS5 > WCS15, OM, ApP100, ApP200, ApP300 WCS15 > ApP100, ApP200, ApP300	WCS1 > WCS5, WCS15, OM, ApP100, ApP200, ApP300 WCS5 > WCS15, OM, ApP200, ApP300 ApP200 > OM ApP100 > WCS5, WCS15, OM, ApP200, ApP300	WCS1 > WCS5, WCS15, OM, ApP100, ApP200, ApP300 WCS5 > WCS15, OM, ApP200, ApP300 WCS15 > OM, ApP300 ApP100 > WCS5, WCS15, OM, ApP200, ApP300	WCS1 > WCS5, WCS15, OM, ApP100, ApP200, ApP300 WCS5 > WCS15, OM, ApP100, ApP200, ApP300 WCS15 > OM, ApP200, ApP300 ApP100 > ApP200, ApP300

Note: TDCR (total distance covered relative); HSDR (high speed distance relative); VHSDR (very high speed distance relative); SDR (sprint distance relative); PLR (player load relative); ACCR (the number of total accelerations relative); ACCHR (the number of high accelerations relative); WCS15 (worst case scenario of 15 minute of duration); WCS5 (worst case scenario of 5 minute of duration); WCS1 (worst case scenario of 1 minute of duration); ApP100 (Area per player < 100 $m^2 \cdot player^{-1}$); ApP200 (Area per player between 100 and 200 $m^2 \cdot player^{-1}$); ApP300 (Area per player > 200 $m^2 \cdot player^{-1}$); OM (official match).

Procedures

The participants undertook their traditional weekly training routine. All training sessions were performed on artificial pitches and all training sessions were scheduled at the same time (16:30-18:45). During both training sessions and OM, players' movements were recorded using a portable 10 Hz GPS device that also incorporates a 400 Hz tri-axial accelerometer (Playertek, Dundalk, Ireland). Acceleration activity was measured as a change in speed for a minimum period of 0.5 seconds with acceleration at least of 2 $m \cdot s^{-2}$. These GPS devices seem to be valid and reliable for use in team sports [23] and they were used previously in soccer research [24]. The GPS device was attached to the upper back of each player by means of a special harness, and according to the manufacturer's instructions, all GPS units were activated 10 minutes before the training sessions or OM began.

Statistical analysis

Descriptive statistics (mean ± SD and confidence intervals) are reported for all variables. The data were tested for normality using quantile-quantile plots (Q-Q plots) and the Kolmogorov-Smirnov test of normality. Linear mixed models were performed to analyse the differences between SSG formats (ApP100, ApP200 and ApP300), mean OM and WCS with different durations (WCS15, WCS5, and WCS1). The players' identity was modelled as a random effect to take into account the repeated measurements. Effect size (ES) was established using Cohen's *d*. Concretely, the ES was calculated according to the formula $d = (M_2 - M_1/SD_{pooled})$, where M_1 and M_2 are the means of the two groups and SD_{pooled} is the square root of the weighted average SD. According to Cohen [25], ES were classified as *trivial* (< 0.1), *small* (0.1-0.3), *moderate* (0.3-0.5), *large* (0.5-0-7) and *very large* (> 0.7). Data analysis was conducted using SPSS Statistics (IBM Corp. Released 2017. IBM SPSS Statistics for Macintosh, Version 25.0. Armonk, NY: IBM Corp.) software with a significance value set at $p < 0.05$.

RESULTS

Descriptive statistics for selected physical performance variables and differences between formats (different WCS, OM, ApP100, ApP200, and ApP300) are shown in Table 3. All external load measures analysed (TDCR, HSDR, VHSDR, SDR, PLR, and ACCHR) were significantly higher in WCS1 compared to WCS of longer duration and SSGs with different ApP. Specifically, when TDCR is analysed, it was found that all WCS were significantly higher than the SSG formats ($p < 0.001$; ES: 0.8–5.3). Additionally, ApP300 elicited significantly higher TDCR values compared to ApP100 ($p < 0.05$; ES: 0.62). Considering HSDR and VHSDR, WCS with different duration (WCS1, WCS5 and WCS15) were significantly greater than all SSG formats ($p < 0.001$; ES: 1.3–5.3) Moreover, SSGs with ApP300 and ApP200 had significantly higher HSDR ($p < 0.05$; ES: 1.6 and ES: 1.1, respectively) and VHSDR ($p < 0.05$; ES: 1.7 and ES: 0.9, respectively) values than ApP100. SDR was significantly higher in all WCS compared to all SSG formats analysed ($p < 0.01$; ES: 2.9–1.4). However, no differences were found between SSGs taking into consideration SDR values. Regarding mechanical measures (PLR, ACCR, and ACCHR), WCS1 was significantly greater compared to both worst-case scenarios of longer duration and SSGs with different ApP ($p < 0.001$). Significantly higher PLR values were found in WCS5 ($p < 0.05$; ES: 1.8-1.1) and WCS15 ($p < 0.05$; ES: 0.3–0.8) compared to the SSGs analysed. Furthermore, ApP200 and ApP300 showed lower PLR values than ApP100 ($p < 0.05$; ES: 0.4 and ES: 0.5, respectively). Taking into consideration acceleration values, both total and high-intensity accelerations, for WCS5 and ApP100 significantly higher ACCHR was found than for WCS15 (ES: 1.5 and ES: 1.3, respectively), ApP200 (ES: 1.8 and ES: 1.5, respectively) and ApP300 (ES: 2.3 and ES: 1.7, respectively) (Table 3).

The differences between playing positions and game type taking into consideration TDCR, HSDR, VHSDR, and SDR are outlined in Figures 1, 2, 3, and 4, respectively. The analysis showed interactions between game type and player positions ($p < 0.001$) for TDCR (Figure 1). Particularly, WCS1, WCS5, and WCS15 showed higher values than SSG formats for CD ($p < 0.05$; ES: 4.6–0.5), FB ($p < 0.05$; ES: 7.5–1.1), MF ($p < 0.05$; ES: 13.9–0.5), WM ($p < 0.05$; ES: 5.2–1.1) and FW ($p < 0.05$; ES: 6.1–1.1). Furthermore, only WM ($p < 0.05$; ES: 6.5–1.4) and FW ($p < 0.05$; ES: 5.5–1.7) showed significantly greater values during WCS analysed compared to OM. Additionally, WM and CD SSGs played on ApP200 and ApP300 showed significantly higher ($p < 0.001$) TDCR values than ApP100. Figure 2 shows interactions between playing position and game type. All positions obtained higher ($p < 0.005$) HSDR values during all WCS compared to sided game formats, except for MF. For this position, no differences were found between WCS15 and ApP200, and ApP300 ($p > 0.05$). Figure 3 underlines the interactions between playing position and game type for VHSDR. Specifically, CD ($p < 0.05$; ES: 5.2–1.3), FB ($p < 0.05$; ES: 6.2–2.1), and WM ($p < 0.05$; ES: 4.9–1.4) positions showed higher VHSDR values during all WCS in comparison with all SSG formats, except for MF and FW. For these two positions, differences were not found between WCS15 and ApP200, and ApP300 ($p > 0.05$). Only WM exhibited significantly higher VHSDR values during OM compared to ApP100 ($p < 0.05$; ES: 2.5). Figure 4 shows the differences between WCS and sided games taking into consideration the SDR. Considering WCS1, all positions reported higher SDR values compared to all SSGs and OM. No differences were found between WCS15 and ApP200 and ApP300, except for FB and WM. Significantly higher SDR values were recorded in WCS15 compared to ApP100 for FB and WM ($p < 0.05$; ES: 3.2 and 2.0, respectively).

Mechanical values, ACCHR and PLR are shown in Figure 5 and Figure 6, respectively. ACCHR values were significantly greater during WCS1 compared to WCS5 (ES: 3.8) and WCS15 (ES: 4.6), OM (ES: 5.5), and all SSG formats ($p < 0.001$; ES: 5.1–2.1). ApP100 showed significantly higher ACCHR values compared to other SSG formats (ApP200 and ApP300) ($p < 0.05$; ES: 1.4 and 1.6,

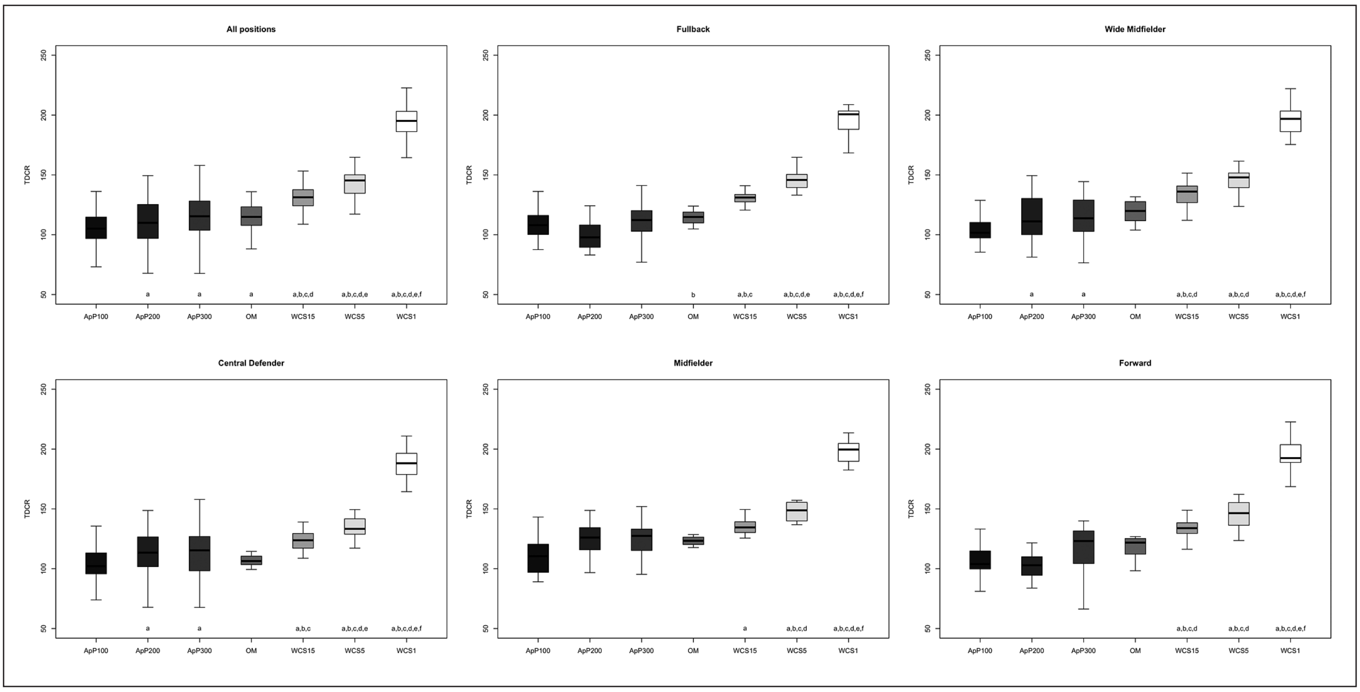

FIG. 1. Significant differences between different WCS and various sided games considering total distance covered relative (TDCR); a: significant differences compared to ApP100; b: significant differences compared to ApP200; c: significant differences compared to ApP300; d: significant differences compared to OM; e significant differences compared to WCS15; f: significant differences compared to WCS5.

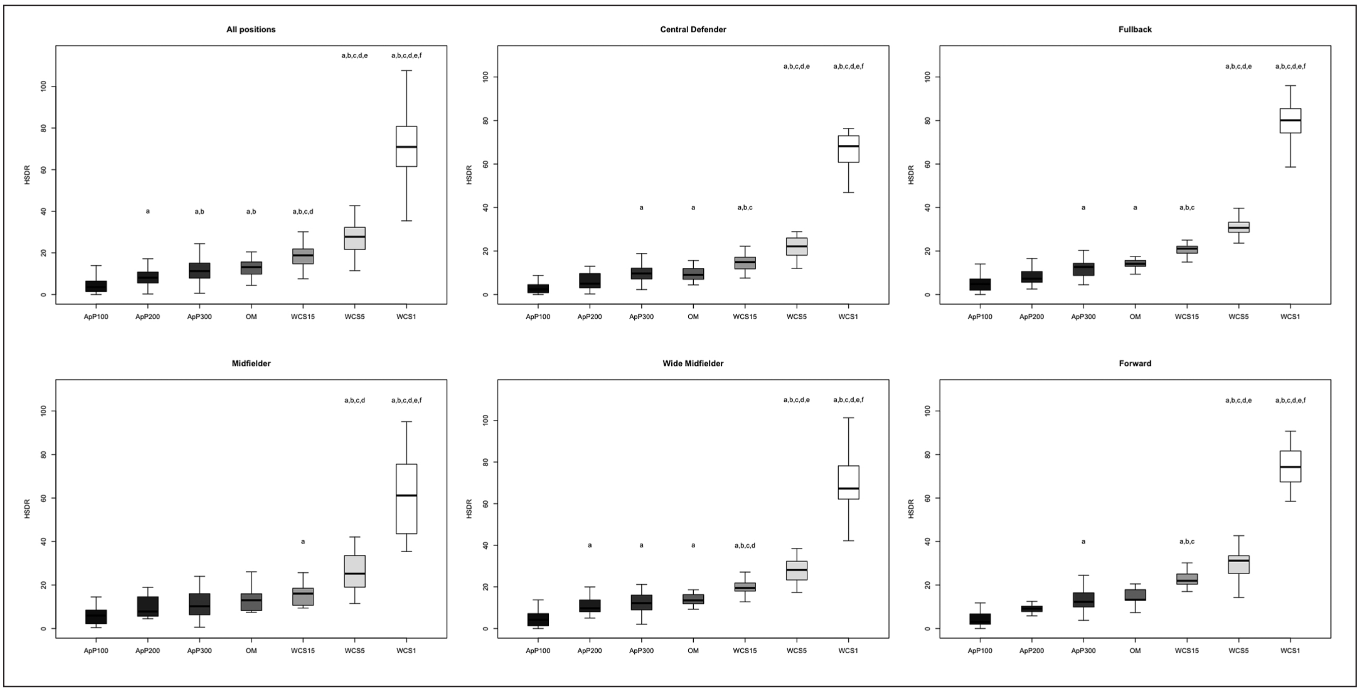

FIG. 2. Significant differences between different WCS and various sided games considering high-speed distance relative (HSDR); a: significant differences compared to ApP100; b: significant differences compared to ApP200; c: significant differences compared to ApP300; d: significant differences compared to OM; e significant differences compared to WCS15; f: significant differences compared to WCS5.

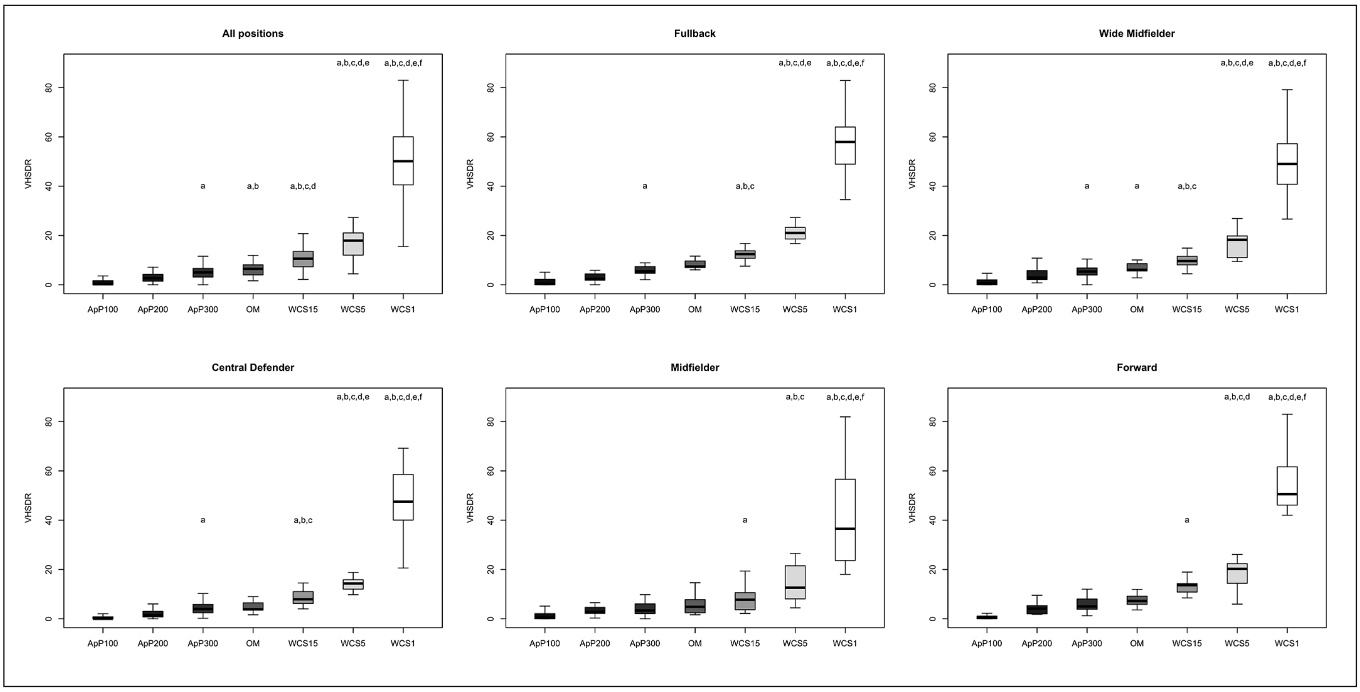

FIG. 3. Significant differences between different WCS and various sided games considering very high-speed distance relative (VHSDR); a: significant differences compared to ApP100; b: significant differences compared to ApP200; c: significant differences compared to ApP300; d: significant differences compared to OM; e significant differences compared to WCS15; f: significant differences compared to WCS5.

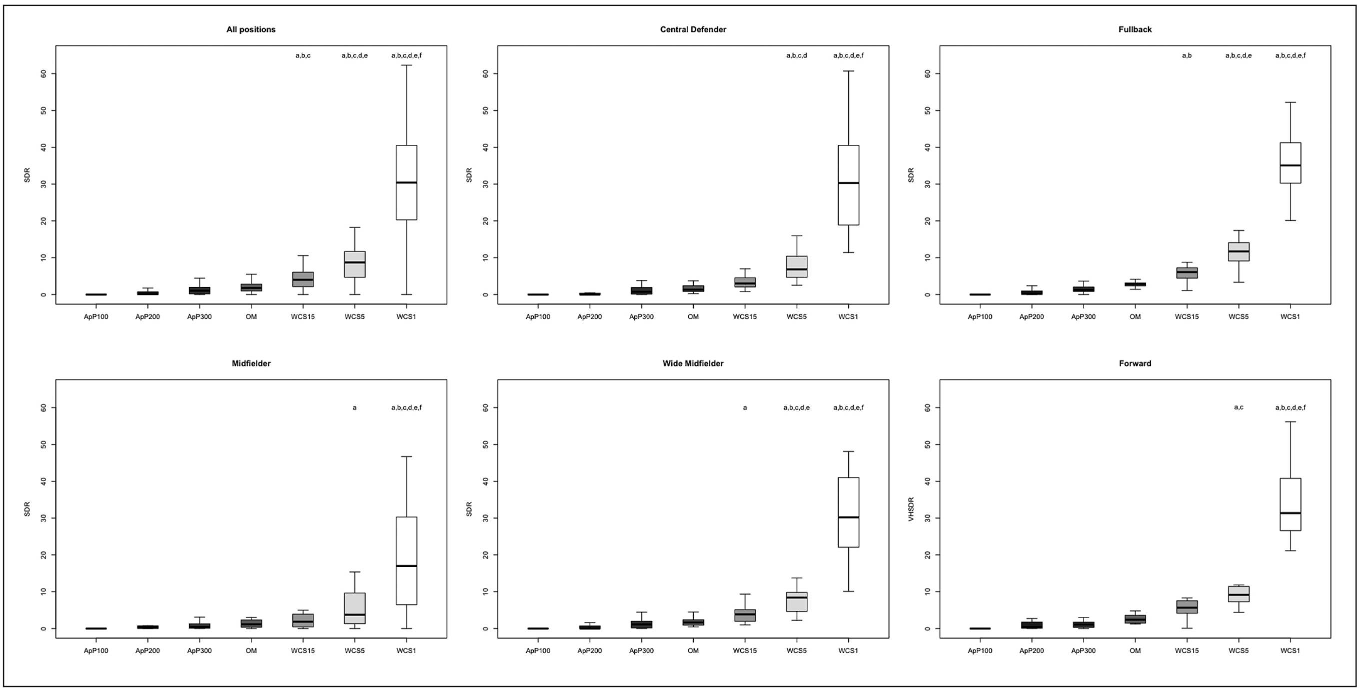

FIG. 4. Significant differences between different WCS and various sided games considering sprint distance relative (SDR); a: significant differences compared to ApP100; b: significant differences compared to ApP200; c: significant differences compared to ApP300; d: significant differences compared to OM; e significant differences compared to WCS15; f: significant differences compared to WCS5.

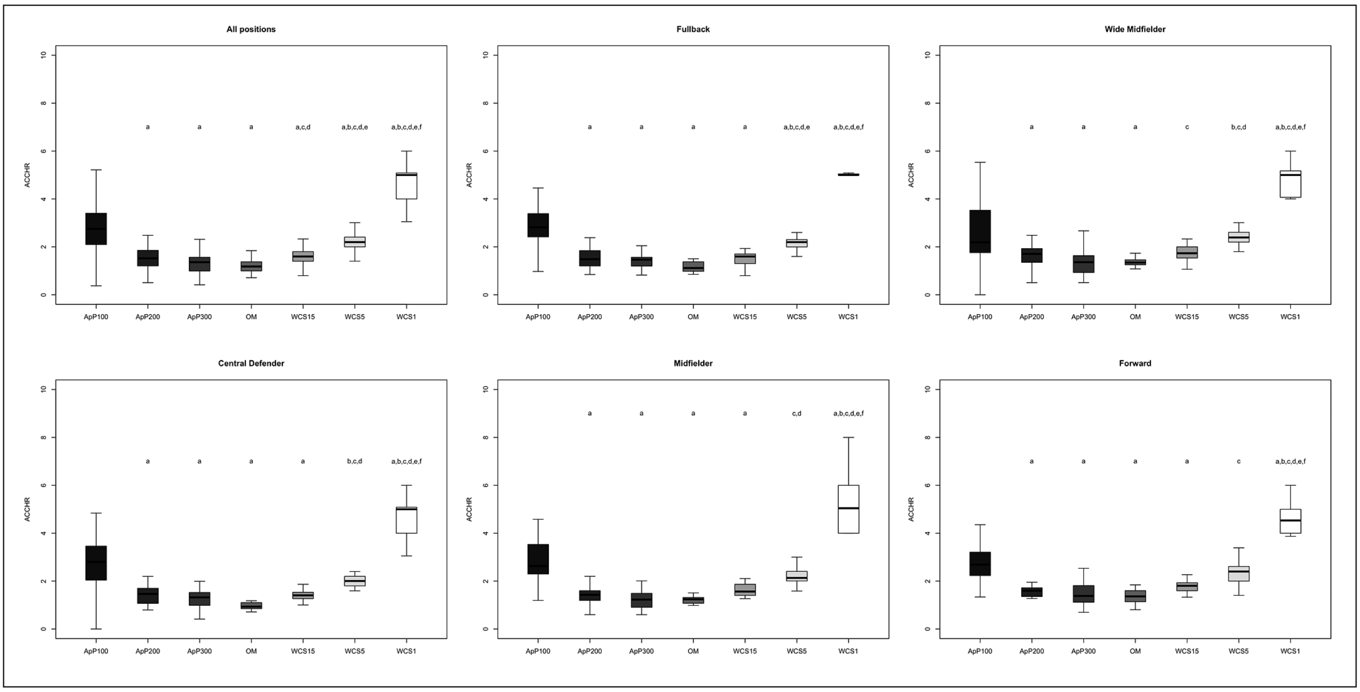

FIG. 5. Significant differences between different WCS and various sided games considering number of total high-intensity accelerations relative (ACCHR); a: significant differences compared to ApP100; b: significant differences compared to ApP200; c: significant differences compared to ApP300; d: significant differences compared to OM; e significant differences compared to WCS15; f: significant differences compared to WCS5.

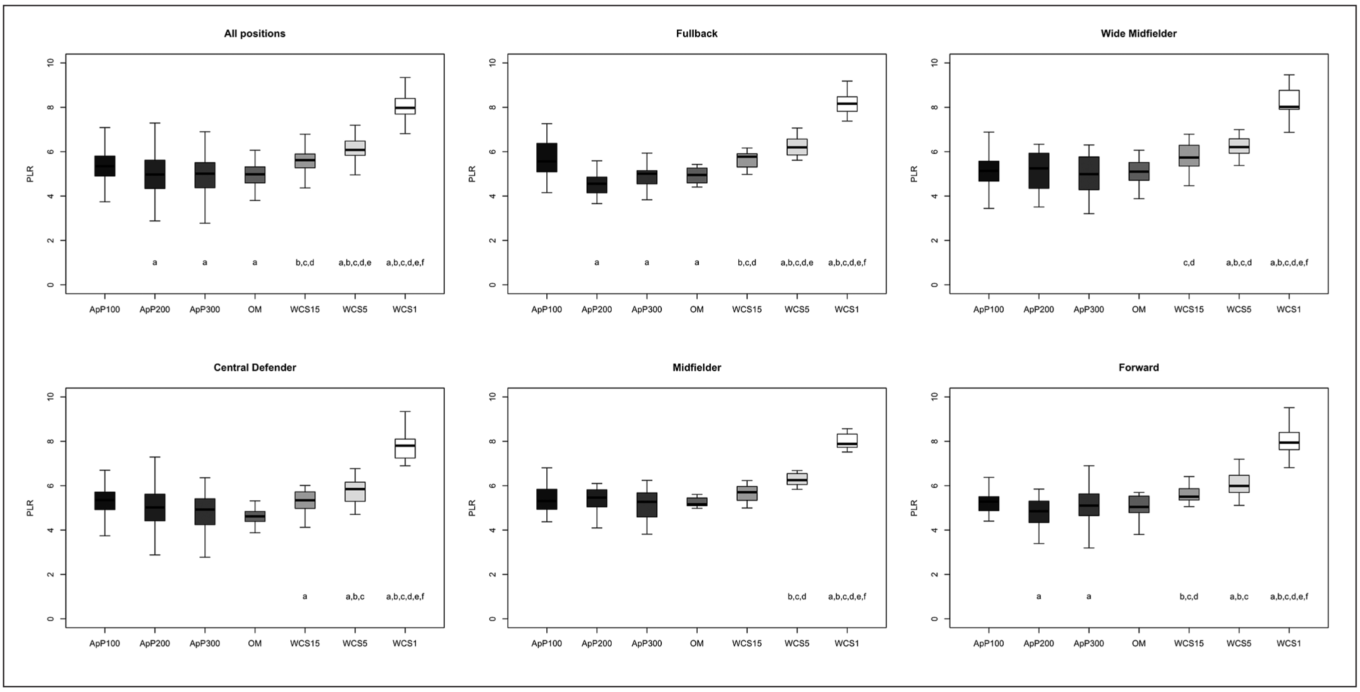

FIG. 6. Significant differences between different WCS and various sided games considering player load relative (PLR); a: significant differences compared to ApP100; b: significant differences compared to ApP200; c: significant differences compared to ApP300; d: significant differences compared to OM; e significant differences compared to WCS15; f: significant differences compared to WCS5.

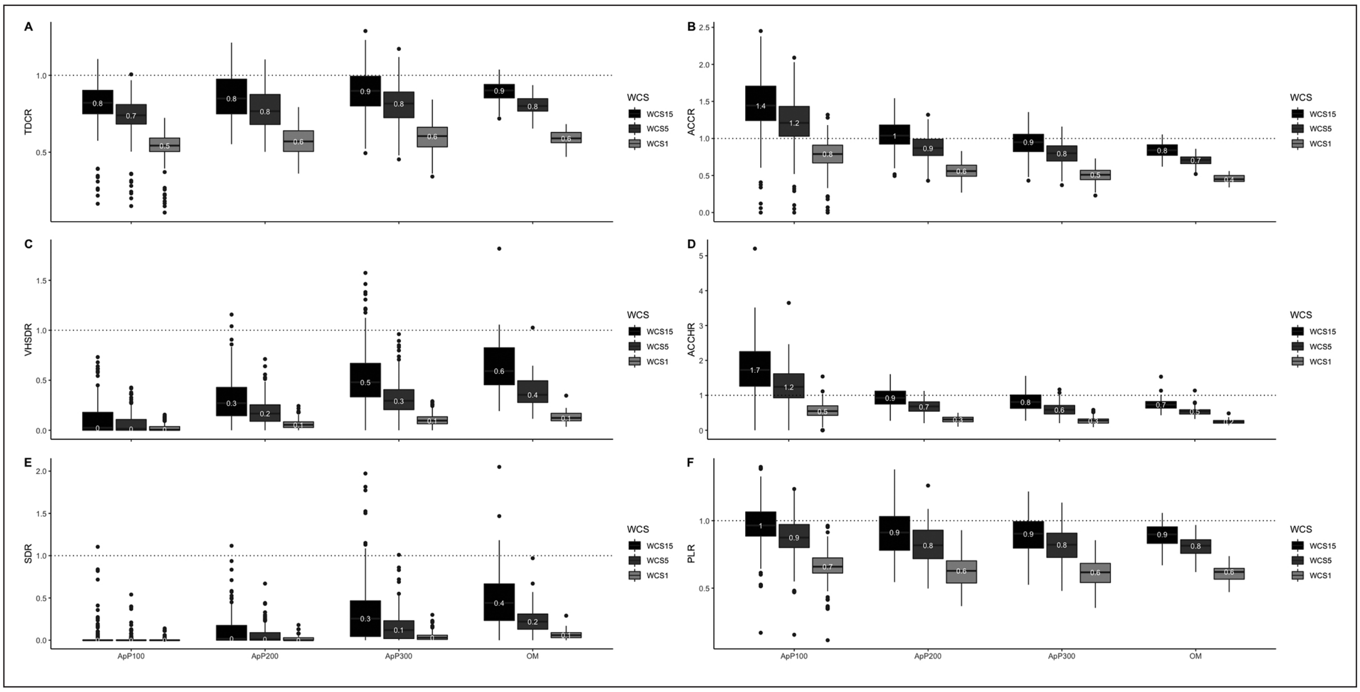

FIG. 7. Various-sided games and official matches percentages (%) according to different worst-case scenarios for all players' positions. ApP100: Area per player (<100 $m^2 \cdot player^{-1}$); ApP200: area per player (ranged from 101 to 200 $m^2 \cdot player^{-1}$); ApP300: area per player (ranged from 201 to 350 $m^2 \cdot player^{-1}$). A): total distance covered relative (TDCR): B): total number of accelerations relative (ACCR); C): very high-speed distance relative (VHSDR); D): total number of high-intensity accelerations relative (ACCHR); E): sprint distance relative (SDR); F): player load relative (PLR)

respectively), OM ($p < 0.05$; ES: 1.7) and WCS15 ($p < 0.05$; ES: 1.2) for all positions analysed separately. Interactions between playing positions and game type considering PLR are shown in Figure 4. WCS1 showed significantly greater PLR values compared to the other formats analysed for all positions considered ($p < 0.001$; ES: 5.4–3.3). FB and FW had higher PLR values during ApP100 in comparison with ApP200 ($p < 0.05$; ES: 1.6 and 0.8, respectively) and ApP300 ($p < 0.05$; ES: 1.2 and 0.3, respectively).

Figure 7 shows the different SSG formats and OM, considering the relative load normalized across all three analyzed WCS for all players' positions together. The ApP100 format represents, 50, 70, and 80% compared to WCS1, WCS5, and WCS15 respectively for TDCR. Taking into account VHSDR and SDR, ApP100 greatly underestimates the worst-case scenarios of match play (WCS1: 2 and 0%, WCS5: 7 and 2%, and WCS15: 11 and 3%, respectively). Considering mechanical values, the ApP100 format overestimated or reached similar values according to the worst-case scenarios for both ACCR (WCS1: 80%, WCS5: 120%, and WCS15: 140%) and ACCHR (WCS1: 50%, WCS5: 120%, and WCS15: 170%). The results obtained for the ApP200 format analysing TDCR were similar to what was observed in the ApP100 format. The ApP200 format represents 60, 80, and 80% compared to WCS1, WCS5, and WCS15 respectively for the above-mentioned variable. Considering high-intensity locomotor activities (HSDR and SDR), ApP200 did not exceed 30% compared to worst-case scenarios of match play (WCS1: 6 and 2%, WCS5: 20 and 7%, and WCS15: 30 and 10%, respectively). Regarding mechanical values, the ApP200 format reached values below the worst-case scenarios of competition for both ACCR (WCS1: 60%, WCS5: 90% and WCS15: 100%) and ACCHR (WCS1: 30%, WCS5: 70%, and WCS15: 90%, respectively). The ApP300 format represents 60, 80, and 90% compared to WCS1, WCS5, and WCS15 respectively for TDCR. Taking into account VHSDR and SDR, ApP300 underestimates the worst-case scenarios of match play (WCS1: 10 and 4%, WCS5: 30 and 10%, and WCS15: 60 and 30%, respectively). Analysing mechanical values, the ApP300 format underestimated values according to the worst-case scenarios for both ACCR (WCS1: 50%, WCS5: 80%, and WCS15: 90%) and ACCHR (WCS1: 30%, WCS5: 60%, and WCS15: 80%).

DISCUSSION

The main purpose of this study was to determine whether the physical performance of young soccer players during various SSGs underload, replicate, or overload the requirements of the worst-case scenarios (WCS) during match play considering external load measures. To the authors' knowledge, no previous study has analysed the differences between WCS and SSG according to ApP with young soccer players. Our main findings were that WCS5 and WCS1 showed significantly higher values than SSG formats (ApP100, ApP200, and ApP300) and OM taking into account locomotor variables (TDCR, HSDR, VHSDR, and SDR). However, no significant differences were found between WCS15 and SSGs when sprint distances were analysed in most playing positions. Regarding mechanical (ACCHR) values, ApP100 showed significantly higher values than the WCS, except for WCS1.

There were differences between worst-case scenarios and ApP formats for the players depending on their field position. WCS1 and WCS5 were higher for TDCR values compared to other formats across all playing positions. However, considering WCS15, we found that TDCR was higher than the ApP200 and ApP300 for all positions, except for midfielders. Maybe the greater distance per minute reached in this position during both training sessions [26] and during SSG formats compared to other positions [27, 28] could explain these outcomes, since they are related to the positional role of linking defence and attack. These findings are in line with previous research [17, 20]. Therefore, these tasks seem less appropriate to replicate the most demanding phases of match play in the TDCR. Hence, SSGs with different ApP (ApP100, ApP200, and ApP300) reached 53, 57, and 60% respectively of TDCR of the WCS1. However, when using a bigger format (i.e., ApP300), the results showed similar values to different worst-case scenarios. Therefore, these tasks could be optimal to prepare TDCR worst-case scenarios of greater duration (i.e., WCS5 and WCS15).

In relation to high-intensity activities (i.e. HSDR, VHSDR), similar tendencies were found. HSDR and VHSDR were significantly higher in WCS1 and WCS5 compared to the different SSGs for all positions. However, no significant differences were found in HSDR and VHSDR between WCS15 and ApP200, and ApP300 for midfielders. A possible explanation for this fact could be that midfielders produce less HSDR and VHSDR during official matches [29]; hence, a lesser peak of 15 minutes was reached. In consequence, there are no differences between WCS15 and SSGs with larger area per player. Significant differences were found when we analysed the rest of the playing positions. FB and WM reached the greatest values during competitions in these variables; therefore, big differences exist between the most demanding passages and sided games. Regarding SDR values, WCS1 was higher than SSGs for all playing positions. Similarly, WCS5 was higher than SSGs for CD, FB, and WM, except for MF and FW. Once again, the shorter sprint distance reached for both positions during match play could be behind these outcomes. Additionally, no differences were found between WCS15 and SSGs for most positions. Hence, SSGs could be a good solution when the practitioners aim to prepare the most demanding passages of 15 minutes duration.

Current soccer presents more high-intensity actions and greater sprint distances [30], being decisive in both attacking and defensive soccer situations, and they are considered a key measure of physical performance in soccer [31, 32]. In contrast, one of the most used tasks during the training process is the SSGs [33]. However, the SDR and VHSDR observed during these types of drills were significantly lower than the demands observed in the worst-case scenarios of the competition taking into account different time periods in all playing positions. According to Dalen et al. [20], the discrepancy between SSGs and match peaks with respect to VHSDR and SDR could be due to several factors such as the size of the pitch during SSGs. The frequent use of smaller pitch size (ApP100 and ApP200) during the training sessions could be behind these differences. In addition, the reduced peak VHSDR and SDR recorded in ApP300 compared to WCS could potentially be due to the time constraints, pacing strategies, and psychological or motivational factors resulting in fewer opportunities to reach similar values to those found in the most demanding phases of match play [17, 34]. According to Riboli et al. [6], we would need more than 350 $m^2 \cdot player^{-1}$ to replicate the official match peaks of high intensity and sprint distance in elite adult players. In consequence, we could mention that SSGs do not prepare players adequately for the most demanding phases of competition, specifically for WCS1 and WCS5, in relation to VHSDR and SDR. However, sided games with larger areas could be used to prepare WCS15 since no differences were found between WCS15 and SSG formats for each position analysed. Consequently, coaches and practitioners should consider the appropriate exposure of players to HSDR and SDR with the aim of either developing or maintaining their capacity to perform high-intensity efforts required frequently during WCS of match play [35]. Thus, the results of this study show that supplementary high-speed running drills should be planned and periodized suitably concurrently with SSGs to prepare for WCS for young soccer players [36, 37], specifically for positions with high demands of high-intensity and sprint distances (i.e. FB and WM). Additionally, this type of training could reduce the risk of non-contact hamstring injuries [38, 39, 40] and therefore should be considered in the practice.

Previous research concluded that accelerations and decelerations remained unchanged across different ApP used [6, 41]. Hence, no differences in accelerations and decelerations were found by Gaudino et al. [41] between SSGs with different areas per player. Conversely, we found that SSGs played on small areas (i.e., ApP100) had higher ACCHR values compared to WCS15 and WCS5 for all field positions, except for wide midfielders, where no differences were found. Wide midfielders reach the highest number of high-intensity accelerations during match play [16, 42]. Accordingly, similar values were observed between ApP100 and worst-case scenarios for this play position. However, it seems that SSG formats did not stimulate players sufficiently to cope with acceleration demands that occurred during WCS1 taking into consideration all play positions. We observed that players performed a higher number of both total and high-intensity accelerations per minute during ApP100 compared to WCS15 and WCS5. However, the greatest values were found during WCS1. Present data are in line with Dalen et al. [20], who observed that during SSG (4 vs 4) with professional soccer players, a higher number of ACCR was performed compared to the peak 5-minute intensity. Similarly, Martín-García et al. [16] also with professional Spanish soccer players reported that SSGs (i.e., 5 vs 5 and 6 vs 6) represented approximately 115% in relation to WCS5 for the ACCHR values. Nevertheless, neither research group reported data for WCS using time windows of shorter duration (i.e., WCS1). Hence, taking into account our results, it seems that when aiming to prepare players for the most demanding phases of 1-minute duration a supplementary task emphasizing ACCR and ACCHR values may be needed, since the ApP formats analysed represented a maximum of 78 and 56% respectively, compared to WCS1. However, if the aim is to prepare WCS with a longer time window, it seems that both ApP100 and ApP200 SSG formats may be suitable.

The present research has some limitations. First, more observations analysing ApP300 would be needed to reach more powerful conclusions. Secondly, the varying duration and training prescription between SSG formats is a limitation as this could have influenced the pacing strategies of players and it should be into account when the results are analysed. As another limitation, we only took into account the average values of SSGs without considering the most demanding phases during these drills. More research analysing the WCS and the SSGs' peaks could elucidate this topic. Lately, internal load (i.e., heart rate and the rate of perceived exertion) were not examined. Hence, an aggregate analysis between internal and external load would provide more accurate information. However, the impossibility of collecting the rate of perceived exertion after each SSG format during the daily real-life training routine may limit the opportunity to monitor consistently the internal and perceived load.

CONCLUSIONS

This study provides useful information for practitioners on the impact of SSG formats on physical load in relation to the WCS of competitive match play. The results highlight the importance of expressing the demands of the game formats relative to the WCS since we found that WCS5 and WCS1 were significantly higher than SSG formats (ApP100, ApP200, and ApP300) and OM taking into account locomotor variables (TDCR, HSDR, VHSDR, and SDR) and mechanical variables (ACCR, ACCHR, and PLR). In addition, larger SSG formats had greater TDCR and VHSDR values than smaller formats. However, when we analysed mechanical variables (ACCHR and PLR), we found that smaller SSGs had higher values compared to larger SSGs and OM. Only the ACCHR values exceed the values in the WCS5 and WCS15 during ApP100 formats, while the demands of other measures do not do so in any cases. It seems that if the objective is reaching ACCHR values like WCS, ApP100 formats could be valid. However, it may be necessary to design other types of tasks when practitioners aim to reach locomotor values (TDCR, HSDR, VHSDR, and SDR) similar to the most demanding passages of match play.

The present findings have several practical applications. In the first instance, to replicate the locomotor (TDCR, HSDR, and SDR) and mechanical values (ACCR, ACCHR, and PLR) reached during the WCS1 it seems that supplementary drills should be planned since the SSGs analysed did not cope with the physical demands of the most demanding phases of match play. Similarly, SSG formats with specific sprinting rules, individualized positional drills, transition-sided games, or running-based exercises seem to be needed when the objective is to reproduce VHSDR, and SDR values reached during WCS5. However, to prepare WCS15, sided games with larger areas could be a good choice since no significant differences were found between WCS15 and SSG formats for all positions analysed. The variables that have the lower percentage in relation to the most demanding phases of competition in all SSG formats studied, especially in the smallest formats of training games, are TDCR, VHSDR, and SDR. Lately, the different WCS during matches used in this study could be used as benchmarks to develop position-specific supplementary high-speed running training for elite young soccer players. This study provides useful information for coaches and practitioners on the impact of SSG formats on physical external load in relation to the WCS of competitive match play. The results highlight the importance of taking into account the most demanding passage of play to plan and periodize training load across the microcycle. Additionally, it seems important to compare match peaks with SSGs to assess the physical load imposed and include supplementary running drills if required.

Conflict of interest

The authors declared no conflict of interest.

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A comparison in knee flexor and extensor strength following ACL reconstruction in international, male soccer players receiving patellar tendon or hamstrings grafts

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ABSTRACT: The aim of this study was to compare knee extensor and flexor strength recovery following anterior cruciate ligament (ACL) reconstruction between bone-patellar tendon-bone (BPTB) and hamstring tendon (HT) grafts in international male soccer players undergoing comparable 6-month rehabilitation programmes. Seventeen players underwent ACL reconstruction with either an autogenous BPTB graft or HT graft. Knee extensor and flexor peak torques were measured at 3 months and 6 months in the injured and contralateral legs following surgery using isokinetic dynamometry. The *moderate–large* asymmetries in knee extensor peak torque between legs at 3 months across graft types (BPTB: p = 0.002, g = -0.94; HT: p = 0.02, g = -0.55) were reduced to *trivial* asymmetries at 6 months (BPTB: p = 0.30, g = -0.19; HT: p = 0.40, g = -0.16), with a non-significant difference in limb symmetry index (LSI) between grafts at 6 months (p = 0.62, g = -0.24). Similarly, *moderate–large* asymmetries in knee flexor peak torque between legs at 3 months across graft types (BPTB: p = 0.13, g = -0.50; HT: p = 0.01, g = -0.97) were reduced to *trivial-small* asymmetries at 6 months (BPTB: p = 0.25, g = 0.18; HT: p = 0.01, g = -0.47); however, a superior LSI was evident with BPTB compared to HT grafts at 6 months (p = 0.007, g = 1.43, *large*). Strength and conditioning professionals working with soccer players who are rehabilitating from ACL reconstruction after receiving a HT graft should give adequate attention to delivering suitable hamstring exercises that ensure optimal strength restoration.

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INTRODUCTION

Soccer is the most popular team sport worldwide, with more than 275 million active players [1]. Soccer players perform a range of intense movements, such as accelerations, decelerations, jumps, kicks, changes in direction, and tackles during training and matches. In turn, many scenarios surrounding these movements including being tackled or tackling an opponent, regaining balance following kicking, and landing from jumping have been observed to take place when professional soccer players sustain an anterior cruciate ligament (ACL) injury [2]. The incidence rate of ACL injury in European professional male soccer players has been reported to range from 0.04 to 0.06 per 1000 h of combined training and match exposure [3–5]. In turn, ACL injuries are among the most devastating injuries encountered by professional soccer players, requiring extensive rehabilitation involving long lay-off times from training and competition [6]. The return time to competition of professional soccer players is particularly important given the economic and performance implications for professional soccer teams accompanying the absence of players due to ACL injuries.

A complete or partial ACL rupture can lead to recurrent instability, meniscus tears, chronic pain, and osteoarthritis [7, 8]. To reduce the risk of further damage, arthroscopically assisted ACL reconstruction has become the most common method to repair a complete ACL rupture, in which an autograft (own tissue) or allograft (tissue taken from another person) replaces the torn ligament [9]. In turn, use of the central third of the patellar tendon (bone-patellar tendon-bone [BPTB]) or use of the semitendinosus and gracilis tendons (hamstring tendons [HT]) are the most frequently used graft types for ACL reconstruction [10]. Although acceptable knee function and stability have been observed following ACL reconstruction using both graft types [11], they will each inherently impair the strength of muscles surrounding the knee, with deficits of nearly 50% reported at 4 weeks after ACL reconstruction [12, 13].

Although a slight predominance of one leg over the other is common in soccer players [14], inter-limb asymmetries in knee extensor and flexor strength of > 10% have been suggested to raise knee injury risk [15]. In this regard, adequate functional recovery following ACL reconstruction is accepted when strength in the injured leg in relation to the contralateral leg reaches a limb symmetry index (LSI) of ≥ 90% [16]. In contrast, inadequate knee extensor strength following ACL reconstruction yields greater rates and magnitudes of load transmission from distal to proximal segments of the leg to increase the risk of ACL graft re-rupture, contralateral knee injury, or premature degenerative changes in the repaired knee joint [2, 17]. Also, optimizing knee flexor strength is crucial when undergoing rehabilitation following ACL reconstruction given that this muscle group buffers shear forces by preventing anterior slide of the tibia relative to the femur [18]. Furthermore, hamstring activation stabilizes the knee in response to external varus and valgus loads [19]. Despite the importance of restoring knee extensor and flexor strength following ACL reconstruction, low rates of competitive [20] and professional [6] male soccer players with BPTB [6, 20] and HT grafts [6] have been reported to achieve the desired LSI of ≥ 90% at 6–9 months following surgery [20] or when returning to unrestricted play [6]. Nevertheless, there is a lack of data directly comparing knee extensor and flexor strength recovery between BPTB and HT autografts in professional male soccer players. Such a comparison is essential given that graft type selection for ACL reconstruction may influence muscle strength recovery and therefore the duration required for a safe return to competition [21].

While there has been a lack of research on this topic specifically in soccer players, comparisons in strength recovery following ACL reconstruction between different graft types have been conducted in recreationally active individuals [22–24], non-athletes [25], non-professional athletes [26–29], military cadets [30], and athletes competing at varying playing levels pooled together [31, 32]. In addition to varied activity and playing levels, the available data have largely been pooled across athletes competing in different sports [27, 28, 30] and across sexes [21–28, 30–32]. Although these studies provide important insight into strength recovery following ACL reconstruction, the existing evidence may not be transferable to professional male soccer players considering that higher strength capacities have been observed in players competing at this playing level compared to lower levels [33]. Furthermore, professional soccer players likely have greater access to wider resources (e.g., practitioner supervision, facilities, equipment) during the rehabilitation process compared to players competing at lower playing levels, aiding player recovery. Likewise, evidence stemming from pooled findings across players competing in different sports [27, 28, 30] and across sexes [21–28, 30–32] should not be simply applied to male soccer players, given the different knee extensor and flexor strength levels reported according to these factors [34] and varied approaches adopted in managing the rehabilitation process [16]. Therefore, examination of knee strength recovery following ACL reconstruction should be conducted strictly in professional male soccer players for greater specificity in evidence for application in this population.

Review of the existing evidence comparing knee extensor and flexor strength recovery following ACL reconstruction between BPTB and PT grafts reveals inconsistent findings [21–28, 30–32]. Specifically, some research has documented significantly inferior knee extensor strength with BPTB autografts compared to HT autografts (5 months–5 years following surgery) [21, 23–26], while other research reported non-significant differences in knee extensor strength between graft types (6 months–3 years following surgery) [22, 26–28, 30–32]. In contrast, studies have reported inferior knee flexor strength with HT autografts compared to BPTB autografts (5–29 months following surgery) [21, 22, 24, 26, 27, 32], while separate research demonstrated non-significant differences in knee flexor strength between graft types (6 months–5 years following surgery) [23, 25, 28, 30, 31]. Although professional male soccer teams are under immense pressure for players to return to unrestricted play within 6 months [35] following ACL reconstruction, there is a lack of data documenting recovery in knee extensor and flexor strength up to 6 months following surgery using BPTB and HT autografts. Therefore, the aim of this study was to quantify and compare knee extensor and flexor strength recovery following ACL reconstruction between BPTB and HT autografts in international male soccer players undergoing comparable 6-month rehabilitation programmes.

MATERIALS AND METHODS

This study adopted a within- (inter-limb comparisons) and between-subject (BPTB vs. HT autografts) design to compare knee extensor and flexor strength recovery following ACL reconstruction in international male soccer players undergoing comparable 6-month rehabilitation programmes. Data were gathered at a private physiotherapy fitness centre Femur over a 4-year period until December 2022. All procedures were approved by the Human Research Ethics Committee of the Faculty of Medical Sciences at University of Kragujevac, in Serbia (01-11122) in accordance with the Helsinki Declaration.

Subjects

Seventeen international male soccer players from 15 different teams with a primary diagnosis of ACL deficiency underwent arthroscopically assisted ACL reconstruction with either an autogenous BPTB graft (n = 8, age: 23.1 ± 4.0 years [range: 18–28 years], height: 182.1 ± 2.7 cm; body mass: 77.5 ± 3.5 kg) or HT graft (n = 9, age: 24.8 ± 4.9 years [range: 19–32 years], height: 182.7 ± 7.5 cm; body mass: 76.5 ± 7.7 kg). Only soccer players competing at the international level immediately prior to sustaining the ACL injury were recruited to ensure that an elite playing sample was examined [36]. Subjects were able to participate in the study if free from any significant meniscus lesions (only a partial meniscectomy at most), chondral damage (as assessed either from magnetic resonance imaging or by the orthopaedic surgeon at the time of surgery), previous ACL injury (in the injured or contralateral leg), and other musculoskeletal injuries that could negatively affect the results of the study. Accordingly, 4 of the 21 soccer players originally recruited were excluded, leaving 17 players (from Serbia, Croatia, Ukraine and Switzerland) participating in the study. All subjects provided written informed consent after the procedures of the study were explained, including the risks and benefits associated with participation.

Procedures

Subjects were allocated to the BPTB or HT group based on the autograft technique used for their ACL reconstruction. Both the BPTB and HT grafts were secured on the femur and tibia using interference screws. In the BPTB group, the central third of the patellar tendon was harvested with a vertical incision by blocking the patellar and tibial bones. A standard longitudinal incision over the pes anserinus was used for harvesting the HT graft. The BPTB autograft was between 9 and 10 mm in diameter, while the HT autograft was between 7 and 9 mm in diameter. All operations were performed by the same orthopaedic surgeon who specialized in conducting both ACL reconstruction techniques. The technique was selected for each subject according to their own choice with input from the surgeon. Injuries to both the dominant and non-dominant legs were involved in the sample (dominant leg: n = 7; non-dominant leg: n = 10). All subjects underwent the same standardized 6-month rehabilitation programme at the same private physiotherapy fitness centre. Isokinetic knee (extension and flexion) muscle strength was measured at 3 months and 6 months following surgery during the rehabilitation process. All testing sessions were carried out in similar environmental conditions for all subjects (~22 °C and ~60% relative humidity) and at a similar time of day (09:00 to 11:00). A verbal explanation and demonstration of the testing procedures were given to each subject prior to each testing session. Subjects completed a standardized warm-up prior to the isokinetic strength tests, consisting of a 5-min moderate-intensity exercise bout on a cycle ergometer (Group Cycle Ride, TechnoGym, Gambettola, Italy) [37, 38] followed by passive stretching exercises focused on the quadriceps, hamstrings, hip adductors, and calf muscles [39], as well as three submaximal knee extension and flexion movements for each leg at an angular speed of $60° \cdot s^{-1}$. Stretching positions were held for short durations (15 s per muscle group) to avoid any subsequent negative impacts on performance [38] and ensure that proper body alignment was attained, involving subjects being in a comfortable and correct position that optimizes range of motion without causing pain [39, 40]. This study extends upon smaller scale exploratory research examining isokinetic knee extension and flexion strength recovery in 8 of the players examined without comparisons between graft types [41].

Rehabilitation

Subjects followed a 6-month rehabilitation programme, which involved a 90-min session delivered on 6 days per week under the supervision of the same physical therapist, who was highly experienced in managing soccer players following ACL reconstruction. Rehabilitative progression was determined for each subject using criteria in published guidelines [17, 42]. The rehabilitation programme was divided into phases based on the stage of tissue recovery and the ability of the knee joint to withstand loading demands (0–4 weeks, 5–8 weeks, 9–12 weeks, 13–18 weeks, and 19–24 weeks). During the first 3 days following surgery, focus was placed on range of motion (gradual progress with ~90° achieved by the end of week 1 and full knee flexion achieved in week 4 or 5) as well as managing pain and swelling. Subjects were on crutches for 2 weeks following surgery, after which full weight bearing was permitted as tolerated. Hydrotherapy was implemented for 2 weeks (e.g., deep water running, lunging, squatting, underwater cycling) 18 days after thread removal (thread removal was 16–18 days following surgery across subjects). Electrical stimulation (Compex SP 2.0; Compex Medical, Switzerland) was administered for 4 weeks after surgery to reduce the arthrogenic muscle inhibition effects of swelling, support the recovery of knee extensor strength, and activate the inhibited motoneurons. Movement complexity and speed of activities were systematically increased across isometric, isotonic, and isokinetic exercises. The rehabilitation protocol followed by subjects has been previously described in detail [41]. The load ratio for the quadriceps in seated knee extensions and hamstrings in seated leg curls differed between groups for the first 4 months of the rehabilitation programme (i.e., quadriceps:hamstrings of 60:40 for BPTB group and 40:60 for HT group). The quadriceps and hamstring muscles were equally loaded in both groups (i.e., 50:50) in months 5 and 6 of the rehabilitation programme.

Isokinetic muscle strength

Knee extensor and flexor peak torques were measured at 3 months and 6 months following surgery using an isokinetic dynamometer (HUMAC-NORM, Model 770; Computer Sports Medicine Inc., Stoughton, MA, USA). The reliability (intraclass correlation coefficient = 0.82–0.93, typical error = 5.7–7.7 N·m) of the isokinetic dynamometer at an angular velocity of $60° \cdot s^{-1}$ has been supported previously [43]. Each isokinetic strength test was performed in the concentric-concentric mode at an angular velocity of $60° \cdot s^{-1}$, which has been suggested to be the most sensitive in capturing asymmetries between legs in peak torque measurements for the knee extensors and flexors in athletes who have undergone ACL reconstruction [44].

Subjects were seated in a chair with hips flexed to 90°. The trunk was fixed to the chair with two straps crossing the chest and a further strap positioned across the waist. Handles on either side of the chair were grasped during testing for consistent arm positioning. Straps were fastened across the thigh and malleoli on the tested leg to restrict any lateral movement, allowing only flexion and extension at the knee. The contralateral leg was fixed with the foot positioned behind an ankle stabilizer. Subjects performed five extension and flexion movements interspersed with 2 min of passive rest between movement types. Standardized instructions and verbal encouragement were given to each subject during testing. The contralateral leg was assessed first, followed by the injured leg using the same procedure with a 3-min passive resting period applied between legs. The highest peak torque (N·m) values recorded during knee extension and flexion were taken separately as outcome measures for each leg. LSI between legs and hamstrings:quadriceps ratio (H:Q) (concentric phase) within each leg were calculated as follows:

$$\text{LSI} = \frac{\textit{Injured peak torque}}{\textit{Non-injured peak torque}} \text{x } 100\%$$

$$\text{H:Q} = \frac{\textit{Hamstring peak torque}}{\textit{Quadriceps peak torque}}$$

Statistical analysis

An *a priori* power analysis using G*power software (version 3.1.9.4; Heinrich Heine University Düsseldorf, Düsseldorf, Germany) recommended a sample size of 16 players using an estimated effect magnitude based on research examining isokinetic muscle strength at 3 months and 6 months following ACL reconstruction in a subset of the present sample ($p = 0.05$, effect size [ES] = 0.30; power = 0.80) [41]. Normality of all data was confirmed using the Shapiro-Wilks test. Consequently, all data were reported as mean ± standard deviation (SD). Differences in outcome measures between BPTB graft and HT graft groups (graft effect), time points at 3 months and 6 months (time effect), injured and contralateral legs (leg effect), and muscle groups (muscle effect) were examined using separate 2 × 2 × 2 mixed analyses of variance (ANOVAs) with two within-subjects factors (either time and leg effects or time and muscle effects), and one between-subjects factor (graft effect). Partial eta-squared (η^2) was utilized to indicate the ES for each mixed ANOVA, and was interpreted as [45]: *no effect* (≤ 0.04); *minimum effect* (0.05–0.25); *moderate effect* (0.26–0.64); or *strong effect* (> 0.65). Post-hoc comparisons between timepoints, between legs, or between muscle groups were examined using paired t-tests. Post-hoc comparisons between graft groups were examined using unpaired t-tests. Hedge's g (with 95% confidence intervals [CI]) was also calculated to determine the ES for all post-hoc pairwise comparisons and was interpreted as [46]: *trivial* (< 0.20); *small* (0.20–0.49); *moderate* (0.50–0.79); or *large* (≥ 0.80). Statistical analyses were performed using IBM SPSS software (version 19; IBM Corp., Armonk, NY, USA). Statistical significance was accepted at $p < 0.05$.

RESULTS

The results of each mixed ANOVA are presented in Table 1, with the mean ± SD for each outcome measure presented in Figure 1. Individual data, the median, minimum, maximum, and corresponding interquartile (25th and 75th percentiles) range in knee extensor peak torque, knee flexor peak torque, the H:Q for the injured and contralateral leg, as well as the LSI for the knee extensors and flexors at 3 months and 6 months following surgery are shown in Figure 2.

A 2 × 2 × 2 mixed ANOVA revealed a significant time*leg interaction ($p < 0.001$, $\eta^2 = 0.64$), with subsequent significant main effects of time ($p < 0.001$, $\eta^2 = 0.67$) and leg ($p < 0.001$, $\eta^2 = 0.55$) in knee extensor peak torque. Follow-up comparisons (Figure 3a) revealed a significant *moderate* increase in knee extensor peak torque in the injured leg between 3 months and 6 months across both graft types (BPTB: $p < 0.001$, g = 0.80; HT: $p = 0.01$, g = 0.54), whereas a significantly *small* increase (BPTB: $p = 0.04$, g = 0.21) and non-significant *trivial* increase (HT: $p = 0.36$, g = 0.17) were observed in the contralateral leg between these timepoints. In addition, significant *moderate–large* asymmetries in knee extensor peak torque between the injured and contralateral legs at 3 months for both graft types (BPTB: $p = 0.002$, g = -0.94; HT: $p = 0.02$, g = -0.55) were reduced to non-significant *trivial*

TABLE 1. Statistical outcomes from the mixed ANOVAs showing time (3 months vs. 6 months), leg (injured vs. contralateral legs) or muscle (knee flexor limb symmetry index vs. knee extensor limb symmetry index), graft (bone-patellar tendon-bone vs. hamstrings tendon grafts), and interaction effects for knee extensor peak torque, knee flexor peak torque, peak torque hamstrings:quadriceps ratio (H:Q), and limb symmetry index in international, male soccer players who underwent anterior cruciate ligament reconstruction.

Effect	Knee extensor peak torque		Knee flexor peak torque		Peak torque H:Q		Effect	Limb symmetry index	
	p	η^2, *interpretation*	p	η^2, *interpretation*	p	η^2, *interpretation*		p	η^2, interpretation
Time	**< 0.001**	0.67, *strong*	**< 0.001**	0.60, *moderate*	0.19	0.11, *minimum*	Time	**< 0.001**	0.57, *moderate*
Time*Graft	0.14	0.14, *minimum*	0.82	0.00, *no effect*	0.45	0.04, *minimum*	Time*Graft	0.20	0.11, *minimum*
Leg	**< 0.001**	0.55, *moderate*	**0.001**	0.55, *moderate*	0.24	0.09, *minimum*	Muscle	0.38	0.05, *minimum*
Leg*Graft	0.22	0.10, *minimum*	**0.02**	0.33, *moderate*	0.07	0.21, *minimum*	Muscle *Graft	**0.01**	0.37, *moderate*
Time*Leg	**< 0.001**	0.64, *strong*	**0.04**	0.26, *moderate*	0.32	0.07, *minimum*	Time* Muscle	0.37	0.05, *minimum*
Graft	0.63	0.02, *no effect*	0.74	0.01, *no effect*	0.18	0.11, *minimum*	Graft	0.63	0.02, *no effect*
Time*Leg*Graft	0.16	0.13, *minimum*	0.63	0.02, *no effect*	0.91	0.00, *no effect*	Time* Muscle* Graft	0.85	0.00, *no effect*

Note: bolded p value indicates statistically significant effect at $p < 0.05$.

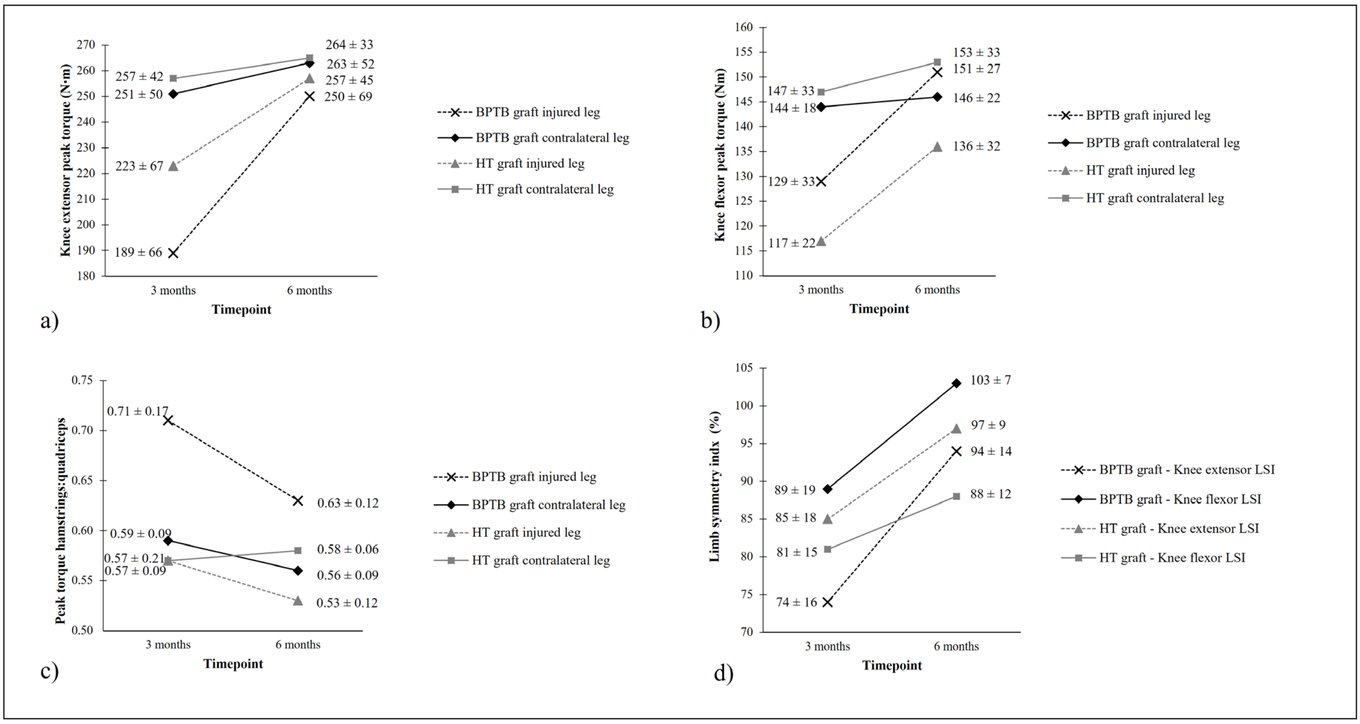

FIG. 1. Mean ± standard deviation for (a) knee extensor peak torque, (b) knee flexor peak torque, (c) peak torque hamstrings:quadriceps ratio, and (d) limb symmetry index (LSI) in international male soccer players who underwent either a bone-patellar tendon-bone (BPTB) graft or hamstring tendon (HT) graft for anterior cruciate ligament reconstruction taken at 3 months and 6 months following surgery during the rehabilitation process.

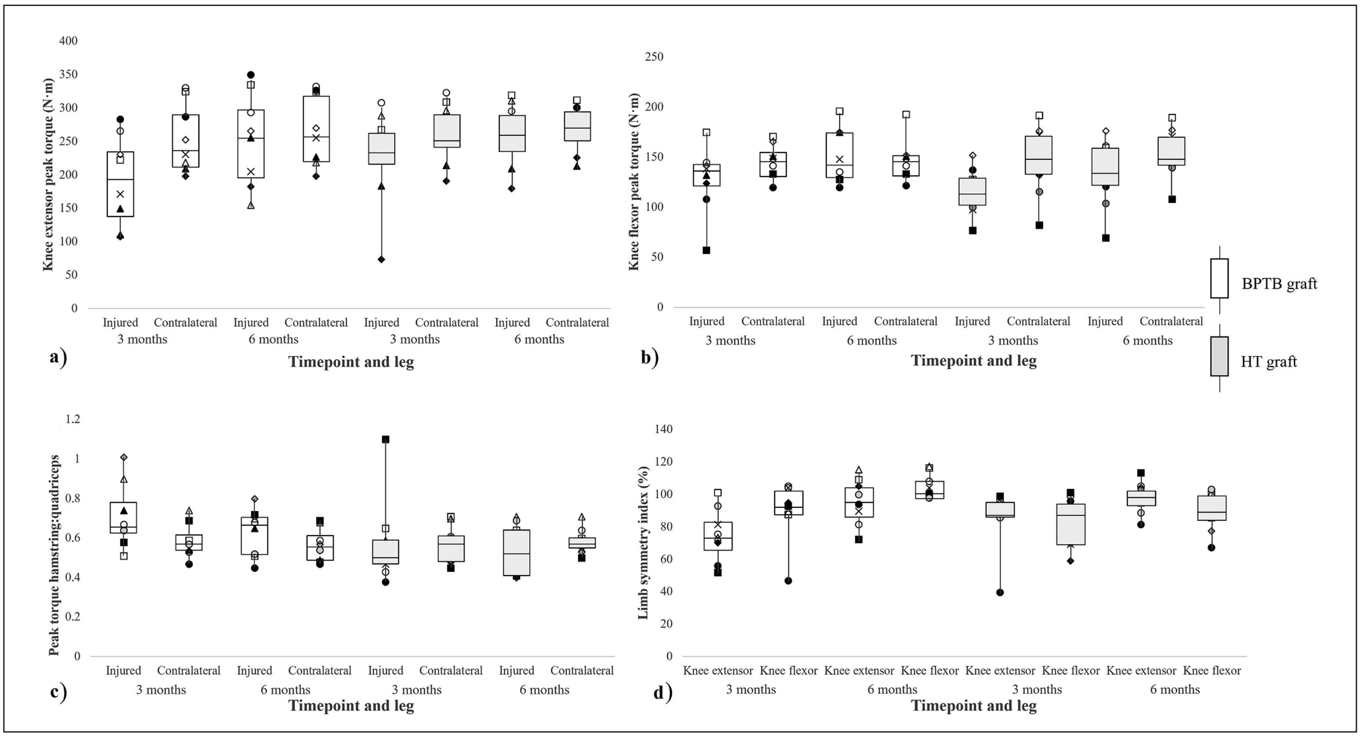

FIG. 2. Individual data points for each subject and descriptive values for (a) knee extensor peak torque, (b) knee flexor peak torque, (c) peak torque hamstrings:quadriceps ratio, and (d) leg symmetry index in international male soccer players who underwent either a bone-patellar tendon-bone (BPTB) graft or hamstring tendon (HT) graft for anterior cruciate ligament reconstruction taken at 3 months and 6 months following surgery during the rehabilitation process.
Note: Each marker represents a different subject. In the box plots, whiskers indicate the minimum and maximum values, the boundary of the box closest to zero indicates the 25th percentile, the black line within the box indicates the median, and the boundary of the box farthest from zero indicates the 75th percentile.

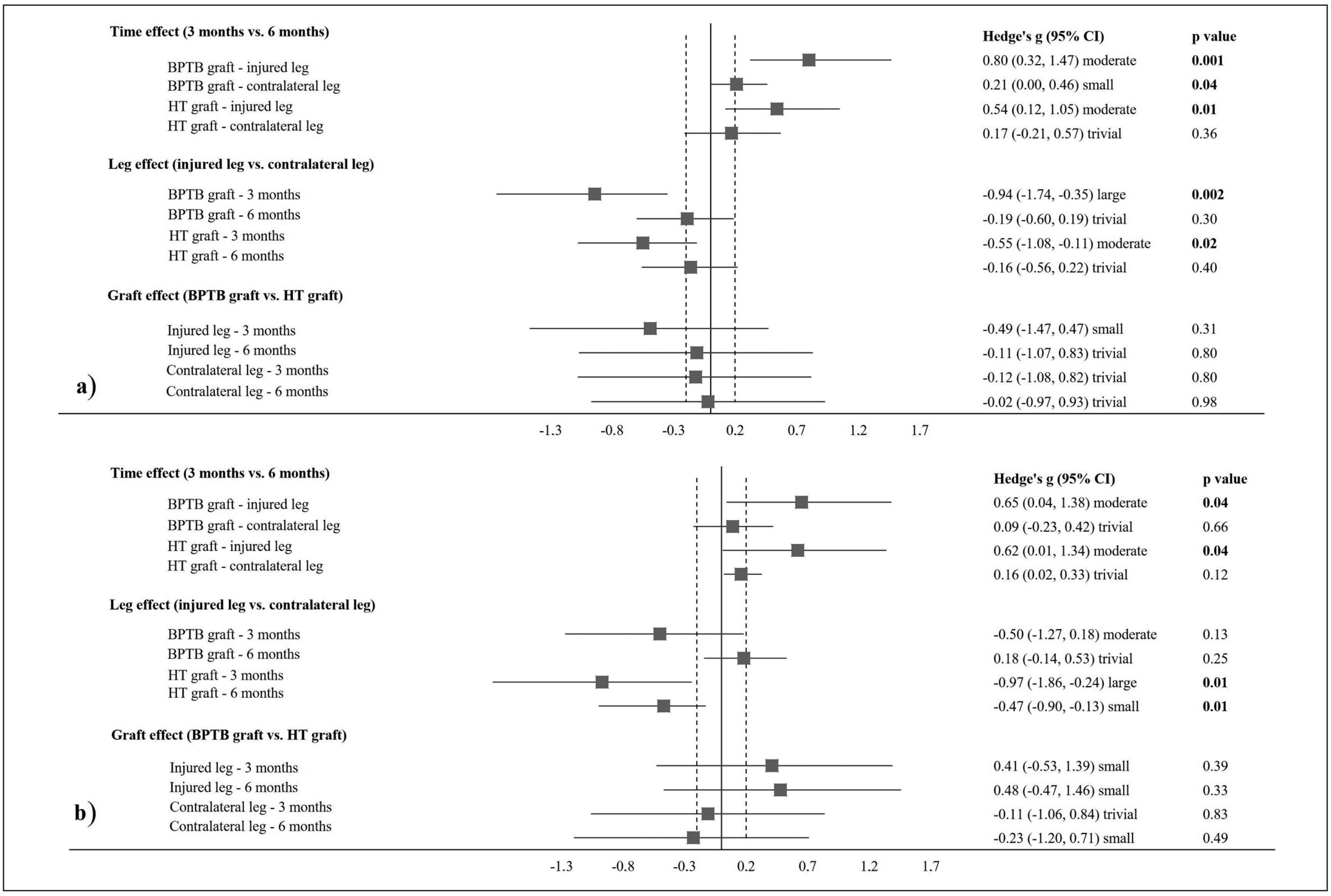

FIG. 3. Statistical pairwise comparisons for (a) knee extensor peak torque and (b) knee flexor peak torque between timepoints, legs, and graft types in international male soccer players.

differences between legs at 6 months (BPTB: p = 0.30, g = -0.19; HT: p = 0.40, g = -0.16).

A 2 × 2 × 2 mixed ANOVA revealed a significant time*leg interaction ($p = 0.04$, $\eta^2 = 0.26$), with subsequent significant main effects of time ($p < 0.001$, $\eta^2 = 0.60$) and leg ($p < 0.001$, $\eta^2 = 0.55$) in knee flexor peak torque. Follow-up comparisons (Figure 3b) revealed a significant *moderate* increase in knee flexor peak torque in the injured leg from 3 months to 6 months across both graft types (BPTB: p = 0.04, g = 0.65; HT: p = 0.04, g = 0.62), with non-significant *trivial* changes evident in the contralateral leg between these timepoints (BPTB: p = 0.66, g = 0.09; HT: p = 0.12, g = 0.16). A significant *large* asymmetry in knee flexor peak torque between the injured and contralateral legs at 3 months in the HT graft group (p = 0.01, g = -0.97) was reduced to a significant *small* difference between legs at 6 months (p = 0.01, g = -0.47). In addition, a non-significant *moderate* asymmetry in knee flexor peak torque between the injured and contralateral legs at 3 months in the BPTB graft group (p = 0.13, g = -0.50) was reduced to a non-significant *trivial* difference between legs at 6 months (p = 0.25, g = 0.18).

A 2 × 2 × 2 mixed ANOVA revealed non-significant interactions and main effects across all comparisons for H:Q, with non-significant *trivial–moderate* effects evident for all follow-up pairwise comparisons (Figure 4a).

A 2 × 2 × 2 mixed ANOVA revealed a significant muscle*graft interaction ($p = 0.01$, $\eta^2 = 0.37$), with a subsequent significant main effect of time ($p < 0.001$, $\eta^2 = 0.57$) in LSI. Follow-up comparisons (Figure 4b) revealed significant *moderate–large* increases in knee extensor LSI from 3 months to 6 months across both graft types (BPTB: p = 0.01, g = 1.18; HT: p = 0.02, g = 0.76), with non-significant *small–large* increases evident in knee flexor LSI between these timepoints for both graft types (BPTB: p = 0.07, g = 0.87; HT: p = 0.38, g = 0.47). Non-significant *small–moderate* differences were observed between knee extensor LSI and knee flexor LSI for both graft types at 3 months (BPTB: p = 0.05, g = -0.76; HT: p = 0.66, g = 0.22) and 6 months (BPTB: p = 0.07, g = -0.72; HT: p = 0.08, g = 0.77). There was a significant *large* difference in knee flexor LSI at 6 months in favour of the BPTB graft compared to the HT graft (p = 0.007, g = 1.43).

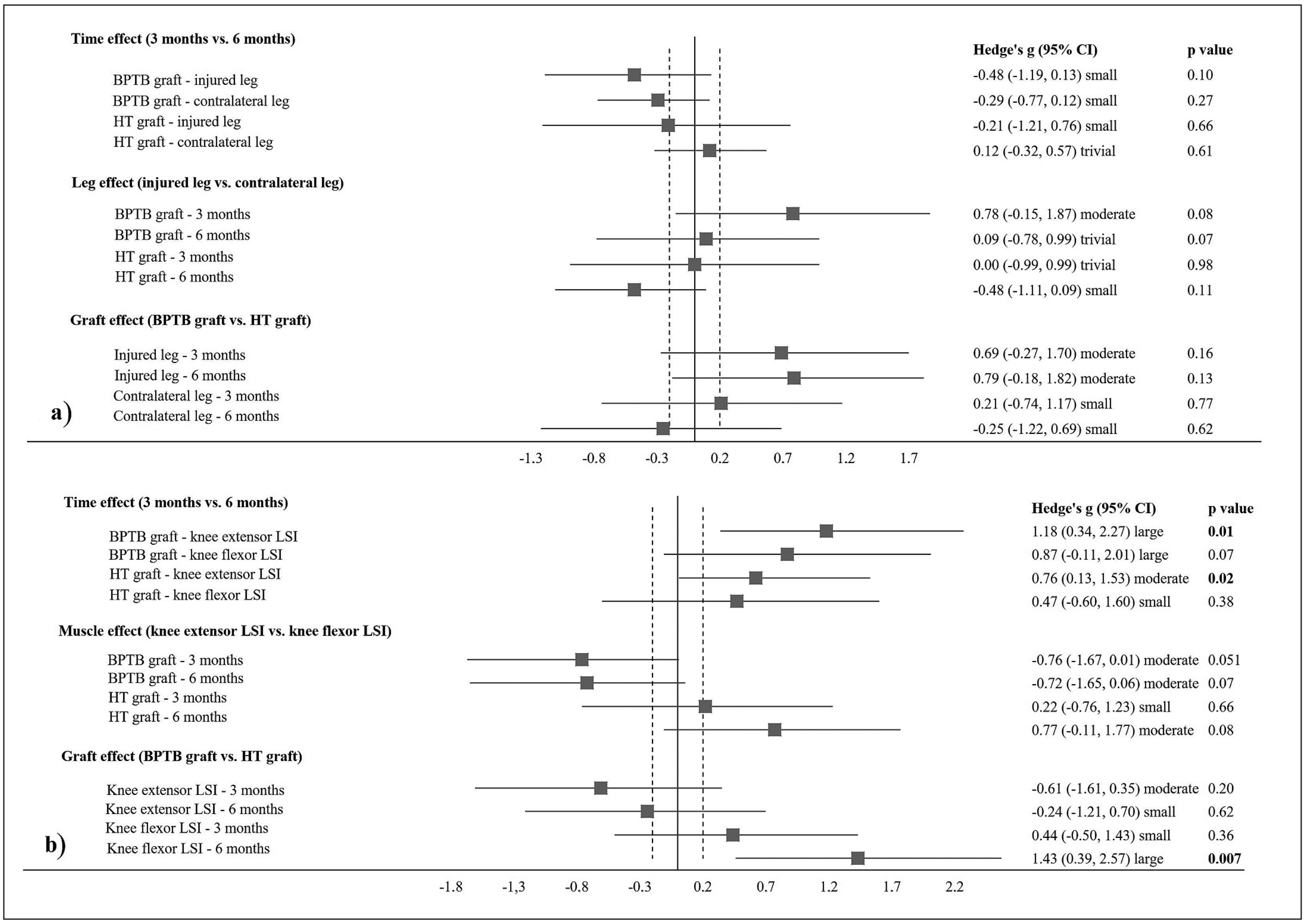

FIG. 4. Statistical pairwise comparisons for (a) peak torque hamstrings:quadriceps ratio and (b) leg symmetry index (LSI) between timepoints, legs, muscles, and graft types in international male soccer players.

DISCUSSION

The present results revealed that knee extensor peak torque was almost equivalent (BPTB: 0%; HT: 3%) to the contralateral leg regardless of the graft type used at 6 months following ACL reconstruction. Specifically, *moderate–large* asymmetries between legs in knee extensor peak torque at 3 months following reconstruction were reduced to *trivial* magnitudes at 6 months, with a desired difference of < 10% between legs across both graft types (BPTB: 6%; HT: 3%). Similarly, *moderate–large* asymmetries between legs in knee flexor peak torque at 3 months following reconstruction were reduced to *trivial–small* magnitudes across graft types at 6 months (BPTB: 0%; HT: 12%). However, despite the *trivial–small* asymmetries between legs in knee flexor peak torque at 6 months following reconstruction, graft-related comparisons revealed a *large* difference in knee flexor LSI with inferior strength recovery in the HT group compared to the BPTB group.

Comparisons across timepoints revealed *moderate* improvements in knee extensor peak torque in the injured leg, with LSI exceeding 90% for both graft types at 6 months following ACL reconstruction. The improved knee extensor strength across time was further underpinned by *trivial* asymmetries between legs at 6 months following surgery for both graft types. Aligning with our results, several previous studies [22, 26–28, 30–32] have reported comparable knee extensor LSI across ACL reconstructions involving either BPTB or HT grafts. In contrast, some research has demonstrated significantly lower knee extensor LSI with a BPTB graft compared to a HT graft following ACL reconstruction [17, 18, 20, 21]. It has been postulated that neural factors such as a higher active motor threshold, reduced motor evoked potentials, brain plasticity, abnormal excitability of both spinal reflexive and corticospinal pathways, and damaged mechanoreceptors may underpin the prolonged weakness in the knee extensors sometimes observed after ACL reconstruction when using a BPTB graft [47]. Nevertheless, the bulk of existing research [22, 26–28, 30–32] and the novel findings we provided for a professional athlete sample (i.e., international-level, male soccer players) suggest that both graft types are sufficiently and equally effective in restoring knee extensor strength following ACL reconstruction. However, caution should be taken when making comparisons between our findings and those reported previously considering disparities in the timeframe adopted between ACL reconstruction and strength assessment (6 months [31], 9 months [26], 11 months [22], 12 months [32], 28 months [28], 29 months [27], and 36 months [30]) and angular velocities used during isokinetic dynamometry assessments ($60°·s^{-1}$ [27, 28, 30, 32], $90°·s^{-1}$ (17), $120°·s^{-1}$ [26], $180°·s^{-1}$ [22, 31], and $300°·s^{-1}$ [22, 30, 31]). Specifically, longer rehabilitative periods prior to strength assessments may enable patients to better restore muscle strength regardless of the graft type used. Moreover, faster isokinetic angular velocities may produce larger strength deficits in assessments due to the greater recruitment of type II muscle fibres [25], which undergo more pronounced atrophy than type I muscle fibres following ACL reconstruction [48]. The limb symmetry in knee extensor strength observed in our study indicates that 6 months may be a sufficient recovery timeframe following a suitable rehabilitation programme to restore quadriceps strength in international male soccer players irrespective of using BPTB or HT grafts. In this regard, attaining suitable inter-limb knee extensor symmetry is important among soccer players given that this attribute has been shown to distinguish between different playing levels [14] and negatively correlate with change-of-direction and sprint performance [49], which are key movements performed during competition [50].

Like the knee extensors, we observed *moderate–large* improvements in knee flexor peak torque in the injured leg across timepoints; however, knee flexor strength reached an equivalent level to the contralateral leg only in the BPTB group, with a strength deficit of 12% apparent in the injured leg for the HT group at 6 months following ACL reconstruction. Similar to our findings, some researchers have observed greater asymmetries between legs in knee flexor strength among general patients [21], recreationally active patients [22], and non-professional athletes [26, 27] receiving a HT graft compared to a BPTB graft at various timepoints following reconstruction (i.e., 5–24 months) and using varied angular velocities during strength assessments (i.e., $60°·s^{-1}$ – $300\ °·s^{-1}$). Opposite to our findings, some studies have observed comparable knee flexor LSI between HT and BPTB graft types in recreationally active individuals [23], non-athletes [25], non-professional athletes [28], military cadets [30], and participants with varied activity levels [31] at various timepoints following reconstruction (i.e., 5–11 months) and using a range of angular velocities in strength assessments ($60°·s^{-1}$ – $300°·s^{-1}$). However, despite some research showing comparable LSI between graft types following reconstruction (19, 21, 24, 26, 27), none of these studies demonstrated that the patient samples examined had reached the recommended strength recovery level (LSI > 90%) by 6 months with HT grafts during the rehabilitation process. In turn, the deficit in knee flexor strength with HT grafts compared to BPTB grafts consistently reported across various patient samples following ACL reconstruction may be partly attributed to chronic neuromuscular inhibition of the donor muscle [17], the slow regenerative capacity of the semitendinosus and gracilis tendons (up to 12–24 months following surgery) [21, 51], and the slower tendon-to-bone healing process (compared to the bone-to-bone tunnel healing evident in BPTB grafts) [52]. Although an almost acceptable knee flexor strength asymmetry between legs of 12% was reached in the HT group in our study, the apparent differences in strength recovery between graft types emphasize that clinicians should ensure that sufficient attention is devoted to hamstring exercises specifically targeting the semitendinosus and gracilis in players receiving a HT graft.

In addition to LSI, the conventional peak torque H:Q has been widely used to screen individuals at risk of sustaining ACL injuries, whereby decreased hamstring strength relative to the quadriceps has been identified as a potential risk factor for ACL injury in athletes [53]. In this regard, dominance in the quadriceps may increase anterior tibial translation and ACL loading, whereas concomitant hamstring coactivation provides dynamic joint stabilization that protects the knee during sport-related tasks [54]. The mean peak torque H:Q values we observed for both graft types at each timepoint were within the normative range (0.5 to 0.8) reported for professional male soccer players [55]. Also, data collected in our study revealed non-significant differences between timepoints, legs, and graft types. Specifically, non-significant changes in peak torque H:Q from 3 months to 6 months may be explained by the parallel strength improvements across both muscle groups we observed. The parallel improvement in knee flexor and extensor strength across the rehabilitation programme may be especially pronounced given the compromised muscle strength encountered after reconstructive surgery irrespective of the graft type used, which was evidenced by the lower LSI between legs we observed at 3 months compared to 6 months following ACL reconstruction. Considering the compromised muscle strength across both graft types, our results also suggest similar postoperative enhancements in H:Q with both BPTB and HT grafts. Furthermore, the peak torque H:Q did not differ between the injured and contralateral legs for players receiving either graft type, which has been proposed as suitable criteria, alongside adequate LSI values, in clearing players for return to unrestricted play [56].

It is important to acknowledge some key limitations of our study when interpreting the findings. First, isokinetic strength assessments immediately prior to surgery, in the early phase of rehabilitation, and taken across a longer time frame (> 6 months) were not conducted; they would have provided a better understanding concerning the effects of each graft type on knee muscle strength recovery and readiness to return to play among the examined subjects. Second, further functional measurements accompanying the strength assessments were not carried out in our study. In this regard, laxity tests [30], single leg hop tests [56], as well as closed and open kinetic chain rate of force development tests [16, 44] could be considered in conjunction with strength tests to indicate a more complete functional recovery status to support rehabilitative progression and determine readiness to play. Third, although isokinetic strength assessments were performed in a concentric:concentric contraction mode to prevent muscle strains, it should be acknowledged that ACL injuries may occur when the quadriceps are undergoing eccentric contraction in soccer [57], which emphasizes the potential importance of eccentric strength assessments during rehabilitation [58]. Fourth, while players having BPTB and HT grafts were comparable with respect to age, height, body mass, competition level, and pre-injury activity levels, a non-randomized design was adopted in our study.

CONCLUSIONS

Our results demonstrate improvements in isokinetic strength, inter-limb symmetry (knee extensor strength asymmetry: BPTB = 6%, HT = 3%, knee flexor strength asymmetry: BPTB = 0%, HT = 12%) and H:Q values across both graft types when following similar 6-month rehabilitation programmes. Since similar rehabilitation programmes were less effective at restoring knee flexor strength in subjects specifically receiving HT grafts, strength and conditioning professionals working with international male soccer players rehabilitating from ACL reconstruction after receiving a HT graft should pay adequate attention to delivering suitable hamstring exercises ensuring that optimal strength restoration occurs within a suitable timeframe for safe return to unrestricted play. Given that our study provides the first data concerning muscle strength recovery relative to graft type in international male soccer players, the provided data may help inform clinicians working with this population on expected outcomes between 3 and 6 months following ACL reconstruction.

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Ethical approval

All procedures were approved by the Human Research Ethics Committee of the Faculty of Medical Sciences (01-11122) in accordance with the Helsinki Declaration.

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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A new statistical approach to training load and injury risk: separating the acute from the chronic load

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ABSTRACT: The relationship between recent (acute) training load relative to long-term (chronic) training load may be associated with sports injury risk. We explored the potential for modelling acute and chronic loads separately to address current statistical methodology limitations. We also determined whether there was any evidence of an interaction in the association between acute and chronic training loads and injury risk in football. A men's Qatar Stars League football cohort (1 465 players, 1 977 injuries), where training load was defined as the number of minutes of activity, and a Norwegian elite U-19 football cohort (81 players, 60 injuries), where training load was defined as the session rating of perceived exertion (sRPE). Mixed logistic regression was run with training load on the current day (acute load) and cumulative past training load estimated by distributed lag non-linear models (chronic load) as independent variables. Injury was the outcome. An interaction between acute and chronic training load was modelled. In both football populations, we observed that the risk of injury on the current day for different values of acute training load was highest for players with low chronic load, followed by high and then medium chronic load. The slopes varied substantially between different levels of chronic training load, indicating an interaction. Modelling acute and chronic loads separately in regression models is a suitable statistical approach for analysing the association between relative training load and injury risk in injury prevention research. Sports scientists should also consider the potential for interactions between acute and chronic load.

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INTRODUCTION

Researchers attempt to identify risk factors for sports injuries to protect the athletes' health and improve sport performance [1]. One potential, modifiable risk factor is training load. Training load is the mechanical, physiological and psychological load resultant of multiple episodes of physical activity performed by an athlete [2]. Hypotheses suggest that not only high or low training load levels may affect injury risk, but also rapid increases in recent training load relative to training load incurred in the past [3]; i.e. a peak in the relative training load [3].

Hulin, Gabbett [4] introduced the Acute:Chronic Workload Ratio (ACWR) to estimate the effect of relative training load on the risk of sports injury [3, 5]. In their model, the most recent training load, the acute load, is divided by the past, or chronic load. In theory, the higher the ratio – the higher the acute load relative to the chronic – the higher the risk of injury [3]. After ACWR became popular, concerns were raised on its theoretical and methodological foundations [6]. Among others: the number of subjective choices involved increased risk of spurious findings due to multiplicity issues [7], the time lengths for the acute and chronic periods were arbitrary [8], and it could not handle an acute or chronic load of 0 [6].

A core principle in the theory underlying the ACWR is that the effect of the acute load depends on the amount of chronic load. If acute load is high, it may not necessarily increase injury risk if the chronic load is also high. The aim of the ACWR was therefore to adjust the acute load to the chronic load, estimating the effect of acute load properly. This adjustment is not always successful when calculating a ratio [6, 9]. Instead, Wang, Vargas [10] suggested modelling the acute load and the chronic load separately. This eliminates the risk that acute load will not be properly adjusted to the chronic load. At the time of Wang et al.'s proposal, several other challenges remained unsolved, including how to estimate the cumulative effect of past training load, the chronic load. Recent research suggests this may be solved by applying the distributed lag non-linear model [11].

The theory that the effect of acute load depends on the level of chronic load suggests an interaction between acute and chronic loads. Previous descriptive research has studied the association of ACWR with injury for different chronic loads [12, 13], but none have so far modelled an interaction between acute and chronic loads outside of the ACWR framework. Whether an interaction can be assessed while chronic load is modelled by distributed lag non-linear model is also unknown. Distributed lag non-linear models can explore time-lagged effects, but it cannot determine what time period is considered "recent" and "past" in the context of relative training load [11].

We hypothesized that exposure to training affects injury risk on the current day, but the training *stimuli* on the current day does not contribute to injury risk on that day. In contrast, the accumulated stimuli (fitness) built on past training days *does* contribute to injury risk on the current day. In addition, if the athlete does not participate in training on the current day, the athlete is obviously not at risk on that day [14]. We argue that the current day of training is therefore markedly different from past training days, and it may thus be possible to consider the current day only as the acute load, and all past observations as chronic load.

Investigating whether there is evidence of an interaction between acute and chronic loads association with injury risk may elucidate whether such interactions are worth considering in future research, and whether they are possible to model using distributed lag non-linear models.

The primary aim of this statistical methodology study was to demonstrate how modelling acute and chronic training loads separately can be used to describe an association between relative training load and injury risk – meant for use in training load research. A secondary aim was to find out whether acute and chronic loads interact in their association with injury risk in football.

MATERIALS AND METHODS

Participants

We analysed eight competitive seasons (2015–2022) from the men's Qatar Stars League injury surveillance registry in football (1 465 players, 1 977 injuries, Supplemental Table S1), and one season from a Norwegian elite U-19 football cohort (81 players [45% female], 81 injuries) described in Dalen-Lorentsen, Andersen [7].

Ethics

The Anti-Doping Lab Qatar Institutional Review Board approved the Qatar Stars League study (E2017000252). The Aspire Zone Foundation Institutional Review Board approved a data sharing agreement between Aspetar Orthopaedic and Sports Medicine Hospital and Oslo Sports Trauma Research Centre. The Norwegian Center for Research Data (5487), and the South-Eastern Norway Regional Committee for Medical and Health Research Ethics (2017/1015), approved the Norwegian elite U-19 study. Ethical principles were followed in accordance with the Declaration of Helsinki, and informed consent was obtained from all participants.

Training load definition

In the Qatar Stars League data (1 136 223 observations, 12% missing data), training load was defined as the daily number of minutes in activity (football training, other training, and/or match-play).

In the Norwegian elite U-19 data (8 494 observations, 24% missing data), training load was defined as: the daily number of minutes of activity (football training, other training, and/or match-play), multiplied by the player's rating of perceived exertion on a scale from 0 to 10, deriving the session Rating of Perceived Exertion (sRPE) [15].

Missing data were imputed using multiple imputation (Supplemental Figure S1–S2) [16, 17].

Injury definition

Injuries in Qatar Stars League players were recorded prospectively using the Sport Medicine Diagnostic Coding System classification [18, 19]. We recorded all injuries that reduced training or match play participation (time-loss injuries). The player was considered injured until the team medical staff allowed full training and match

TABLE 1. The risk of injury in Qatar Stars League football players estimated by a logistic regression model.

Parameter[1]	OR	SE	95% CI	p
Intercept	0.005	0.0004	0.004–0.006	< 0.001
Acute load	0.995	0.0002	0.994–0.995	< 0.001
Chronic load	1.016	0.0012	1.014–1.019	< 0.001

Abbreviations: CI = Confidence Interval; OR = Odds Ratio; SE = Standard Error
[1] Acute load was defined as the current week of training (sum of minutes in activity), while chronic load was defined as the 3 weeks of training prior to the acute week (exponentially weighted moving average [EWMA] of daily minutes in activity)

participation. We did not record injuries that occurred outside football activities. Quality control was performed to ensure injury validity (Supplementary). Injuries were classified as either sudden or gradual onset.

The Norwegian elite U-19 players reported daily whether they had experienced a new health problem, with Briteback AB online survey platform, Norrköping, Sweden. If they had, a clinician conducted a structured interview and classified the health problem as being an injury or an illness according to the Union of European Football Associations guidelines [20]. Only injuries were analysed in this study. Injury definitions in both populations followed the 2006 consensus statement on epidemiological studies in football [21].

Statistical analysis

Simple model example

To demonstrate how acute and chronic loads can be modelled separately to study the relationship between relative training load and injury risk, we performed a simple statistical analysis on the Qatar Stars League data that mimicked traditional methodological choices in the training load and injury risk field.

We ran a logistic regression with injury yes/no as the outcome. The acute load and chronic loads were two independent variables in the model. Acute load was the sum of the current week of training (minutes in activity). Chronic load was the average daily minutes in activity in the concurrent 3 weeks before the acute load week, calculated with the exponentially weighted moving average [22]. The analysis thus represents the so-called uncoupled 1:3 ACWR, which has been recommended over the coupled ACWR [23]. However, instead of calculating a ratio, the acute and chronic loads were modelled as separate independent variables.

We caution that the assumptions of this simple analysis, such as linearity, are unlikely to be met [24, 25].

Advanced statistical approach

The main analysis of this study was an advanced statistical model run to meet two aims: (i) To demonstrate how to model acute and chronic loads separately in an advanced statistical framework, (ii) To test whether there is an interaction between acute and chronic loads' association with injury risk in football.

To estimate the association of relative training load with the risk of injury, a logistic mixed model was run, with injury yes/no as the outcome. A random intercept per player accounted for the possibility that some players are inherently more likely to suffer injuries than others [26]. We denote the model run on the Qatar Stars League data the Qatari model, and the model run on the Norwegian elite U-19 data the Norwegian model.

The independent variables in the model were the acute and the chronic loads. Choice of acute and chronic time windows should be based on hypothesis/rationale or prior evidence [3, 27]. Given our rationale in the introduction and elaborated upon in the discussion, we considered the acute load to be the current day of training (Day 0). The relationship between the acute load and injury risk might be non-linear [28], and therefore we applied restricted cubic splines with 3 knots [25]. The knot locations were based on the range of the training load observations in the Qatar Stars League data (Qatari model) and the Norwegian elite U-19 data (Norwegian model), respectively; subjectively placed knots have shown improved performance over data-driven placement on skewed training load distributions [25].

Chronic load was the training performed during the previous 27 days, excluding day 0. Day -1 is the day before the current day (yesterday), Day -2 two days before the current day, and so on up to Day -27, which is 27 days before the current day (four weeks ago). We assumed that training load values closer to the current day contribute more to injury risk than those distant in time [22]. We also assumed that the association between training load and injury may be different depending on the time since the activity [3]. For example, if hypothetically, 60 minutes of activity three weeks ago decreases risk of injury, while 60 minutes of activity performed yesterday increases risk of injury, we aimed to be able to detect that difference. Therefore, the cumulative effect of chronic load was modelled with a distributed lag non-linear model [11]. This approach estimates the association between training load and the risk of injury, and simultaneously estimates how the association with training load changes depending on the time since the activity. We chose restricted cubic splines to model the association with training load (3 knots), and also restricted cubic splines to model the association with number of days since the activity was performed (4 knots).

An interaction term was added between the acute load (Day 0) and the chronic load (Day -1 to day -27). The main result was a visualization of the predicted probabilities of injury for acute load given different levels of chronic training load. Reference levels of chronic load was chosen by finding examples of zero, low, medium and high chronic load in the original data (Supplemental Table S2).

Since players are only at risk of injury if they participate in an activity, days in which they did not participate in any training or match were removed from the analysis. These observations were still included in the estimation of chronic load.

To see if a simpler approach than distributed lag non-linear model can be suitable, the analyses were repeated using the exponentially weighted moving average on chronic load [22].

Additional analyses were performed on the Qatar Stars League data. First, the Qatari model was performed on sudden – and gradual-onset injuries, separately [18]. Second, we explored the risk of injury for various levels of minutes in activity sustained in the past, using the distributed lag non-linear model.

Statistical analyses were performed in R (4.2.1) with DLNM [29], mice, lme4, and slider [30]; code available online [31].

RESULTS

Simple model example

In the logistic regression, odds ratios (OR) were estimated for the acute load (0.995) and chronic load (1.016) separately (Table 1).

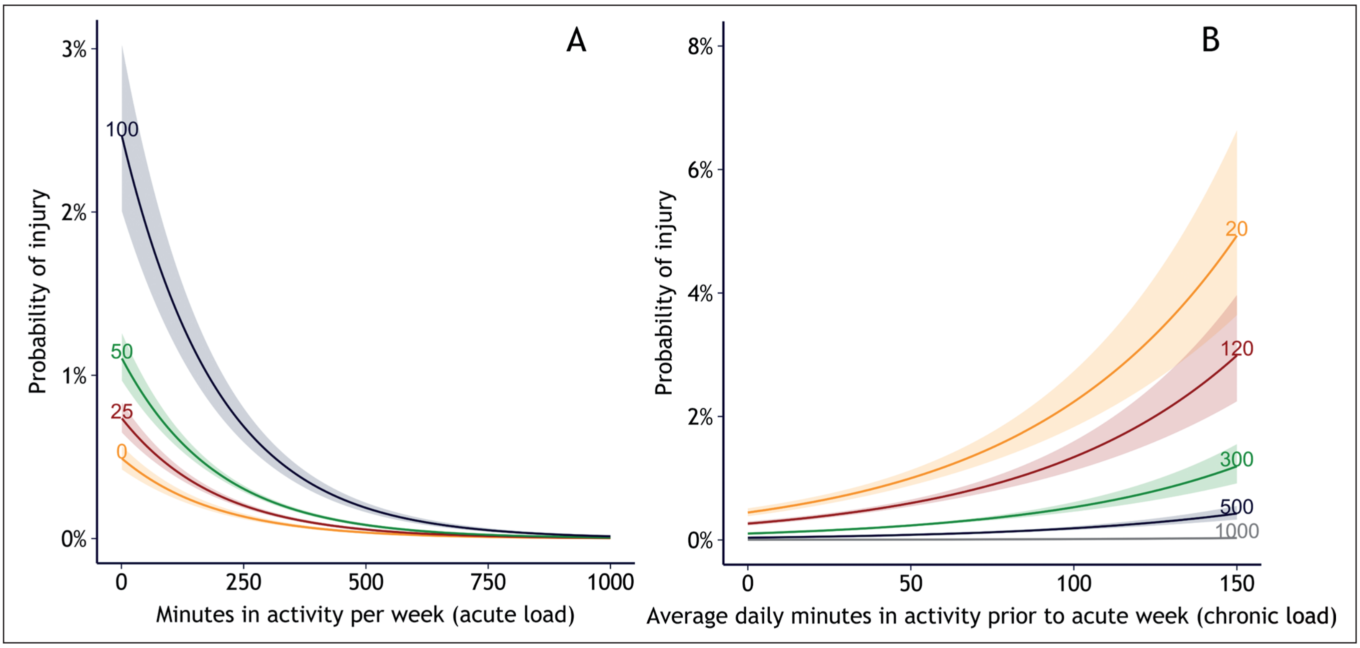

FIG. 1. The probability of injury for each level of (A) acute load and (B) chronic load in Qatar Stars League players (564 206 exposure values, 1 006 injury cases). In (A), the risk is shown for different levels of chronic load: 0, 25, 50, and 100 average minutes in activity the previous 3 weeks. In (B), the risk is shown for different levels of acute load: 20, 120, 300, 500, and 1000 minutes in activity in the current week.

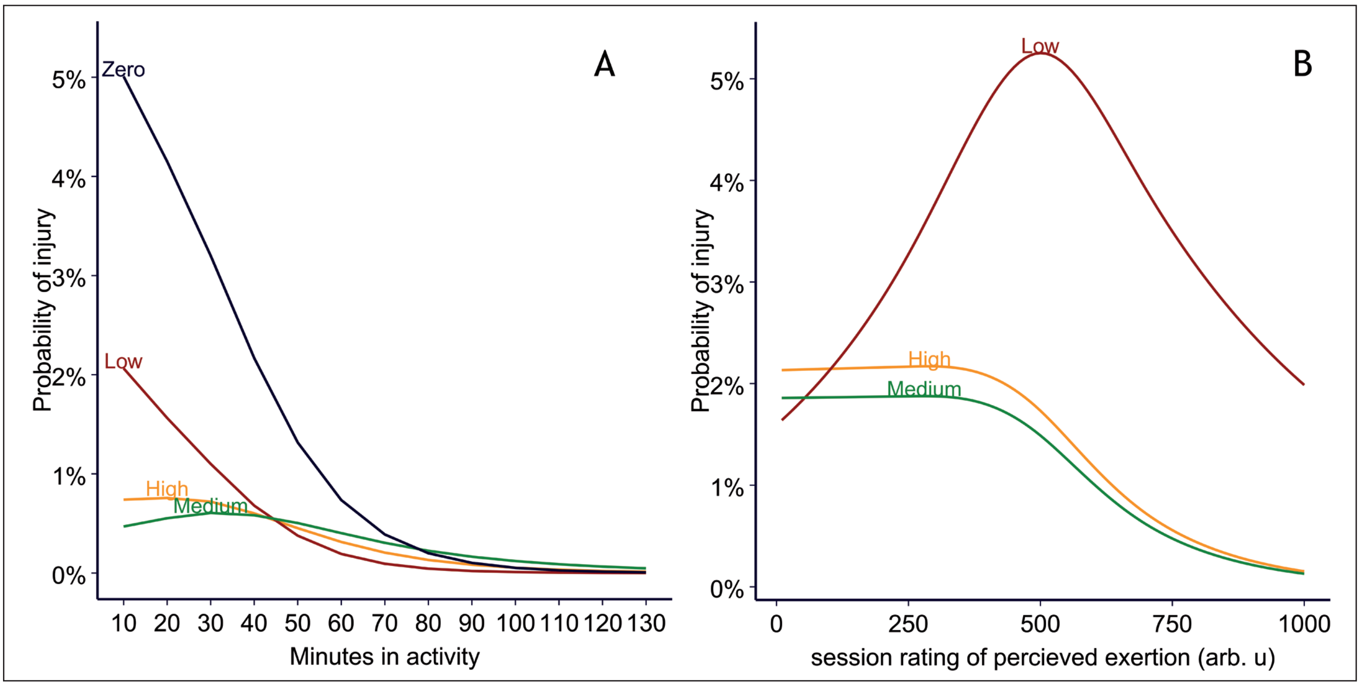

FIG. 2. Estimated probability of injury for each level of acute load (the current day) for (A) Qatari model (420 329 exposure values, 1 977 injuries) and (B) Norwegian model (4 719 exposure values, 60 injuries). The probability is shown for zero, low, medium and high chronic load levels; these are defined in Supplemental Table S1. Due to multicollinearity in the data, confidence intervals could not be estimated. Arb. u = arbitrary units.

This allowed further investigation into the risk of injury for each level of acute load, given the level of chronic load (Figure 1A), and vice versa (Figure 1B). The results showed an increased risk for each decrease in acute load, and increased risk for each increase in chronic load. For example: A player with 20 minutes of training in the current week, who had 150 minutes daily training the previous

TABLE 2. QSL model cofficients for a logistic regression with injury as the outcome and minutes in activity on the current day (acute), and past minutes in activity (chronic) as independent variables.

Term[123]	OR	SE	Lower CI	Upper CI	P
Intercept	0.067	0.329	0.034	0.131	< 0.001
Acute minutes in activity 1	0.950	0.007	0.936	0.964	< 0.001
Acute minutes in activity 2	1.144	0.017	1.105	1.185	< 0.001
Chronic minutes in activity W1 F1	2.166	0.252	1.282	3.659	0.006
Chronic minutes in activity W1 F2	0.455	0.129	0.348	0.595	< 0.001
Chronic minutes in activity W1 F3	1.285	0.110	1.030	1.602	0.027
Chronic minutes in activity W2 F1	0.156	0.374	0.075	0.324	< 0.001
Chronic minutes in activity W2 F2	6.112	0.191	4.207	8.881	< 0.001
Chronic minutes in activity W2 F3	0.841	0.181	0.590	1.200	0.340
Chronic minutes in activity W3 F1	3.252	0.623	0.952	11.109	0.060
Chronic minutes in activity W3 F2	0.578	0.363	0.279	1.198	0.137
Chronic minutes in activity W3 F3	0.673	0.281	0.388	1.168	0.159
Chronic minutes in activity W4 F1	6.432	1.228	0.578	71.55	0.130
Chronic minutes in activity W4 F2	0.319	0.642	0.090	1.126	0.076
Chronic minutes in activity W4 F3	0.404	0.573	0.130	1.256	0.116
Interaction (Acute*Chronic minutes W1 F1)	0.998	0.003	0.991	1.006	0.642
Interaction (Acute*Chronic minutes W1 F2)	1.002	0.002	0.998	1.006	0.429
Interaction (Acute*Chronic minutes W1 F3)	1.000	0.001	0.998	1.003	0.844
Interaction (Acute*Chronic minutes W2 F1)	1.020	0.004	1.012	1.028	< 0.001
Interaction (Acute*Chronic minutes W2 F2)	0.978	0.002	0.974	0.982	< 0.001
Interaction (Acute*Chronic minutes W2 F3)	1.004	0.002	1.001	1.008	0.020
Interaction (Acute*Chronic minutes W3 F1)	0.993	0.006	0.982	1.005	0.243
Interaction (Acute*Chronic minutes W3 F2)	1.010	0.003	1.003	1.017	0.009
Interaction (Acute*Chronic minutes W3 F3)	1.003	0.003	0.997	1.009	0.340
Interaction (Acute*Chronic minutes W4 F1)	0.996	0.009	0.978	1.015	0.678
Interaction (Acute*Chronic minutes W4 F2)	1.005	0.005	0.995	1.015	0.311
Interaction (Acute*Chronic minutes W4 F3)	1.007	0.005	0.997	1.016	0.154

Abbreviations: CI = 95% Confidence Interval, OR = Odds Ratio, QSL = Qatar Stars League, SE = Standard Error

[1] All variables were modelled with splines (420 329 exposure values, 1 977 injuries), and terms represent one of multiple intervals demarcated by knots

[2] The DLNM models a cross-product of the number of minutes in activity (the F-function) and the lag time in which the activity was performed (the W-function). Since F was modelled with 3 knots, and W with 4, the result is a 3*4 permutation of intervals

3 weeks, had 5% increased injury probability, while a player who trained 300 minutes on the current week had 1% increased injury probability, despite having the same amount of chronic load (Figure 1B). This is a common pattern when injured players reduce loads the remaining week, thus have lower loads than uninjured players [32]. Since the ORs were of similar size, this indicates that the acute load (which stretches over just one week) may be more important than the chronic load (which stretches over three weeks).

Association between training load and injury risk

In the main analysis, the acute load was defined as the load on the current day (day 0), and chronic load was defined as the load during the past 27 days (day -1 to day -27). The Qatari model showed decreased probability of injury for each minute in activity on the current day (acute load) with statistical significance ($p < 0.001$, Figure 2, Table 2). This is a typical pattern when players end activity early due to injury. Players who had not participated in an activity in the last 27 days were at highest risk of injury, followed by those who spent a low number of minutes in activity (Figure 2A). Players who spent a high number of minutes in activity were at higher risk than those with medium (Figure 2A). Some relationship slopes were steep, other slopes were gradual, and this variation suggests an interaction between number of minutes in activity on the current day and the minutes in activity the previous 27 days (Figure 2A). All of the 12 interaction terms had narrow confidence intervals (Table 2). This interaction was also present in both sudden onset and gradual onset injuries (Figure S5).

A similar pattern was displayed in the Norwegian model: low chronic sRPE increased risk of injury, followed by high, with the lowest risk at medium levels of chronic sRPE (Figure 2B). Also, like the Qatari model, the Norwegian model exhibited major changes in the slopes between the different levels of chronic sRPE, indicating an interaction (Figure 2B). However, the model failed to estimate coefficients for certain spline intervals on the chronic load (Table S3).

The relationship shape between the training load variables did not change by including random effects (Figure S3), and some of the coefficients were inestimable in the mixed model. Therefore, random effects were not included in the final models.

The additional models, where chronic load was calculated with the exponentially weighted moving average, failed to discover an association between chronic training load and injury risk (Figure S4).

In the additional model exploring how the relationship between training load and injury risk changes with time on the Qatar Stars League data, activities performed on the day before the current day (day -1) contributed most to the risk of injury on the current day (OR = 1.1 for 60 minutes of activity, 95% confidence interval (CI) = 1.05–1.18, Figure 3). The risk declined exponentially the more distant in time the activity was performed, ending at approximately OR = 1.02 (CI = 1.01–1.04) for 60 minutes of activity performed 19 to 22 days prior to the current day. A low number of minutes in activity (10–40 minutes) on a day in the past substantially increased risk of injury for the current day, a high number (90–120 minutes) moderately increased risk, and a medium number (40–80 minutes) slightly increased risk, regardless of whether the activity was performed 1 day prior to the current day, 10 days prior, or 27 days prior (Figure 3B–D).

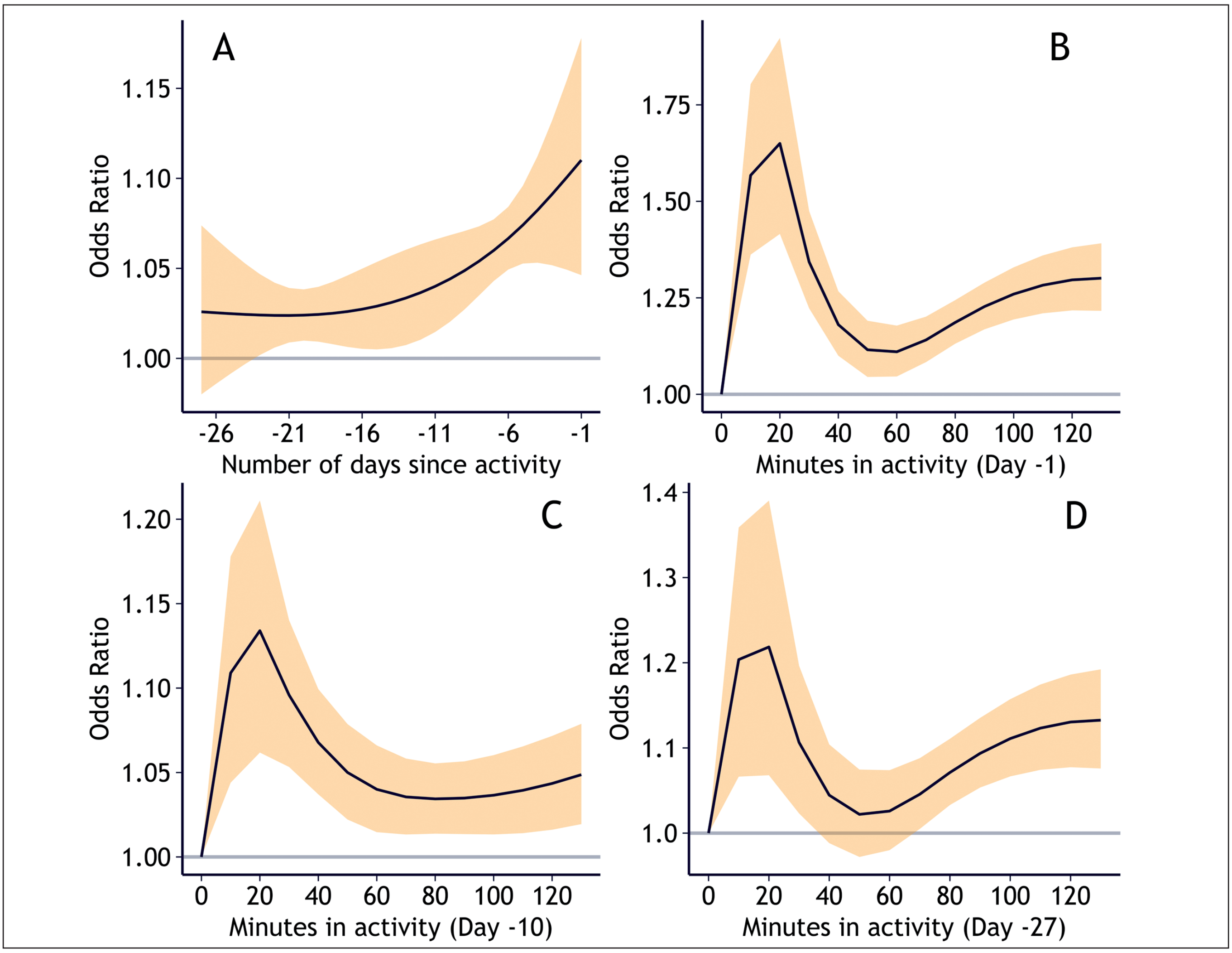

FIG. 3. Injury risk profiles of chronic load in Qatar Stars League players (1 136 223 exposure values, 1 977 injuries). Panel A shows the risk of 60 minutes of activity for each day in the past: -1 is the risk of injury if the activity occurred the day prior to the current day, and -27 is the risk if the activity occurred 27 days before the current day. Panels B, C, and D shows how the risk of injury changes for each level of minutes in activity if the activity occurred (B) 1 day prior to the current day, (C) 10 days prior to the current day, (D) 27 days prior to the current day. Y-axes for B–D are not on the same scale, to better show the relationship shape. Yellow bands represent 95% confidence intervals.

DISCUSSION

This is the first study to explore the potential of modelling acute and chronic training loads separately to estimate the association between relative training load and injury risk in sport. In a simple model example, where traditional definitions of acute and chronic load was used, the new statistical approach provided separate effect estimates for the acute, current week of training (OR = 0.995, 95% CI = 0.994–0.995) and the chronic, previous three weeks of training (OR = 1.016, 95% CI = 1.014–1.019).

In our main analysis, where acute load was defined as the current day and chronic load as the previous 27 days (4 weeks), acute load (minutes in activity) was associated with the probability of injury in Qatar Stars League football (Qatari model). This was properly adjusted for the cumulative association with chronic load. Signs of an association between acute load (sRPE) and injury risk could also be gleaned in a Norwegian elite U-19 football population (Norwegian model), although with high uncertainty due to a small sample size.

We also investigated whether there was an interaction between acute and chronic training loads. Evidence of an interaction was found, as in both the Qatari and the Norwegian models, the relationship slopes for acute training load varied considerably for different levels of chronic training load.

Modelling acute and chronic loads separately

Modelling the acute and chronic load separately successfully estimated the association of acute load adjusted for the levels of chronic load, in both our simple model example and the more advanced statistical model (main analysis). This investigation did not require calculating a ratio, a method that has been severely critiqued [6, 33]. One advantage of modelling acute and chronic separately over the ACWR is that analysts can determine which time period, acute or chronic, is more important concerning injury risk. In addition, while using the ACWR would require choosing among multiple ways of calculation [7], the current approach required few such choices, and reduced the risk of multiple testing issues.

In the main analysis, low chronic training load displayed highest risk, followed by high chronic load, then medium chronic load with the lowest risk, in both the Qatari and Norwegian model. In addition, having zero chronic load the last four weeks (a month without football) showed the highest risk of injury in the Qatari model. Importantly, this could not have been discovered if we had used any form of ratio, as the denominator would be 0 [9].

Association and interaction between acute and chronic loads in football

The Qatari model indicated decreased injury risk for each minute spent in activity on the current day ($p < 0.001$). The Norwegian model displayed a similar trend, although non-significant ($p > 0.05$), and injury risk increased if chronic load (cumulative past sRPE) was low. We suspect that players who ended activity due to an injury skewed the models toward decreased risk with increased exposure to training load. This effect was amplified in the Qatari model, which only included time-loss injuries and time in exposure – no measure of the training intensity. This is a general and – yet – unsolved challenge for studies that aim to estimate the association between training load and injury risk.

Interestingly, the slopes of the association between chronic load and injury risk varied considerably in the Qatari model: High and medium chronic load slowly declined in risk for each level of acute load, while low chronic load declined rapidly (Figure 2A). This interaction was also present when stratified on sudden onset and gradual onset injuries. In the Norwegian model, low chronic load both increased and decreased risk at different levels of acute load (Figure 2B). Therefore, to improve injury prevention research, we would recommend future training load and injury risk studies consider and explicitly model these interactions.

The model that estimated chronic load with the exponentially weighted moving average failed to discover an association between chronic load and injury risk. Given the large sample size of the Qatar Stars League data, we speculate whether this approach could estimate the effects at all, even in a larger study.

The distributed lag non-linear model allowed exploration of time-lagged effects between chronic load and injury risk [11]. In the Qatar Stars League population, the risk of injury declined exponentially for each day further back in time the activity was performed. Furthermore, a low number (10–40) or a high number (80–120) of minutes in activity on a day in the past both increased risk of injury on the current day, while a medium number (40–80 minutes) decreased risk in comparison. This fits the hypotheses that both too much and too little training may increase risk of injury [34].

Background for considering acute load as the current day of training

A consistent challenge with traditional methods of estimating relative training load's effect on injury risk is choosing the time periods for acute and chronic load [8, 35]. Subjectively deducing the cut-off may be arbitrary [35], cut-offs based on previous research may not be sport-specific [6], and data-driven approaches risk multiple testing issues and reduced comparability [32].

We hypothesized that the current day (Day 0) has special properties compared to past days of training load exposure, which allows it to be modelled separately.

On the current day, injury risk increases with sheer exposure to the physical activity itself. Players cannot sustain an injury if they do not participate in an activity [3]. On the other hand, if players did not participate in an activity on certain days in the past, those days would still contribute to the cumulative effect of past training load. Thus, the effect of a training load value of 0 changes drastically if it is on the current day versus past training load days.

Hypotheses suggest that both high and low levels of training load may increase injury risk [34]. Too little training will not build enough fitness for the tissue to tolerate upcoming training load levels. Too much training may potentially damage the tissue, and the tissue may not regenerate in time for the next training or match-play exposure. These hypotheses pertain mostly to past training load. On the current day, the player enters with fitness and fatigue resultant of the past. The adaptations built during the current day of training will not likely come into play until later (that day or during the successive days). The fatigue, will, however affect the current training and day. Hence, the shape of the relationship between training load and injury risk (linear, or various non-linear), may depend on whether the event was in the past, or on the current day.

In a real-time setting, the current and future days of training or match-play load are the most modifiable. One cannot change training load that happened in the past. Team sports coaches develop training schedules for a year, for a month, but most importantly for a week ahead, often according to the match schedule, in so-called training micro-cycles [36]. Weekly risk estimates cannot inform how training load should be distributed on each day within a week or micro-cycle [24], but daily risk estimates can. Studies interested in causal inference and developing load management programs should take this into consideration when choosing time periods for acute and chronic loads.

Future perspectives

In this paper, we have showed the potential of modelling acute and chronic training loads separately. While this study focused on football, we believe the proposed method can handle sport-specific circumstances, such as tapering, and can be considered for both individual and team sports. In addition, although this study only assessed associations, this statistical approach can be used in studies of causal inference or prediction, given that methodological considerations for each of the respective study aims are taken into account [37]. Finally, our simple model example shows that an advanced approach is not needed to model acute and chronic loads separately. It can be used with any choice of time periods for acute and chronic loads, which is particularly relevant for studies that only have access to data at a weekly level.

Distributed lag non-linear modelling is a flexible approach to handling the complexity of chronic load. The R-package was, however, developed in epidemiology, and not yet adapted to interactions. Future research is needed in implementation of distributed lag non-linear models for the context of training load.

Limitations

Limitations of this study were: (i) Due to multicollinearity in our data, confidence intervals around predictions in Figure 2 could not be estimated, (ii) the Qatar Stars League data only had minutes of activity, and no other training load variables or variable describing the intensity of the activity; (iii) the Norwegian elite U-19 data had only sRPE – the player's perception of the training exertion and the duration of the activity. Different groups of players can perceive the same physiological stimuli differently [38]; the Norwegian elite U-19 sRPE responses were above other football populations [39, 40]. In this regard, training load is a multidimensional construct, and ideally, both internal and external training loads should be used [2].

CONCLUSIONS

To assess the association between recent (acute) training load relative to past long-term (chronic) training load on injury risk, a ratio has traditionally been calculated. Ratios have several challenges and cannot handle chronic loads of 0. Modelling the acute and the chronic load separately is intuitive and potentially a simple solution to this problem. When using this statistical approach, the acute load adjusts for the level of chronic load without calculating a ratio. Furthermore, signs of an interaction between acute and chronic training load were present in both football populations studied. Researchers in the field of training load and injury risk should consider interactions in their respective sport to improve injury prevention research.

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Conflict of interest declaration

The authors declare no conflict of interest.

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SUPPLEMENTARY

Injury validation in Qatar Stars League registry

The team physician in each club was in charge of collecting the data, using standardized tools. We distributed a study manual outlining the details of data collection to the contact person before the team's enrollment into the study. We also organized demonstration sessions every time a new team physician joined the program. We recorded data using a custom-made Microsoft Office Excel® file (Microsoft Corporation, Readmon, WA, USA) for quick data entry, using pull-down menus to classify each injury based on the Sport Medicine Diagnostic Coding System. Injury cards were also provided in Microsoft Office Word® (Microsoft Corporation, Readmon, WA, USA) to assist clinicians in taking notes during daily clinical activity, prior to entry into the master data file. We asked the clubs to submit their data every month by email. Data quality control was done on a monthly basis to validate the data.

TABLE S1. Characteristics of 1 465 Qatar Stars League players for the 3 365 studied player' seasons.

Characteristic[1]	Mean (SD)
Age (n = 564)	25 (5)
Height (n = 535)	174 (21)
Weight (n = 548)	71 (16)
Player position (n = 725)[2]	**N (%)**
Defenders	231 (32%)
Goal Keepers	81 (11%)
Midfielders	316 (44%)
Strikers	97 (13%)

[1]Variables had missing data, and descriptives are calculated on observed values (n).
[2]One player could change positions across multiple seasons, and therefore be included multiple times in the calculation.

TABLE S2. Chronic load profiles used as reference values in Figure 1 (main article), Figure S3 and Figure S5, from the day before the current day (-1) to 27 days prior to the current day (-27).

	Qatar Stars League[1]				Norwegian elite U-19[2]		
Day	Zero	Low	Medium[3]	High[4]	Low	Medium[3]	High[4]
-1	0	60	90	45	80	480	720
-2	0	60	27	45	0	0	630
-3	0	60	79	90	0	720	540
-4	0	0	60	80	0	588	1260
-5	0	0	30	80	0	120	0
-6	0	0	63	80	0	0	560
-7	0	0	30	90	0	450	0
-8	0	0	63	140	0	30	0
-9	0	0	60	105	0	0	1230
-10	0	0	11	70	0	540	0
-11	0	0	78	40	0	900	810
-12	0	0	15	15	0	390	0
-13	0	0	77	45	0	90	0
-14	0	0	13	45	0	240	0
-15	0	0	78	90	0	370	320
-16	0	0	75	90	0	30	0
-17	0	0	0	90	0	360	0
-18	0	0	0	90	0	60	0
-19	0	0	70	90	0	0	0
-20	0	0	70	90	0	540	0
-21	0	0	70	45	0	55	630
-22	0	0	26	90	0	0	360
-23	0	0	70	30	0	0	0
-24	0	0	70	45	0	0	960
-25	0	0	70	45	0	30	360
-26	0	0	70	90	0	540	0
-27	0	0	70	45	0	630	420
Total	0	180	1435	1900	80	7163	8800

[1] Measured in minutes in activity
[2] Measured in session Rating of Perceived Exertion (sRPE) in arbitrary units
[3] The total sum was the median in the corresponding dataset
[4] The total sum was the 75% quantile in the corresponding dataset

TABLE S3. Model coefficients for a logistic regression with injury as the outcome and sRPE on the current day (acute), and past sRPE (chronic) as independent variables in the Norwegian elite U-19 data.

Term[123]	OR	SE	Lower CI	Upper CI	p
Intercept	0.035	1.110	0.004	0.308	0.003
Acute sRPE	1.001	0.003	0.996	1.006	0.656
Acute sRPE	0.997	0.002	0.992	1.001	0.177
Chronic sRPE W1 F1	0.111	1.055	0.014	0.883	0.038
Chronic sRPE W1 F2	0.972	0.660	0.266	3.544	0.965
Chronic sRPE W1 F3	2.661	0.638	0.758	9.343	0.126
Chronic sRPE W2 F1	369558.600	4.787	30.843	4.43E+09	0.007
Chronic sRPE W2 F2	0.122	2.538	0.001	17.66	0.407
Chronic sRPE W2 F3	0.230	2.724	0.001	48.581	0.589
Chronic sRPE W3 F1	0.000	15.939	0.000	390.613	0.108
Chronic sRPE W3 F2	13.162	6.383	0.000	3647113	0.686
Chronic sRPE W3 F3	4.529	6.798	0.000	2924533	0.824
Chronic sRPE W4 F1	0.000	33.76	0.000	0.324	0.046
Chronic sRPE W4 F2	22218.120	13.56	0.000	8.02E+15	0.461
Chronic sRPE W4 F3	92.306	15.116	0.000	8.11E+14	0.765
Interaction (Acute*Chronic sRPE W1 F1)	1.005	0.002	1.001	1.009	0.016
Interaction (Acute*Chronic sRPE W1 F2)	1.000	0.001	0.997	1.002	0.866
Interaction (Acute*Chronic sRPE W1 F3)	0.999	0.001	0.996	1.001	0.259
Interaction (Acute*Chronic sRPE W2 F1)	0.971	0.009	0.954	0.988	0.001
Interaction (Acute*Chronic sRPE W2 F2)	1.005	0.005	0.996	1.014	0.310
Interaction (Acute*Chronic sRPE W2 F3)	0.999	0.005	0.990	1.009	0.900
Interaction (Acute*Chronic sRPE W3 F1)	1.056	0.026	1.003	1.111	0.038
Interaction (Acute*Chronic sRPE W3 F2)	0.989	0.014	0.962	1.016	0.418
Interaction (Acute*Chronic sRPE W3 F3)	1.008	0.012	0.984	1.033	0.500
Interaction (Acute*Chronic sRPE W4 F1)	1.161	0.057	1.039	1.298	0.009
Interaction (Acute*Chronic sRPE W4 F2)	0.967	0.030	0.912	1.025	0.262
Interaction (Acute*Chronic sRPE W4 F3)	1.017	0.027	0.964	1.074	0.535

Abbreviations: CI = 95% Confidence Interval, OR = Odds Ratio, SE = Standard Error, sRPE = session Rating of Perceived Exertion in arbitrary units

[1] All variables were modelled with splines, and terms represent one of multiple intervals demarcated by knots

[2] The DLNM models a crossproduct of the number of minutes in activity (the F-function) and the lag time in which the activity was performed (the W-function). Since F was modelled with 3 knots, and W with 4, the result is a 3*4 permutation of intervals

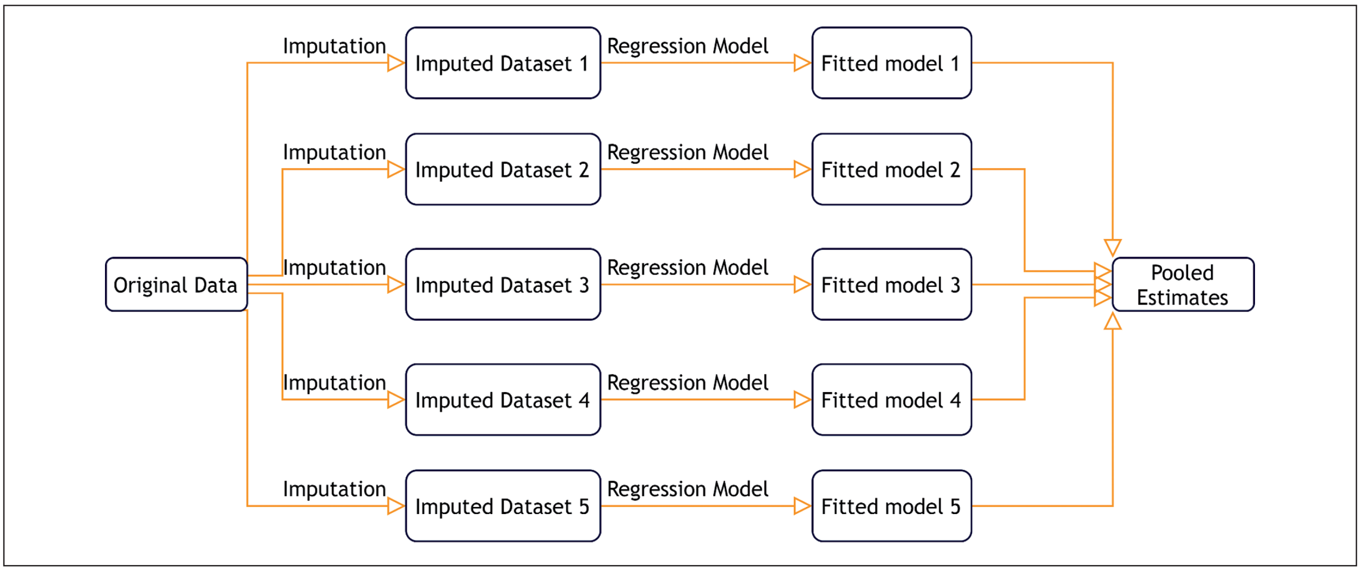

FIG. S1. Illustration of the modelling process in the framework of multiple imputation. The imputation was performed in accordance with recommendations in "Flexible Imputation of Missing Data, Second Edition" by Stef van Buuren (Van Buuren, 2018a), also available online (Van Buuren, 2018b). Missing time in activity in minutes, and sRPE values, were predicted and imputed using predictive mean matching (Barzi & Woodward, 2004), which has previously been shown to be a valid approach for count data (Van Buuren, 2018a). For the minutes in activity, a poisson regression imputation was compared with the PMM with validation plots, before choosing PMM. All non-derived variables were used to predict imputed values, including age, sex, player position, type of training activity, among others. The response variable, injury, was also used to predict imputed values (Moons et al., 2006), but was not itself imputed before analysis (Peters et al., 2012). The number of imputed datasets was five, which is recommended in most cases (Van Buuren section 2.8). The imputation was validated by comparing the distribution of the imputed versus the original data (see Figure S2). Five models were fitted and pooled using Ruben's Rules for the final models (results in Table 1 and Table 2, main article).

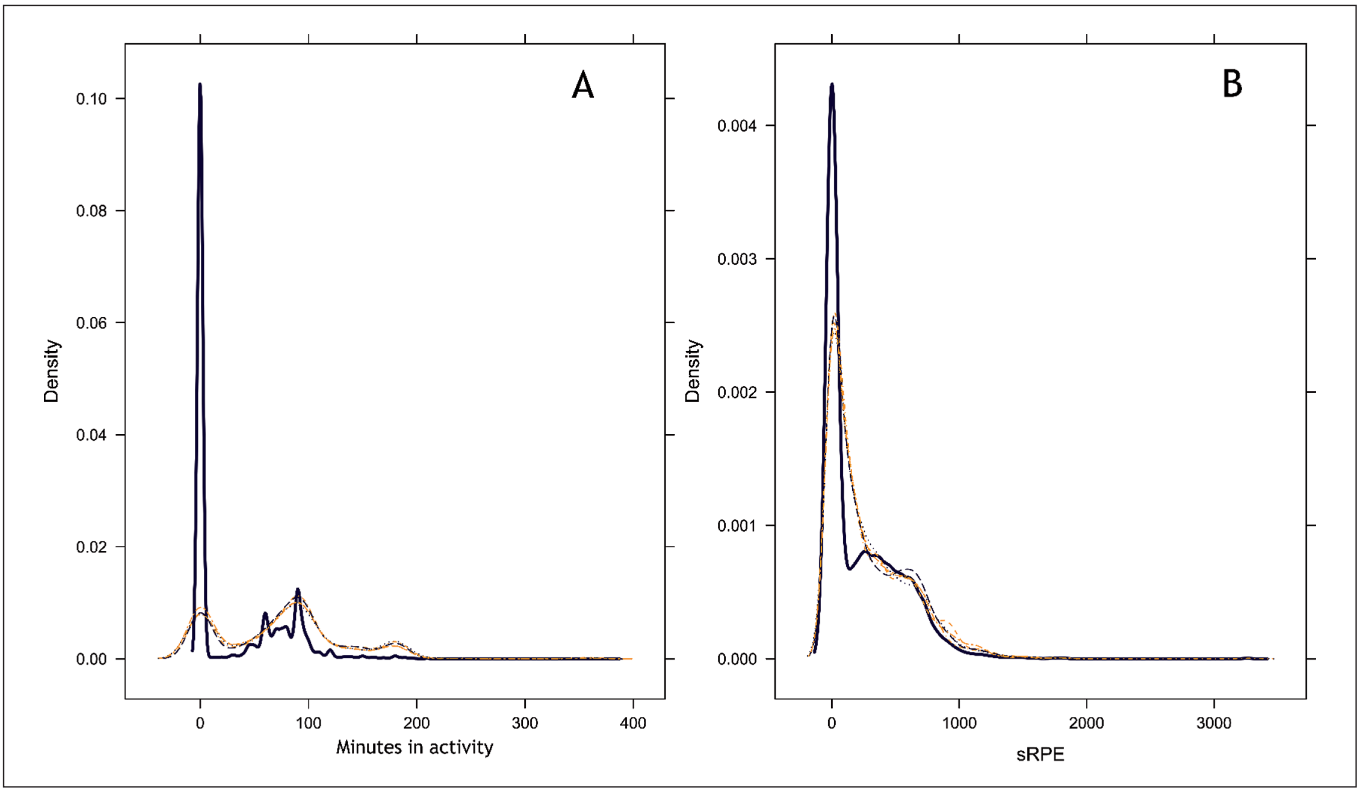

FIG. S2. Distribution of original data values (blue) compared to imputed values from five imputed datasets (yellow) for (A) daily minutes in activity in a Qatar Stars League football population, and (B) daily session Rating of Perceived Exertion (sRPE) measured in arbitrary units in a Norwegian elite U-19 football cohort. The mismatch between the distribution of imputed data and original data in (A) is expected. Although 12% of the Qatar Stars League exposure observations were missing, on days that players suffered an injury, the missing rate was 36%. The missing mechanism was therefore missing at random, and missing probability increased if injury = yes. Since players are unlikely to be injured on days with no activity (exposure = 0), one would expect the imputed distribution to skew less towards 0 than the original data.

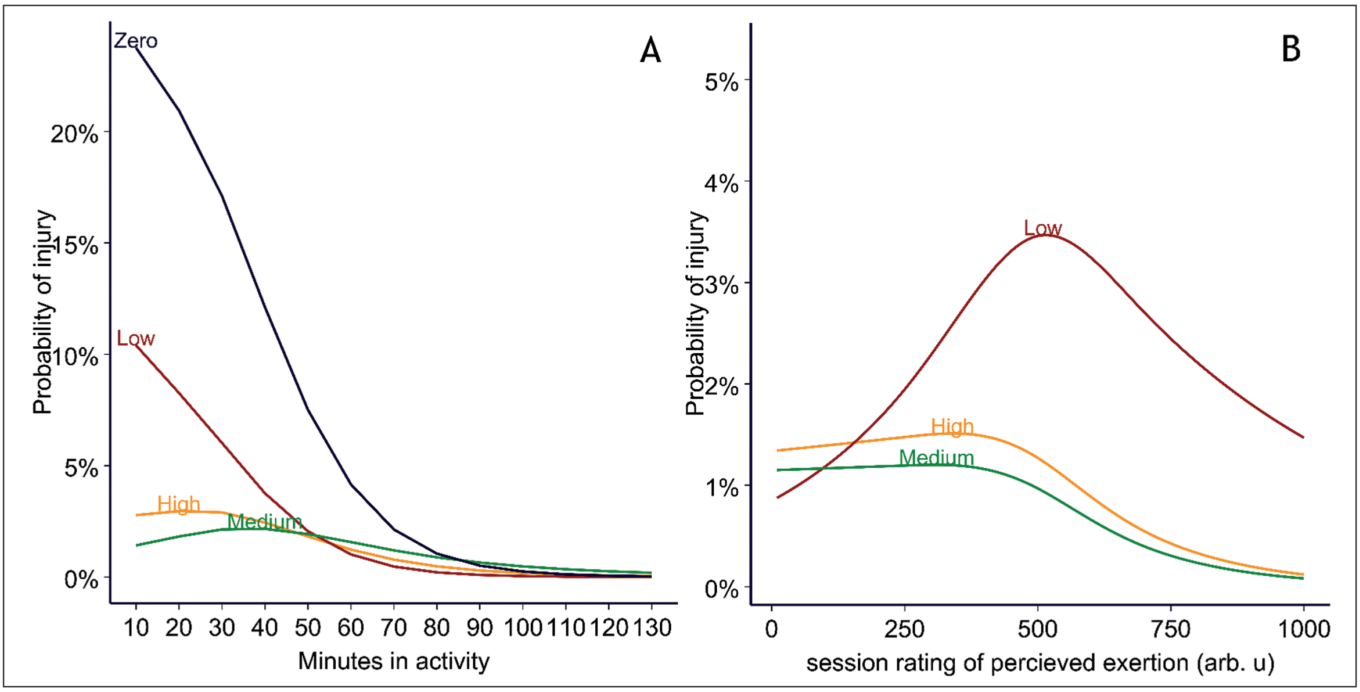

FIG. S3. Probability of injury on the current day (Day 0) predicted by logistic regression models with random effects. Shown for each level of training load variables used in (A) Qatar Stars League model (420 329 exposure values, 1 977 injuries) and (B) Norwegian elite U-19 model (4 719 exposure values, 60 injuries). The probability is shown for zero, low, medium and high cumulative chronic training load levels, as defined in Table S2. Arb. u = arbitrary units.

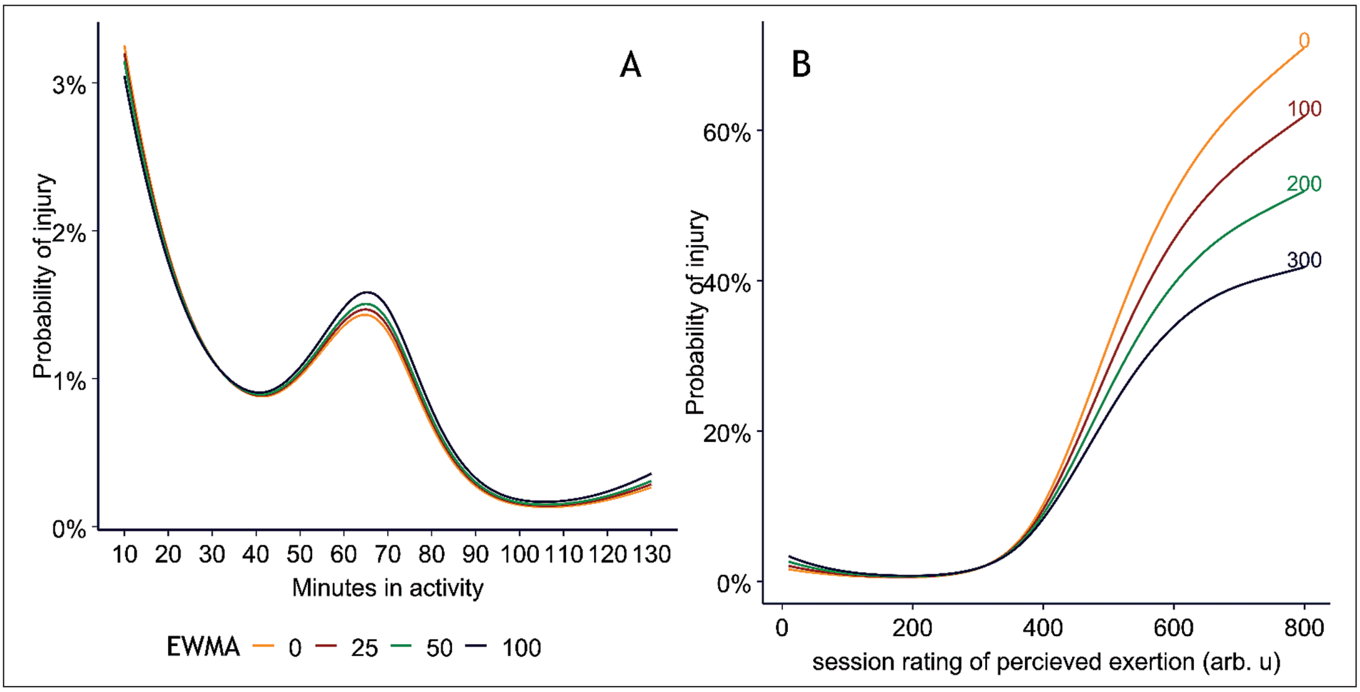

FIG. S4. Probability of injury on the current day (Day 0, acute load) predicted by logistic regression models, using the exponentially weighted moving average to calculate cumulative chronic load. Shown for each level of training load variables used in (A) Qatar Stars League model (420 329 exposure values, 1 977 injuries) and (B) Norwegian elite U-19 model (4 719 exposure values, 60 injuries). The probability is shown for zero, low, medium and high levels of the exponentially weighted moving average. Arb. u = arbitrary units.

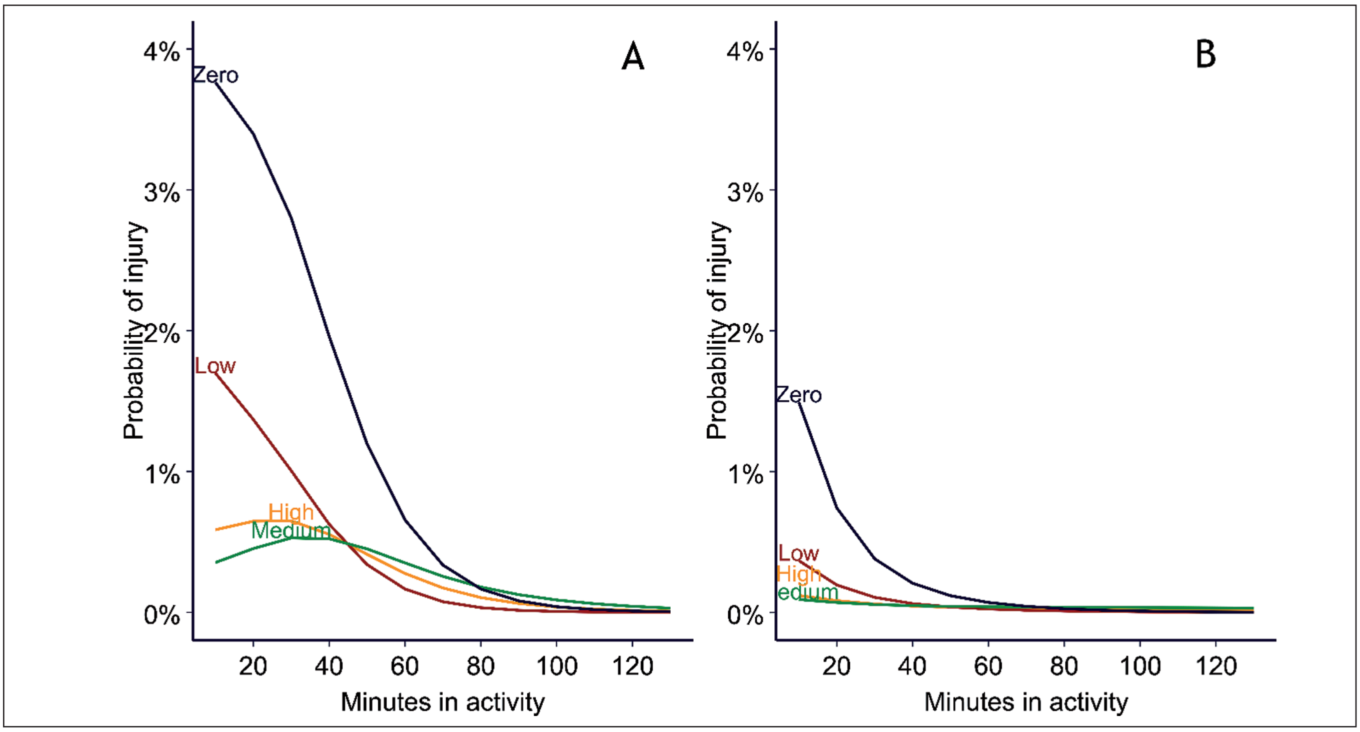

FIG. S5. Probability of injury on the current day (Day 0, acute load) for each minute in activity in the Qatar Stars League population (420 329 exposure values), stratified by (A) sudden onset injuries (n = 1 625) and (B) gradual onset injuries (n = 320). The probability is shown for zero, low, medium and high cumulative chronic minutes in activity. The probability is shown for zero, low, medium and high cumulative chronic training load levels, as defined in Table S2.

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Ages at peak height velocity in male soccer players 11–16 years: relationships with skeletal age and comparisons among longitudinal studies

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ABSTRACT: Estimated ages at take-off (TO) and at peak height velocity (PHV) based on two models and maturity status based upon age at PHV and skeletal age (SA) were compared in a longitudinal sample of male soccer players. In addition, estimated ages at PHV in 13 longitudinal samples of soccer players were compared. The longitudinal height records of 58 players of European ancestry, measured annually on four or five occasions between 11 and 16 years, were modeled with Superimposition by Translation and Rotation (SITAR) and Functional Principal Component Analysis (FPCA) to estimate ages at TO and PHV. SAs were assessed with the Fels method. Ages at PHV in 13 longitudinal samples of soccer players (Europe 7, Japan 6) were evaluated with meta-analysis. Estimated ages at TO, 11.2 ± 0.8 (SITAR) and 11.0 ± 0.8 (FCPA) years, and at PHV, 13.6 ± 0.9 (SITAR) and 13.7 ± 0.0 (FCPA) years, were similar. An earlier age at PHV was associated with advanced skeletal maturity status (rho = -0.77 at ~14 years). Ages at PHV among European players indicated a north (later) – south (earlier) gradient, and were later than ages at PHV among Japanese players. In summary, ages at TO and PHV were similar with SITAR and FPCA, and ages at PHV were most strongly correlated with SA at ~14 years. Mean ages at PHV showed a north-south gradient among European samples, and were later compared to Japanese samples.

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Talent Identification

INTRODUCTION

Acceleration in the rate of growth in height in late childhood/early adolescence marks the onset or take-off (TO) of the adolescent growth spurt. The rate of growth accelerates until it reaches a peak (peak height velocity, PHV) and then decelerates until growth in height ceases in late adolescence or young adulthood. Ages at TO and at PHV and other parameters of the adolescent spurt are estimated from longitudinal height records. Early estimates were based on graphic plots of heights for individuals or on estimated increments in height between measurements. The development of mathematical models for evaluating longitudinal height records subsequently facilitated estimates of the parameters. Most models provide estimates of age at PHV (years), PHV (cm/year) and height at PHV (cm), while some also provide estimates of age, velocity of growth and height at TO, and of adult height [1–5]. Nevertheless, the procedures provide a convenient means for comparing individual and/or group differences in parameters of the adolescent spurt in height [6].

Longitudinal studies of parameters of the growth spurt are largely limited to samples from Europe, North America and Japan, and to a lesser extent Latin America. Estimated ages at PHV among youth from the different regions overlap, although estimates for Japanese youth tend to be somewhat earlier. Recent studies of U.S. youth also indicate overlap in mean ages at PHV among ethnic groups, though estimates for American Black youth tend to be at the early end of the distribution. Corresponding data for youth in other geographic areas are limited [6].

Ages at PHV based on longitudinal samples of youth participating in different sports, in contrast, are not extensive [7, 8]. This is a function of difficulties inherent in longitudinal studies *per se*, and also the selectivity of sport, differential persistence in a sport (drop out) and associated factors, e.g., injury, changing interests, and changes in teams/ clubs, among others. Nevertheless, coaches and trainers are increasingly interested in monitoring growth in heights and weights of youth players over relatively short intervals in an effort to individualize training and to reduce the risk of injury during the adolescent growth spurt [9, 10]. As such, variation in the timing and intensity of growth in height at TO and PHV among youth athletes is important.

In the context of the preceding, the purposes of this study are threefold: first, to compare two methods for estimating parameters of the adolescent growth spurt in a longitudinal sample of male soccer players 11–16 years of age; second, to evaluate maturity classifications based on age at PHV, an indicator of maturity timing, and on skeletal age (SA), an indicator of maturity status at the time of observation; and third, to compare estimated ages at PHV reported for longitudinal samples of soccer players from Europe and Japan.

MATERIALS AND METHODS

Participants

Data for the present study were part of the *Coimbra Soccer Longitudinal Project*, which followed the guidelines established by the declaration of Helsinki [11]. Formal approval was obtained from the *University of Coimbra Sports Sciences and Physical Education Board*, and included agreements with the Presidents of the respective soccer clubs. Written consent was obtained from parents or legal guardians of the players, and players were informed that participation was voluntary and that they could withdraw from the study at any time.

The baseline sample included 87 U13 players 11–12 years of age from five clubs in the midlands of Portugal; the players were classified as *infantiles* in the Portuguese Soccer Federation. All players except one were of European ancestry. At baseline, the sample had 1–6 years of experience in soccer (median 3 years), and participated in 3–5 training sessions (~90 minutes) and one game (usually on Saturday) per week.

Heights and weights, among other anthropometric dimensions, were initially measured within a two week interval in December; players who persisted at the respective clubs were subsequently measured within the same two week interval in December over the next five seasons. All measurements were taken by a single observer (MJCS) at the University of Coimbra. Heights, with shoes removed, were measured to the nearest 0.1 cm using a stadiometer (Harpenden 98.603, Holtain Ltd, Croswell, UK). Weight was measured to the neared 0.1 kg using a SECA scale (model 770, Hanover, MD, US). Intra-observer technical errors of measurement were 0.27 cm for height and 0.47 kg for weight. Chronological age (CA) at each observation was calculated as the difference between date of birth and date of a hand-wrist radiograph (see below) for observations one, three and five, and between date of birth and date of measurement for observations two and four.

Over the five years, 59 players (68% of the baseline sample) had four or five annual height measurements. The longitudinal sample did not differ significantly from their 28 teammates at baseline: respectively, CA, 11.9 ± 0.5 and 11.7 ± 0.5 years; SA, 12.0 ± 1.4 and 11.8 ± 1.6 years; height, 144.8 ± 6.9 and 144.3 ± 6.5 cm; and weight, 37.6 ± 6.0 and 38.8 ± 7.0 kg; the distribution of players by pubic hair status also did not significantly differ.

Parameters of the Adolescent Growth Spurt

The longitudinal height records of 58 players of European ancestry were successfully modeled with two methods to estimate parameters of the adolescent spurt: Superimposition by Translation and Rotation (SITAR) and Functional Principal Component Analysis (FPCA). The heights of one player of non-European ancestry limited to four observations were not successfully modeled.

The SITAR model [12, 13] available in the R package *sitar* [14] fits the raw height data for all players with a curve (defined as a B-spline), superposes the curves of all players, averages the curves and then back-projects the average curve into the original data as a growth model through uniform transformations: translation and rotation. A total of 269 measurements were available for the 58 players. Visual inspection of the model based on running plots with the raw data showed that the model fit the data very well. The mean residual was 0.0 cm by definition; the standard deviation of the residuals was 0.47 cm and the mean absolute value of the residuals was 0.36 cm.

The FPCA growth model [15] is based on a combination of general Functional Data Analysis (FDA) and FCPA [16, 17]. The complete postnatal growth curves of individual boys in the Brno Growth Study were the training set, which was fitted by the B-spline curves of the raw data for all soccer players. The splines were modeled with the FPCA procedure; 12 Principal Components (6 for phase and 6 for amplitude of the curves) were then used as a generative model to fit the newly analyzed data based on the Levenberg-Marquardt optimization algorithm. Details of the specific calculations and functions of the model are available in the R package *growthfd* [15, 18]. The mean of the 269 model residuals was 0.04 cm and the standard deviation of the residuals was 0.44 cm; the mean absolute value of the residuals was 0.33 cm.

The accuracy of estimates of parameters of the adolescent spurt in height depends on the model. Models differ significantly in the shape of the curve between points and in the extent to which they take into account information about the actual course of human growth, i.e., whether they are more 'mathematical' or more 'empirical'. The present study computed estimates using two models that account for data of this nature. Both the SITAR and FCPA methods provided estimates of age, velocity of growth and height at TO and at PHV for each player.

Estimates of age at PHV based on one of the protocols (SITAR) in the present analysis were previously used in a study evaluating the validity of predicted ages at PHV among the soccer players [19]. The present study compares parameters of the growth spurt based on two different models, SITAR and FCPA. Of note, heights of one player in the earlier analysis were not successfully modeled with the two protocols used in the present study.

Skeletal Age

Posterior-anterior radiographs of the left hand-wrist of players were taken at observations one, three and five. The Fels method [20] method was used to estimate SA. The mean difference between independent assessments of SAs of 20 radiographs by two individuals and the inter-observer technical error of measurement were, respectively, 0.03 ± 0.04 years and 0.12 years, while the inter-observer intra-class correlation was 0.99. Standard errors for SA assessments at observations one, three and five ranged, respectively, from 0.27 to 0.30 year (median 0.29), from 0.29 to 0.49 year (median 0.35), and from 0.30 to 0.48 (median 0.37) year.

Analysis

Descriptive statistics (means and standard deviations) at each observation for the longitudinal sample were calculated for CA, height and weight, for SA and SA minus CA at the three observations, and for estimated ages at TO and PHV (years), velocities of growth at TO and at PHV (cm/year), and heights at TO and at PHV (cm) based on the SITAR and FPCA methods. The differences between parameters of the growth spurt with the two methods were evaluated with paired sample t-tests and tests of equivalence using 90% equivalence boundaries representative of a moderate effect ($\pm$ 0.5 of Cohen's d). Spearman rank order correlations (rho) between ages at PHV based on the SITAR and FCPA models and the differences of ages at PHV based on the respective models were calculated.

Each player was also classified as late (delayed), on time (average) or early (advanced) maturing based on ages at PHV with the two models and also on SAs at observations one, three and five. A band of plus/minus one standard deviation of the respective mean ages at PHV for the total sample defined on time or average maturity status. Estimates ages at PHV outside the range of plus/minus one standard deviation were classified as either late (age at PHV above one standard deviation of the respective mean ages) or early (age at PHV less than one standard deviation of the respective mean ages). Similarly, an SA within $\pm$ 1.0 year of CA defined average skeletal maturity status, while an SA younger than CA by > 1.0 year and an SA older than CA by > 1.0 year defined, respectively, late (delayed) and early (advanced) skeletal maturity status. The range of $\pm$ 1.0 year allows for error associated with assessments of SA and approximates standard deviations for SAs within specific CA groups [21]. Four players were skeletally mature at observation five and an SA was not assigned. At observation five, 42 players had radiographs, but three did not have height and weight measures; of the 40 players with measures of height and weight, one did not have a radiograph.

Means and standard deviations were calculated for ages at PHV for players in each of the maturity groups defined by the SITAR and FCPA methods, and also for SA-CA differences in the respective skeletal maturity status groups at observations one, three and five. Concordance of maturity status classifications based on the two estimates of age at PHV and on skeletal maturity status at the three observations was evaluated with chi square and unweighted Cohen's Kappa coefficients.

In addition to estimated ages at PHV for the present sample of Portuguese players, ages at PHV for 12 longitudinal samples of soccer players from Europe and Japan were compiled from the literature [6]: six samples from Europe: Wales [22], Denmark [23], Belgium [24], Spain [25–27], England [28] and the Netherlands [29], and six samples from central Japan [30–34]. Estimates of age at PHV were based on a variety of methods, and several studies including the present study reported estimated ages at PHV based on two or three methods. Three studies provided estimates for subsamples of Spanish players from the same club. Excluding estimates based on graphic and incremental methods [22, 28] and the FPCA method (present study), and limiting the estimate for Spanish players to that based on the largest sample [27], ages at PHV in the 13 samples of soccer players from Europe and Japan were subjected to a meta-analysis using the methods available in the R-Package *metaphor* [35] within the R-software, version 3.5.3 [14]. Sample sizes, means and standard deviations for age at APHV in each of the 13 studies were used as estimates of effect size. The Random Effect Model was used as it can be reasonably assumed that the population with the same grand mean age at PHV was not sampled in the studies of soccer players (i.e., the populations actually differed in ages at PHV). The restricted maximum likelihood method (REML estimator) was used to estimate the between-sample variance (τ^2, tau-squared).

RESULTS

Descriptive statistics for CA, height and weight at each observation and for SA at observations one, three and five in the longitudinal sample of soccer players are summarized in Table 1. Corresponding statistics for parameters of TO and PHV, and results of t-tests and Cohen's d are summarized in Table 2. Although quite similar, mean ages at TO, SITAR 11.2 ± 0.8 years and FPCA 11.0 ± 0.8 years, and mean ages at PHV, SITAR 13.6 ± 0.9 years and FCPA 13.7 ± 0.9 years, differ significantly. Estimated heights at TO, SITAR 141.1 ± 5.7 cm and FCPA 140.2 ± 6.0 cm, and at PHV, SITAR 157.1 ± 5.7 cm and FCPA 157.9 ± 5.6 cm, also differ significantly. In contrast, estimated velocities of growth in height at TO, SITAR 4.6 ± 0.5 cm/year and FCPA 4.6 ± 0.4 cm/year, and at PHV, SITAR 9.7 ± 1.3 cm/year and FCPA 9.8 ± 1.3 cm/year, do not differ significantly.

Estimated ages and heights at PHV with the two methods are highly correlated, 0.99 and 0.98 ($p < 0.001$), respectively, while the

TABLE 1. Means (M) and standard deviations (SD) for chronological age (CA), skeletal age (SA), height and weight for the longitudinal sample of soccer players by observation (Obs).

Obs	N	CA, yrs		SA, yrs		Height, cm		Weight, kg	
		M	SD	M	SD	M	SD	M	SD
1	58	11.9	0.5	12.0	1.4	144.9	6.9	37.6	6.0
2	58	12.9	0.5			151.7	7.9	42.3	7.3
3	58	13.9	0.5	14.2	1.1	159.2	7.7	48.7	8.4
4	55	14.9	0.5			165.5	6.7	54.9	7.9
5[a]	40	15.9	0.5			169.3	5.3	60.1	6.3
5[b]	35	15.8	0.5	16.3	1.1	169.2	5.4	59.7	6.2
5[c]	4	16.8	0.2			171.5	5.0	64.9	6.1

[a]Total sample of players with measures of height and weight at observation five; one player did not have a radiograph; [b]Not skeletally mature; [c]Skeletally mature

TABLE 2. Means (M) and standard deviations (SD) for estimated parameters at take-off (TO) and at peak height velocity (PHV) based on the SITAR and FPCA methods, differences between the respective estimates (SITAR minus FPCA) with the two methods, and results of the t-tests.

Parameters	SITAR			FPCA			SITAR – FPCA			
	M	SD	Range	M	SD	Range	M	SD	t	Cohen's d
Age at TO, yrs	11.24	0.79	9.94–13.00	10.99	0.82	8.55–12.81	0.25	0.70	2.73**	0.36
TO, cm/yr	4.62	0.52	3.37–6.06	4.58	0.36	3.85–5.67	0.03	0.47	0.56	0.07
Height at TO, cm	141.1	5.7	130.0–153.8	140.2	6.0	125.0–153.0	0.90	3.32	2.06*	0.27
Age at PHV, yrs	13.62	0.90	11.92–15.59	13.66	0.88	11.90–15.49	-0.04	0.12	2.60**	0.34
PHV, cm/yr	9.71	1.26	6.69–13.56	9.81	1.33	6.97–14.53	-0.10	0.87	3.80**	0.50
Height at PHV, cm	157.1	5.7	145.9–169.7	157.9	5.6	147.7–170.1	-0.51	1.02	0.84	0.11

*p < 0.05, **p < 0.01

TABLE 3. Frequencies and cross-tabulations of maturity status classifications (late, on time, early)1 based on ages at PHV with the SITAR and FPCA models, percentage agreement, Chi square (X^2) and Cohen's Kappa (κ); means and standard deviations for ages at PHV in the respective maturity groups are also indicated.

Age at PHV: FPCA, yrs		Age at PHV: SITAR, yrs			Total
		Late	On time	Early	
		14.92 ± 0.35	13.54 ± 0.53	12.37 ± 0.20	
Late	14.98 ± 0.27	**8**	1	0	9
On Time	13.69 ± 0.52	3	**36**	0	39
Early	12.36 ± 0.26	0	2	**8**	10
	Total	11	39	8	58
		Agreement 90% c^2 = 77.29* κ = 0.79*			

* (p < 0.01); [1]On time (average) is an age at PHV within ± 1.0 year of the mean age at PHV for the total sample of 58 players with SITAR (13.62 ± 0.90 years): average, 12.72 to 14.52 years; late, > 14.52 years; and early, < 12.72 years; and with FPCA (13.66 ± 0.88 years): average, 12.78 to 14.54 years; late, > 14.54 years; and early, < 12.78 years.

correlation for estimated PHVs with the two methods is slightly lower, 0.77 ($p < 0.001$). Correlations between estimated ages and heights at TO with the two methods, though lower, are significant, 0.62 and 0.84 ($p < 0.001$), while the correlation between estimated velocities of growth at TO with the two methods is lower 0.48 ($p < 0.001$).

The cross-tabulation of maturity classifications based on ages at PHV with each method is shown in Table 3. Overall, 90% of the players are classified as having the same maturity status based on SITAR and FCPA ages at PHV. Four of the six misclassified players have estimated ages at PHV close to the ± 1.0 cut-offs; the differences in ages at PHV (SITAR minus FPCA) are negligible, 0.08, 0.07, 0.05 and 0.08 year. The differences between ages at PHV for two players are somewhat larger, 0.35 and -0.35 year.

Spearman correlations (rho) between maturity classifications based on the differences of SA minus CA and on age at PHV are moderate in early adolescence (~12 years, observation one), -0.53 (SITAR, $p < 0.01$) and -0.54 (FPCA, $p < 0.001$), and higher in mid-adolescence (~14 years, observation three), -0.77 with both methods ($p < 0.001$). The negative correlations indicate an earlier age at PHV among players with an SA in advance of CA (positive difference of SA minus CA).

Cross tabulations of maturity classifications (late, average or early) based on ages at PHV with SITAR and FPCA and on the difference of SA minus CA at observations one, three and five are summarized in Table 4. Maturity classifications based on ages at PHV and SA at observation one (~12 years) and three (~14 years) are concordant in, respectively, 59% and 71% of players for SITAR and in 62% and 74% of players for FPCA estimates. Kappa coefficients are relatively low at observation one, but moderate at observation three. Allowing for small numbers at observation five (~16 years), maturity classifications are concordant in 57% (SITAR) and 60% (FPCA) of the players, and the Kappa coefficient is moderate. Among the four skeletally mature players at observation five, two are classified as on time and two as early maturing based on ages at PHV. Mean ages at PHV for the four skeletally mature players are similar with SITAR (12.57 ± 0.38 years) and FPCA (12.65 ± 0.37 years), and are

TABLE 4. Frequencies and cross-tabulations of maturity status classifications based on ages at PHV with the SITAR and FPCA models and on Fels skeletal ages (SA – CA) at observations 1, 3 and 5, and percentage agreement, Chi square (c^2) and Cohen's Kappa (κ), and means and standard deviations for SA – CA differences in the respective maturity groups are also indicated.

Skeletal Maturity Groups	Skeletal Age[2]	Maturity Groups							
		Age at PHV SITAR[1]				Age at PHV FPCA[1]			
		Late	On time	Early	Total	Late	On time	Early	Total
Observation 1									
Late	(-1.98 ± 0.98 yrs)	**3**	6	0	9	**3**	6	0	9
On Time	(-0.02 ± 0.59 yrs)	6	**25**	2	33	4	**26**	3	33
Early	(1.76 ± 0.62 yrs)	2	8	**6**	16	2	7	**7**	16
Total	(0.16 ± 1.38 yrs)	11	39	8	58	9	39	10	58
		Agreement 59%, c^2 = 11.60**, κ = 0.25*				Agreement 62%, c^2 = 13.49**, κ = 0.31*			
Observation 3									
Late	(-1.48 ± 0.33 yrs)	**5**	3	0	8	**4**	4	0	8
On Time	(0.18 ± 0.46 yrs)	5	**29**	1	35	4	**30**	1	35
Early	(1.66 ± 0.54 yrs)	1	7	**7**	15	1	5	**9**	15
Total	(0.33 ± 1.07 yrs)	11	39	8	58	9	39	10	58
		Agreement 71%, c^2 = 28.75*, κ = 0.45*				Agreement 74%, c^2 = 33.45**, κ = 0.51*			
Observation 5									
Late	(-1.76 ± 0.38 yrs)	**5**	0	0	5	**3**	2	0	5
On Time	(0.00 ± 0.72 yrs)	2	**14**	0	16	1	**15**	0	16
Early	(1.71 ± 0.41 yrs)	0	12	**5**	17	0	10	**7**	17
Mature		0	2	2	4	0	2	2	4
Total	(0.53 ± 1.33 yrs)	7	28	7	42	4	29	9	42
		Agreement 57%, c^2 = 36.90*, κ = 0.45*				Agreement 60%, c^2 = 27.17*, κ = 0.37*			

*($p < 0.01$); [1]See Table 3 for ages at PHV in the respective maturity groups; [2]On time – SA within ± 1.0 year of CA; late – SA behind CA by > 1.0 year; early – SA advance of CA by > 1.0 year

TABLE 5. Ages at PHV (years) and PHV (cm/year) in 13 longitudinal samples of male soccer players in Europe (including the present study) and Japan.

	Competitive	APHV yrs	PHV cm/yr							
Country	**Study**	**Method***	**Level**	**Observations (obs)**	**N**	**M**	**SD**	**Range, yrs**	**M**	**SD**
				EUROPE						
Portugal	Present study	Sitar FPCA	prof club	11–12/15–16 yrs, 4–5 annual obs, 2003–2008	58 58	13.6 13.7	0.9 0.9	11.9–15.6 11.9–15.5	9.7 9.8	1.3 1.3
Wales	Bell [22]	Graphic Moving incr Polynomials	school	12–15 yrs, 4 annual obs, 1981–1984	32	14.2 14.1 14.2	0.8 0.8 0.9		9.6 9.3 9.5	1.8 1.5 1.5
Denmark	Froberg et al. [23]	PB 1	local club	11–16 yrs, semi-annual obs over 6 yrs, 1980s	8	14.2	0.9	12.6–15.7		
Belgium	Philippaerts et al. [24]	Polynomials	prof club	10–13/14–17yrs, annual obs 1996–2000	33	13.8	0.8	12.3–15.9		
Spain (same club)	Carvalho et al. [25]	Polynomials	prof club	10–16 yrs, 4 obs 2009–2014	33	12.9		11.8–15.5†	8.1	
	Monasterio et al. [26, 27]	Sitar	prof club	10–11 yrs-16–18 yrs, > 10 obs, 2000–2020	110 124	13.4 13.5	0.8 0.9		9.9 10.1	1.8 2.0
England	Parr et al. [28]	Sitar Graphic	prof club	5 seasons 12.4 ± 0.6 yrs baseline, 17–20 obs, 2013–2017	27 27	14.1 14.2	0.8 0.8	12.6–15.5	9.8	
Netherlands	Teunissen et al. [29]	PB 1	prof club	4 seasons 11.9 ± 0.8 yrs baseline, 16–25 obs, 2008–2012	17	13.8	0.7	12.6–15.2		
				JAPAN						
Fukui Prefecture	Nariyama et al. [30]	PB 1	school	school records, 1970–1987, 6–18 yrs	83	13.7	1.1		8.8	1.1
Saitama	Saeki et al. [31]	Auxal	school	school records 7–12 yrs + obs JHS	88	13.3	0.9			
Tokyo	Takei et al. [32]	Auxal	rec league	school records + 6 obs over 2 yrs 2011–2016	201	13.4	0.9			
Shizouka	Chuman et al. [23]	Triple logistic	prof club	school record: sub-elite 7–12yrs, club elite obs at 13 yrs	48 16	12.9 12.6	0.9 1.0			
Shizouka	Chuman et al. [34]	Triple logistic	prof club	school records, club 6 obs, 7–15 yrs, 2008–2010	29	12.9	1.0			

* Methods: Moving inc (moving increments), PB 1 (Preece Baines model 1), Auxal (refers to the software package used; the authors do not specify which of the three models implemented in the Auxal program was specifically used to estimate ages at PHV); †estimated 95% credible interval; prof club (professional club level); rec league (recreational league)

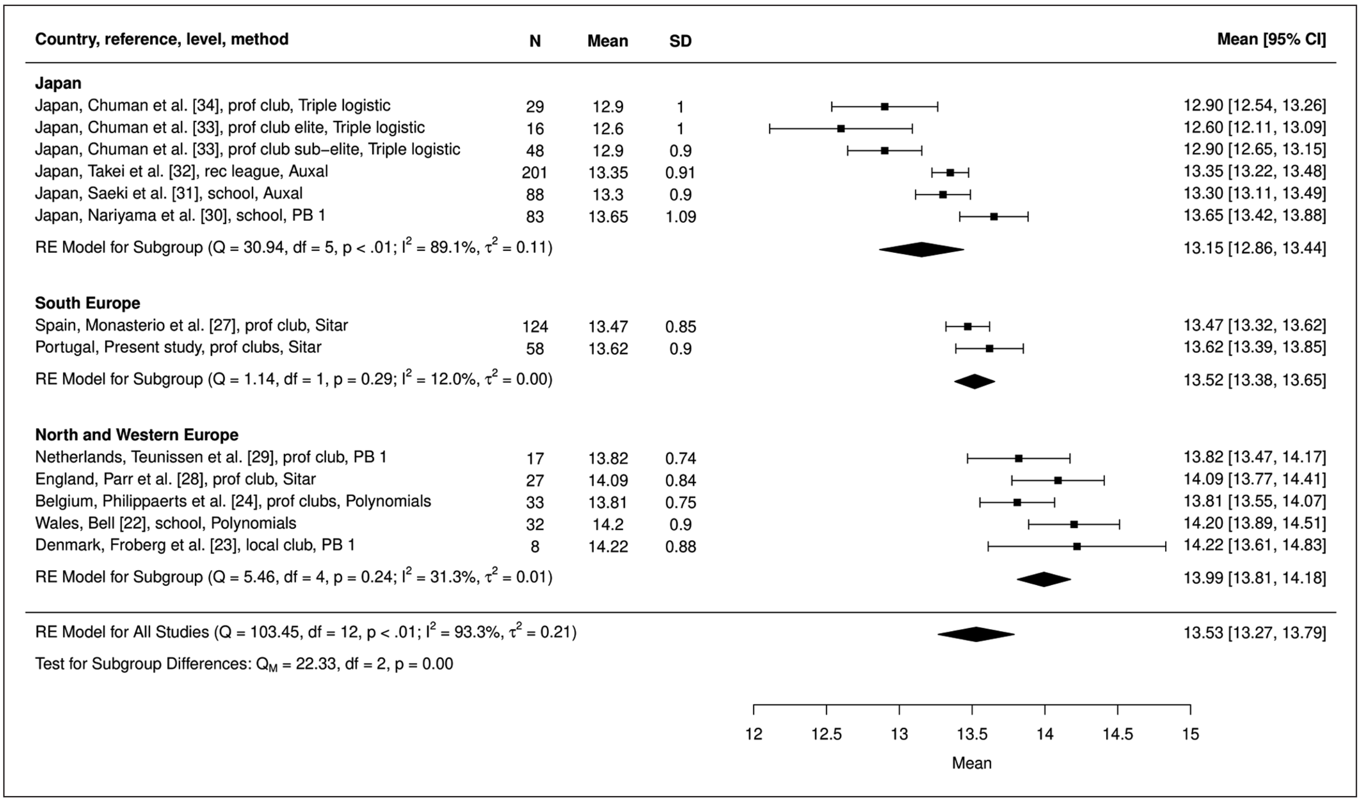

FIG. 1. Aggregation of ages of PHV (years) in samples of male soccer players based on meta-analysis, including the subgroup analysis. Q: Cochran's Q-statistic (weighted sum of squares), QM: Cochran's Q-statistic for subgroups, I^2: percentage of variability in effect sizes which is not due sampling error, τ2: between-study variance in a given set of samples (years squared); plots: means and 95% CIs of individual studies; diamonds: width represents 95% CI for each model aggregated by subsample and for all studies (below).

earlier than mean ages at PHV among non-skeletally mature early maturing CA peers, SITAR (12.90 ± 0.65 years) and FPCA (12.94 ± 0.66 years), respectively.

Ages at PHV of soccer players in the 13 longitudinal series are summarized in Table 5. Mean ages at PHV based on different methods of estimation within several samples are not different. The mean ages at PHV for Portuguese soccer players based on SITAR and FPCA are within the range of mean ages at PHV in the six longitudinal samples of soccer players in Europe, 12.9 to 14.2 years. The earliest estimated mean age at PHV, 12.9 years (standard deviation not reported), based on a two-level polynomial method, is for a sample of 33 Spanish players [25]; estimates based on the SITAR model for larger samples from the same club (n = 110 and 124) are later, 13.4 ± 0.8 years [26] and 13.5 ± 0.9 years [27], respectively.

Estimated mean ages at PHV for players from professional clubs in Europe are somewhat earlier than those for players from a school and local club (Table 5). With the exception of the one subsample of players in Spain [25], means ages at PHV for club soccer players in Europe tend to be later than estimates for players at a professional club in Japan, 12.6 to 12.9 years, which are earlier than estimates for school and recreational league players in Japan.

Results of the meta-analysis of ages at PHV in the 13 samples of soccer players from Europe and Japan indicate significant heterogeneity (Q [df, 12]) = 103.45, $p < 0.001$), while I^2 for the model of all studies is relatively high (93.3%). The effect of geographic location (Japan and Southern, Northern and Western Europe) as a moderator of age at PHV was then evaluated. The Mixed Effect Model indicates a statistically significant moderator effect (Q_M [df, 2] = 22.33, $p < 0.001$); ages at PHV differ significantly among the geographic groups (Figure 1). Age at PHV is latest for players from Northern and Western Europe, earlier for players from Southern Europe, and earliest for players from Japan. Heterogeneity among samples in Northern and Western Europe (professional and local clubs and schools combined) is not significant (Q [df, 4] = 5.46, p = 0.243), while heterogeneity among the samples of professional clubs in Europe (Southern, Northern and Western Europe together) is significant (Q [df, 4] = 15.4260, p = 0.004). By inference, geographic distribution appears to be a more significant factor than level of competition, though the relatively small sample sizes in Northern and Western Europe may have reduced the statistical significance of differences among samples.

DISCUSSION

Differences in estimated mean ages at TO and PHV and estimated mean PHVs based on the SITAR and FPCA models in the sample of 58 Portuguese soccer players, though statistically significant, were small in practical terms (Table 2). Estimated mean ages at TO (11.2 and 11.0 years) and at PHV (13.6 and 13.7 years) with, respectively, the SITAR and FPCA models among soccer players were also within the ranges of reported mean ages in longitudinal samples of European boys spanning the 1970s through the present: ages at TO, 10.4 to 11.8 years (21 estimates), and ages at PHV, 13.0 to 14.5 years (64 estimates). Mean PHVs among soccer players (9.7 and 9.8 cm/year) were also within the range of estimates in the general population, 7.8 to 11.5 cm/year (27 estimates) [6, the reference includes citations for the specific studies].

Concordance of maturity status classifications (late, average or early) based on ages at PHV and on SA minus CA was modest at initial observation, 11.9 ± 0.5 years and higher at the third observation, 13.9 ± 0.5 years (Table 4). The observations were consistent with relationships among indicators of maturity timing close to the time of PHV among 111 boys in the Wrocław Growth Study [36]. Correlations between estimated CAs at attaining SAs of 12.0 and 14.0 years and age at PHV were, respectively, 0.42 and 0.81. Correlations between the two estimates of age at PHV and the difference of SA minus CA in the 58 soccer players were similar at observations one (-0.54) and three (-0.77), i.e., advanced skeletal maturity status at 12 and 14 years was related to an earlier age at PHV, and the association was stronger closer to the time of PHV.

Estimated mean ages at PHV for the 58 Portuguese soccer players based on the SITAR and FPCA models were within the range of mean ages at PHV estimated with several different methods in six longitudinal samples of soccer players in Europe (Table 5). Though limited to a relatively small number of studies, results of the systematic analysis of the 13 samples of soccer players suggested earlier ages at PHV among players in Southern compared to Northern and Western Europe, and earlier ages at PHV among Japanese club players compared to European players (Figure 1). The trend towards earlier ages at PHV among Japanese compared to European soccer players was consistent with that noted in the general population of youth in both regions [6].

Variation in ages at PHV *among individual players* also merits attention; estimated ages at PHV (Table 5) were within the range of longitudinal samples of European boys, 11.3 to 17.3 years [6, 37, 38]. The relatively late CAs at initial observation and limited duration of several studies of soccer players may have affected the estimated ranges. In contrast, studies in Japan are unique in that they commonly use serial height records of players measured annually in April at their respective schools beginning at 7 years of age [30]; the school records were complemented by measurements taken at several leagues and clubs.

Variation in ages at TO among Portuguese players (Table 2) was in the range of ages at TO in three longitudinal samples of European boys, 9.0 to 15.0 years [39–41]. This variation has implications for monitoring the growth status of youth players as implemented by the English Premier League [9]. Heights and weights of all registered academy players 9 years and older are measured every three to four months. Along with corresponding observations for fitness and an academy-wide injury audit, the data provide a potentially unique opportunity to better understand the impact of the interval of the adolescent spurt upon fitness and performance and also on the incidence and burden of injury. Note, however, height measurements at such relatively close intervals require attention to inter- and intra-examiner measurement variability and also to diurnal and seasonal variation in growth. Moreover, heights should not be measured after training and scrimmages.

Based on monthly measurements of heights and weights of soccer players 11–19 years during the course of a season (September through April), estimated monthly increments of > 0.6 cm/month in height and of > 0.3 kg/m^2/month in the BMI, and an estimated monthly decline of > 0.4 kg/m^2/month in the BMI were associated with an increased risk of injury [42]. Extending the monthly increments in height through a year, it was suggested that an estimated velocity of growth in height $\geq$ 7.2 cm/year was indicative that a player was in his growth spurt [10, 42]. The range of estimated PHVs in the sample of 58 soccer players (Table 2), however, suggested that some players with rates of growth < 7.2 cm/year were in their growth spurts.

Epidemiological data suggest enhanced susceptibility to injury during the interval of the growth spurt, especially conditions associated with rapid growth, i.e., Osgood-Schlatter and Sever's disease [43, 44], and overuse [45]. Use of developmentally appropriate training protocols (activities emphasizing core strength, balance, coordination, mobility, and limiting accelerations and decelerations) and management of training loads may serve to mitigate injury risk during the interval of rapid growth [46]. Some athletes may also experience temporary disruptions or regressions in motor performances during the interval of the growth spurt, commonly labeled as adolescent awkwardness [6]. Of potential relevance, recent evidence suggests that coach evaluations of match performances of youth soccer players tend to decline during the growth spurt, but return to prespurt levels at the cessation of the growth spurt [47]. When evaluating youth athletes, it thus is essential that coaches and others involved are aware of the individuality of growth and maturation during the interval of adolescence, specifically variation in timing and tempo of the spurt. Accommodating individual differences may include, for example, delaying decisions until after the growth spurt, reviewing player performance metrics prior to the onset and during the spurt, and/or allowing a player to play down an age group while they adjust to changes associated with the adolescent spurt [48].

Ages at PHV derived from longitudinal height records of individual youth should not be confused with estimates based on predicted maturity offset defined as the time before PHV, and predicted age at PHV estimated as CA minus predicted maturity offset [49, 50].

Though increasingly used in studies of youth athletes spanning pre-adolescence through adolescence, predicted estimates increase with CA and height at prediction and systematically differ from ages at PHV observed in longitudinal studies [6, 37–39, 51].

The present study is not without limitations. The sample was measured on only five occasions spanning 11 and 16 years. Although the CA range was consistent with other longitudinal studies of European soccer players, the selectivity of the sport (many youth are excluded prior to 11 years) and subsequent selectivity and/or differential drop-out as players pass through adolescence merits attention. Of relevance, the relatively late CA at initial observation and limited duration of the study may have influenced estimated parameters in some players. Estimates of skeletal maturity status were also not available at all observations which limited comparisons of skeletal maturity status and timing of PHV. And, the 13 longitudinal studies of soccer players used a variety of methods to estimate ages at PHV which may have influenced the meta-analysis. Although meta-analysis has several limitations, it is an effective means of aggregating data from studies of soccer players that have used different analytical protocols.

CONCLUSIONS

Mean ages at PHV among Portuguese soccer players with SITAR and FCPA were, respectively, 13.6 ± 0.9 and 13.7 ± 0.9 years, and within the range of means and standard deviations for ages at PHV in the general population and among soccer players in Europe. Concordance of maturity status classifications based on age at PHV and SA (SA minus CA) was moderate at observation 1 (early adolescence) and strongest at observation 3 (~14 years, close to PHV). Analysis of ages at PHV in 13 longitudinal samples of European and Japanese soccer players suggested a geographic/ethnic gradient: northern Europe > southern Europe > Japan.

Author contributions

RMM, MJSC, MK, SMK – conceptualization, manuscript preparation; MJCS – funding acquisition for the study; MJCS, AJF, PSS, DVM – data collection, organization; MK, SMK, RMM, SPC – formal analysis, data modeling, statistics; MK – funding for data modeling; MK, SMK, MJCs, RMM, SPC, JMK – manuscript, all authors contributed to, read and approved the final version.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

The data that support the findings of this study are not publicly available due to departmental policy and privacy commitments to the study participants. Nevertheless, the data may be available upon reasonable request to Professor Manuel J. Coelho-e-Silva, Faculty of Sports Science and Physical Education, University of Coimbra, Portugal.

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Impaired pre-competition wellbeing measures can negatively impact running performance in developmental youth female soccer players

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ABSTRACT: This study aimed to determine the association between pre-competition perceived player wellbeing measures and subsequent relative and peak running performance of developmental youth female soccer players (n = 15, age: 16 ± 1 years). Total distance (TD), high-speed (> 3.5 m/s) (HSRD) and very high-speed (> 5.3 m/s) running (VHSRD) were expressed using 1-, 2- and 5-minute epochs and relative (per minute) calculations. Fatigue, sleep quality, upper and lower-body muscle soreness, stress, and mood wellbeing measures were collected via a self-reported questionnaire (1–5 Likert scale). Menstrual cycle phase was collected via a calendar-based countback method. Results demonstrated that reductions in stress was associated with decreased relative and peak TD in all epochs ($p = 0.008$–0.040), relative and peak HSRD ($p = 0.006$–0.039) in 2- and 5-minute epochs as well as VHSRD in 2-minute epochs ($p = 0.026$). For example, a one-point reduction of 'normal' to 'relaxed' is associated with a decrease of 7 m/min in peak TD for 1-minute epochs. One-point increase in fatigue (e.g., 'normal' to 'more tired than normal') displayed a decrease of 7 m/min peak TD for 2-minute ($p = 0.048$) and 9 m/min for 5-minute ($p = 0.007$) rolling epochs. Likewise, one-point increase in lower-body muscle-soreness (e.g., 'normal' to 'increase in soreness/tightness') was associated with a reduction of 6 m/min peak VHSRD for 1-minute epochs ($p = 0.034$). Results suggest that perceived player wellbeing can influence running performance. However, the magnitude of the change in player wellbeing should be considered in a practical sense.

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INTRODUCTION

In team sports such as soccer, an integrated approach to athlete monitoring is essential when seeking to assess player wellbeing and promote optimal performance [1, 2]. Perceived player wellbeing questionnaires are commonly used in high-performance sport to provide a cost-effective, accurate and sensitive evaluation of athletes' wellbeing [1, 2]. Typically formulated utilising 5-, 7- or 10-point Likert scales, these questionnaires monitor fluctuations in self-reported fatigue, sleep quality, muscle soreness, stress and mood [3–7]. Subjective wellbeing measures have demonstrated superior sensitivity and consistency compared to objective measurements such as biochemical markers when assessing responsiveness to acute and chronic loads [8]. The development and implementation of online athlete monitoring apps and wellbeing questionnaires have minimised the necessity for regular, onerous biochemical testing procedures to monitor players [2, 8]. In addition, these apps and questionnaires promote the integration of sex specific factors, such as menstrual cycle phase, into female athlete monitoring practices [9–11]. In turn, supporting coaches, practitioners and medical staff to develop sex specific, evidence-based approaches to maximise competition readiness in female athletes [9–11].

In combination with variables such as player wellbeing and menstrual cycle, metrics related to accumulative (e.g., total distance covered in a match) and relative (e.g., average distance covered per minute of match time) running performance provide valuable data to coaches and practitioners. In particular, increasing importance has been placed on the evaluation of peak running performance [12–15]. For example, Schimpchen et al., [12] reported that sequences of peak high-speed (> 5 m/s) intensity were evenly distributed across 15-minute fixed time periods (e.g., 0–15, 15–30, 30–45 etc.) during competition matches. However, the greatest number of peak intensity sequences for peak total distance, accelerations and decelerations, using 1-, 5- and 10-minute rolling epochs, occurred in the first 15-minutes of match-play [12]. Likewise, Mäkiniemi et al., [16] observed that elite senior female Finnish soccer players covered less total and high-speed (> 3.6 – 5.3 m/s) running distance in the last 15-minute period compared to the first 15-minute period of match-play. As such, the first 15-minute fixed time period provides a practical window of assessing the most demanding period of competition match-play [12, 16].

To date, investigations have reported that reductions in pre-training wellbeing negatively influenced running performance in elite male Australian Football (AFL) [6] and soccer players [3]. Further, Gaelic football [4] and female Lacrosse [17] athletes have reported that pre-training and pre-competition measures of sleep quality, sleep duration and muscle soreness were associated with subsequent changes to running performance in training and competition match-play. While these findings suggest that coaches and practitioners can utilise perceived player wellbeing measures as indicators of readiness to meet these demands, the data reported was limited to accumulative and relative running performance measures [3, 4, 6, 17]. Additionally, these results are not transferrable across sports or genders, and the relationship between pre-competition player wellbeing and subsequent running performance in developmental youth female soccer players remains unknown. Moreover, there is a current lack of investigations that consider menstrual cycle phase in their statistical modelling, which may be a confounding variable in female athlete research [10, 11, 18–20]. In turn, the exclusion of menstrual cycle phase hinders the translation of research to applied practice in female sporting environments [10, 11, 18–20]. It is important to connect changes in pre-competition perceived player wellbeing, accounting for menstrual cycle phase, to practical, significant changes in female soccer players' running performance [10, 11, 18–20]. Thus, the purpose of this study was to determine the association between pre-competition perceived player wellbeing measures and subsequent relative and peak running performance of developmental youth female soccer players.

MATERIALS AND METHODS

Experimental approach to the problem

This study employed a longitudinal observational design. Data was collected on outfield developmental youth female soccer players (n = 15) during a single Australian National Premier League Women's (NPLW) competition season. The NPLW was classified as a sub-elite competition and matches were played throughout a seven-month competition period (March – September). Perceived player wellbeing metrics were collected daily via an online wellbeing questionnaire using mobile devices. The running performance for each player during match-play were captured using a global positioning system (GPS). Players were categorised according to playing position in each match.

Participants

Fifteen (n = 15) outfield academy youth female soccer players (age: 16 ± 1 yrs.; height 165 ± 6 cm; body mass 59 ± 7 kg; Yo-Yo Intermittent Running Test Level 2 (YYIR2) score; 640 ± 48 m) participated in this study. Participants were recruited from the same Australian W-League youth academy program and classified as Tier 2: developmental [21]. A typical training week consisted of 2–3 soccer specific on-field sessions, 1–2 competition matches, and 1–2 gym-based resistance training sessions. Ethical approval was granted by the University of Canberra Human Research Ethics Committee (project number: 1990). All players and parents or guardians were informed about the requirements, risks, and benefits of participation in this study prior to providing their informed written consent.

TABLE 1. Perceived Player Wellbeing Questionnaire, adapted from Wellman et al., [7] and Abbott et al., [22].

Category	Player Response				
	1	2	3	4	5
Fatigue	Always Tired	More Tired Than Normal	Normal	Fresh	Very Fresh
Sleep Quality	Insomnia	Restless Sleep	Difficulty Falling Asleep	Good	Very Restful
Upper-Body Muscle Soreness	Very Sore	Increase in Soreness/ Tightness	Normal	Feeling Good	Feeling Great
Lower-Body Muscle Soreness	Very Sore	Increase in Soreness/ Tightness	Normal	Feeling Good	Feeling Great
Stress Levels	Highly Stressed	Feeling Stressed	Normal	Relaxed	Very Relaxed
Mood	Highly Annoyed / Irritable / Down	Snappiness at Team Mates / Family	Less Interested than usual	Generally Good Mood	Very Positive Mood

Procedures

Player Wellbeing

Players completed an online wellbeing questionnaire via smart phone devices each day between 8:00 AM and 10:00 AM. Players were instructed not to discuss their responses with other players, coaches, staff, parents, or guardians. The questionnaire has been previously utilised and adapted from other studies [7, 22], developed according to recommendations for implementing customised wellbeing questionnaires in athletes [23]. Each variable was measured on a five-point Likert scale (Table 1), and consisted of variables related to fatigue, sleep quality, upper-body and lower-body muscle soreness, stress, and mood [7, 22, 23].

Wellbeing scores from three, two and one day prior to competition as well as morning of competition were collated for analysis to account for the day-to-day fluctuations in player wellbeing as a response to lingering effects. Where players had failed to complete their daily perceived wellbeing questionnaire in one of the days leading to the day of competition, missing data were imputed using an exponential weighted moving average (EWMA) using that player's wellbeing scores from the two preceding and two succeeding days [24]. The use of an EWMA ensured that more weight was given to more recent wellbeing values [24]. A final four-day EWMA score was calculated for each wellbeing variable and included the wellbeing scores of the three preceding days leading to the day of competition, as well as the day of competition.

Menstrual Cycle Phase

The players menstrual cycle phase on a given day was categorised into two phases, follicular and luteal which was determined using a calendar-based counting method [10, 25]. In addition to their daily wellbeing questions, players were asked "*Did you have your period today?*" [10, 25]. A change in responses from "no" to "yes" established the onset of menses and the start of the follicular phase [10, 25]. Furthermore, players were asked "*What was the date of your last period (first day of menstruation)?*". This allowed the luteal phase to be calculated using a retrospective calendar countback method [10, 25]. Where possible, the days in which players did not complete their daily wellbeing, menstrual cycle phase was calculated from completed questionnaires using the preceding and succeeding days [10, 25]. Where players had not yet started menarche or were experiencing amenorrhoea, defined as the absence of menstrual period > 3 months to ≥ 6 months [11], menstrual cycle phase was categorised as 'irregular'.

Running Performance

Each player completed an average of 11 competition matches (range = 6–22), resulting in a total of 165 individual match files for analysis. Playing positions were categorised as central defenders (CD, n = 24 total match files), external defenders (ED, n = 39 total match files), midfielders (MD, n = 45 total match files), external attackers (EA, n = 47 total match files) and central attackers (CA, n = 10 total match files). To account for participants featuring in different playing positions throughout the competition season, players positions were categorised for each individual match accordingly. Data were trimmed so that only the first 15-minutes of on-field playing time was included in the analysis to minimise the influence of any changes in peak running performance ascribed to accumulative match fatigue, score line differences, half-time intervals and other in-game contextual influences. No tactical substitutions took place during this time. Players who were substituted during the first 15-minutes due to injury were omitted from the analysis. During all data collection competition matches, a 4-3-3 formation was used.

Players running performance was collected using 15 Hz global positioning system (GPS) devices (SPI HPU, GPSports, Canberra, Australia). Devices were worn between the scapulae in a fitted garment to limit device movement. Each player was allocated the same GPS device for the duration of the data collection to minimise the effect of interunit error. Each device was turned on 30-minutes prior to the match warm up, to ensure satellite connectivity. Between 4 to 12 satellites were available for connectivity and signal transmission during match-play, satisfying the criteria for ideal positional detection [26]. The horizontal dilution of precision (HDOP) was not reported by the proprietary software (Team AMS, Canberra, Australia). Captured metrics included total distance (TD), high-speed running distance (HSRD), defined as distance covered at > 3.5 m/s, and very high-speed running distance (VHSRD), defined as distance covered at > 5.3 m/s [14]. These thresholds have previously been used for elite youth female soccer players [14]. The inter-unit reliability of the GPS devices (expressed as a coefficient of variation) has been reported as 1.4% for total distance, 7.8% for distance at speeds between 2.0–5.9 m/s, and 4.8% for distance covered at speeds > 5.9 m/s [27].

Following each match, data were downloaded using Team AMS software (GPSports, Canberra, Australia). The TD, HSRD and VHSRD were expressed as relative (i.e., TD/min, HSRD/min, and VHSRD/min) and peak values (i.e., peak TD, peak HSRD and peak VHSRD) for the first 15-minutes. To calculate the peak demands, GPS data were split into 30-second intervals and 1-, 2- and 5-minute rolling sums were calculated. Previous research has reported that fixed epochs underestimate total (7–10%) and high-speed (12–25%) running distance (defined as > 5.5 m/s) in elite senior male soccer players [13] and as such, rolling epochs have been utilised when quantifying peak running performance in elite youth female soccer players [14]. Peak running performance was calculated as the maximum TD, HSRD and VHSRD achieved in each 1-, 2- and 5-minute rolling window. To allow comparison between the different epoch lengths, TD, HSRD and VHSRD were expressed as per minute values relative to epoch length time.

Statistical analysis

Statistical analyses were conducted using R version 4.2.3 [28] and RStudio version 2023.03.0+386 [29]. Separate Linear Mixed Models (LMM) for each epoch length (1-, 2-, 5-minutes) and relative calculations were conducted using the *lmer* function from the *lme4* package [30] to determine the association between the EWMA well-being variables (fatigue, sleep quality, upper-body muscle soreness, lower-body muscle soreness, stress levels and mood scores) (fixed factors) and the peak and relative TD, HSRD and VHSRD (dependant variables). For each LMM, menstrual cycle phase was included as a random factor. In addition, the player position and the unique player identification number were included as nested random factors. Random effects have been reported in the results section as $position{:}athlete_{RE}$ for the variance attributed to the nested random factors, and $menstrual\ cycle_{RE}$ for the variance attributed to the menstrual cycle phase. A Type II Wald F test was conducted using the *Anova* function from the *car* package [31] to determine the significance (alpha = 0.05) of main effects. The assumption of normality was determined upon visual inspection of histograms and Q-Q plots of the residuals. Multicollinearity was inspected for each model prior to analysis using the *vif* function from the *car* package [31]. All fixed factors were found to have *vif* scores less than 5.0, suggesting no evidence of multicollinearity. The assumptions of homoscedasticity and linearity were confirmed upon visual inspection of plots of the fitted values against the residuals [32].

RESULTS

Main effects were identified between stress and relative TD/min ($p = 0.008$, $position{:}athlete_{RE} = 55.24$, $menstrual\ cycle_{RE} = 0.00$), peak TD in 1- ($p = 0.011$, $position{:}athlete_{RE} = 46.62$, $menstrual\ cycle_{RE} = 0.00$), 2- ($p < 0.001$, $position{:}athlete_{RE} = 0.00$, $menstrual\ cycle_{RE} = 0.00$) and 5-minute ($p = 0.040$, $position{:}athlete_{RE} = 0.52$, $menstrual\ cycle_{RE} = 0.00$) rolling epochs, with reduction in stress (e.g., 'normal' to 'relaxed') associated with lower running performance (Figure 1). Main effects for fatigue were found for peak TD in 2- ($p = 0.048$, $position{:}athlete_{RE} = 0.00$, $menstrual\ cycle_{RE} = 0.00$) and 5-minute ($p = 0.007$, $position{:}athlete_{RE} = 0.52$, $menstrual\ cycle_{RE} = 0.00$) rolling epochs, with increased fatigue (e.g., 'normal' to 'more tired than normal') associated with reduced running performance (Figure 1).

Main effects were identified for stress and relative HSRD/min ($p = 0.006$, $position{:}athlete_{RE} = 0.01$, $menstrual\ cycle_{RE} = 0.00$) and peak HSRD in 2- ($p = 0.027$, $position{:}athlete_{RE} = 50.10$, $menstrual\ cycle_{RE} = 3.43$) and 5-minute ($p = 0.039$, $position{:}athlete_{RE} = 3.31$, $menstrual\ cycle_{RE} = 0.57$) rolling epochs, respectively, where reduced stress (e.g., 'feeling stressed' to 'normal') was associated with lower high-speed running performance (Figure 2).

Main effects were identified for lower-body muscle soreness and peak VHSRD in 1-minute ($p = 0.034$, $position{:}athlete_{RE} = 11.07$, $menstrual\ cycle_{RE} = 0.00$) rolling epochs, indicating increased lower-body muscle soreness (e.g., 'normal' to 'increase in soreness/tightness') was associated with lower VHSRD (Figure 3). Main effects were also identified for stress and VHSRD in 2-minute ($p = 0.026$, $position{:}athlete_{RE} = 0.00$, $menstrual\ cycle_{RE} = 0.00$) rolling epochs, indicating that reduced stress was associated with lower

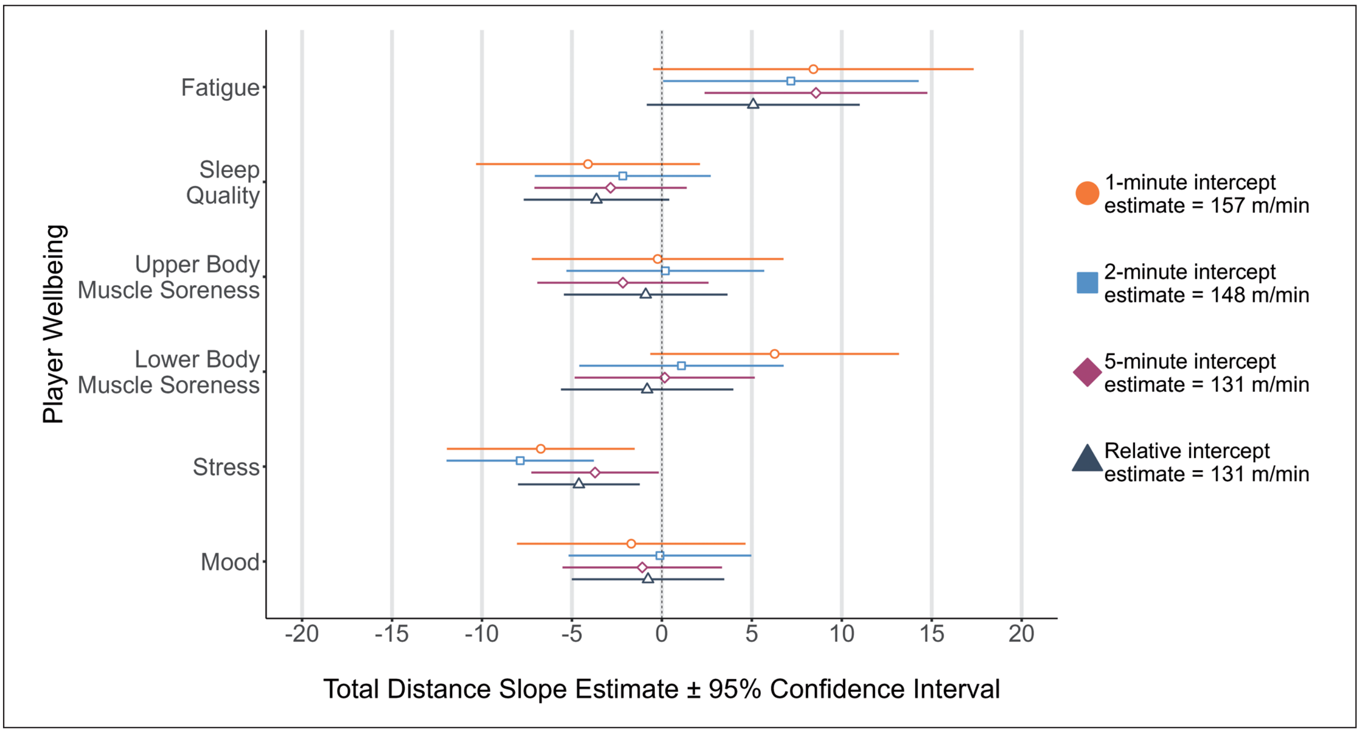

FIG. 1. Total Distance (TD) for 1-, 2-, 5-minute rolling epoch lengths and relative calculations according to changes in player wellbeing.

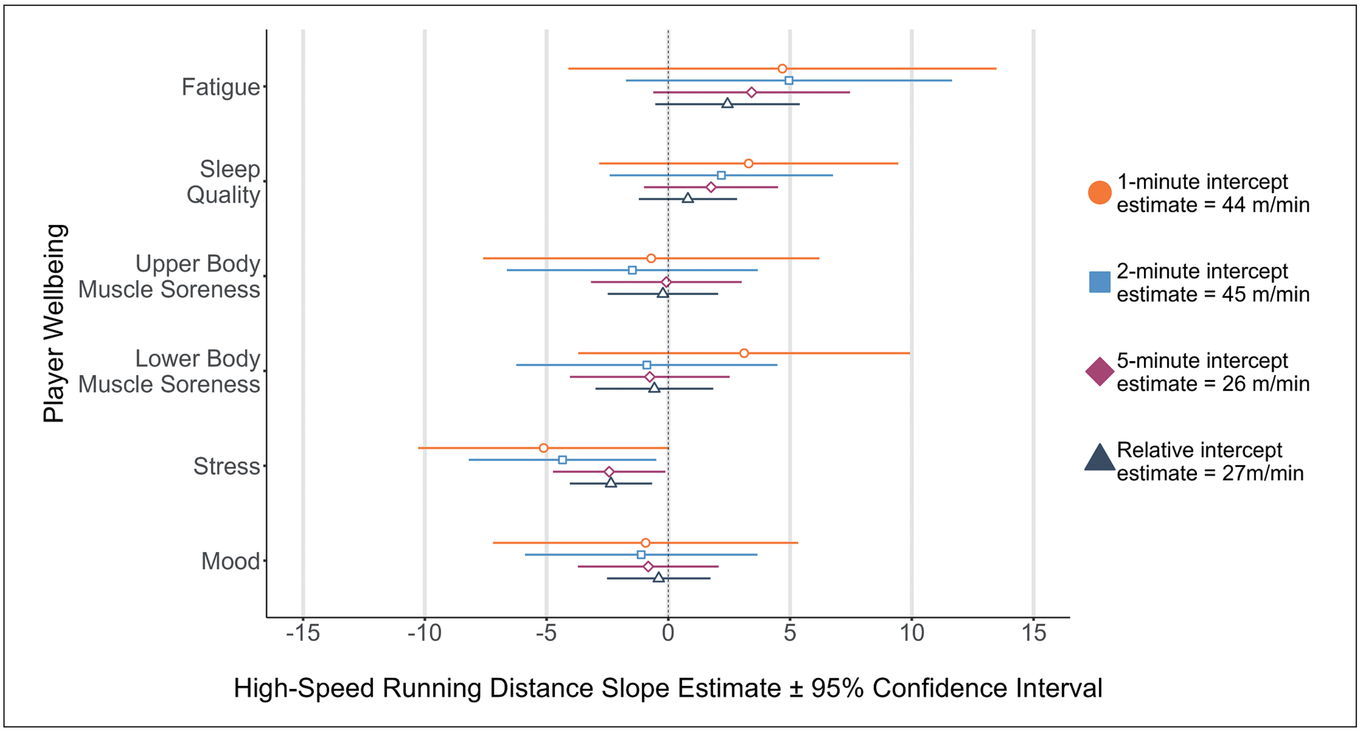

FIG. 2. High-Speed Running Distance for 1-, 2-, 5-minute rolling epoch lengths and relative calculations according to changes in player wellbeing.

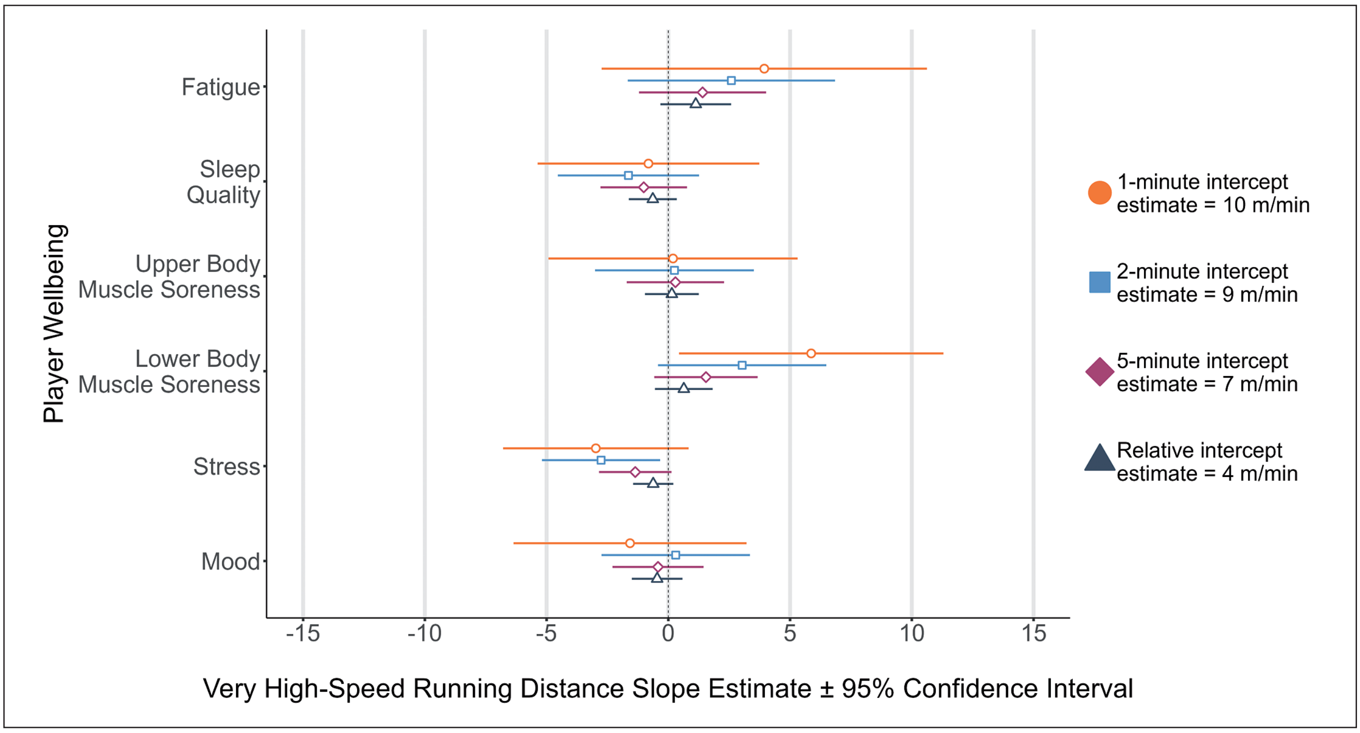

FIG. 3. Very High-Speed Running Distance for 1-, 2-, 5-minute rolling epoch lengths and relative calculations according to changes in player wellbeing.

VHSRD (Figure 3). All other perceived player wellbeing metrics were non-significant across peak TD, HSRD and VHSRD in 1-, 2- and 5-minute rolling epochs as well as relative calculations (p = 0.051 -0.967).

DISCUSSION

The purpose of this study was to determine the association between pre-competition perceived player wellbeing measures and subsequent relative and peak running performance of developmental youth female soccer players. The findings of this investigation suggest that reductions in stress (e.g., 'feeling stressed' to 'normal') were associated with a decrease in relative and peak TD, relative and peak HSRD as well as decreased peak VHSRD. Reported increases of fatigue (e.g., 'normal' to 'more tired than normal') were associated with decreased peak TD. Increased lower-body muscle soreness (e.g., 'normal' to 'increase in soreness/tightness') was also found to be associated with decreased peak very high-speed running. These findings provide evidence to the concept that pre-competition perceived player wellbeing may influence future running performance in early competition match-play in developmental youth female soccer players. Furthermore, a strength in the design of this investigation was the inclusion of menstrual cycle phase as a random factor. The methodology employed in this study provides a simple example of how non-invasive approaches can be employed to increase the quantity and quality of research in female athletes.

Several studies have cited perceptual measures of wellbeing influencing subsequent running performance in AFL [6], field hockey [33], lacrosse [17], and soccer [3] with the use of individual perceptual wellbeing measures (e.g., stress) being more appropriate to inform an expected running output from players rather than a sum of wellbeing measures in Gaelic football [4]. The results of this study agree with previous findings, demonstrating that stress appears to be associated with changes in running performance. For example, Figure 1 shows that a one-point change in a player's perceived stress levels (e.g., 'feeling stressed' to 'normal') is associated with a decrease of 7 m/min in peak TD for 1-minute rolling epochs. Whilst a decrease of 7 m/min for peak TD may not signal a practically meaningful change in running performance, the magnitude in the change of player wellbeing should be considered in a practical sense. For example, a three-point change in a player's perceived stress levels (e.g., 'highly stressed' to 'relaxed') would result in a decrease of 21 m/min in peak TD for 1-minute rolling epochs. Likewise, a one-point change in perceived stress was associated with reductions of 4 m/min at high-speed and 3 m/min at very high-speed during a 2-minute epoch. Therefore, a three-point change in a player's perceived stress levels would result in a decrease of 12 m/min at high-speed and 9 m/min at very high-speed. As such, it appears that the magnitude of change in 'stress' responses prior to competition determines whether the subsequent change in high and very high-speed running performance is trivial (i.e., -4 or -3 m/min), or meaningful (i.e., -12 or -9 m/min) in 2-minute rolling epochs. A player's anticipation to perform in competition has been reported to influence salivary cortisol concentration levels, reflective of increases in cognitive and somatic anxiety preceding competition [34]. In this regard, the increased peak running performance associated with reported perceived states of 'feeling stressed' and 'highly stressed' could be reflective of arousal to perform as opposed to negative state of mental wellbeing. Additionally, these findings could be potentially attributed to the level of competition and participant classification in this investigation [21, 34]. National and regional level players have reported increased cognitive anxiety responses prior to competition when compared to international level athletes [34]. Further research is required to determine whether the impact of stress differs between international, national, and regional youth female soccer players.

A player's ability to accelerate, run at near maximal velocity and change direction at high-speed is critical in soccer and commonly underpins vital match situations such as scoring goals [35, 36]. Previous research has indicated that changes in pre-training ratings of fatigue and composite wellness scores can limit subsequent running performance, which in turn may lead to a detriment in the ability to successfully perform actions at high-speed in crucial match situations [3, 6, 17, 35, 36]. This study reports that increased fatigue were associated with reductions in peak TD in 2- and 5-minute rolling epochs. Developmental youth female soccer players displayed an average decrease of 7 m/min and 9 m/min for 2- and 5-minute rolling epochs, respectively, when reporting a one-point change (e.g., 'normal' to 'more tired than normal') in fatigue. Consequentially, a three-point change would constitute a decrease of 21 m/min for 2- and 27 m/min for 5-minute rolling epochs. However, considering that there was no reported association between fatigue and relative high-speed and very high-speed running or peak high-speed and very high-speed running, the results imply that the change in peak TD associated with fatigue is reflective of player running performance at < 3.5 m/s (i.e., low speed running). It appears alterations of running performance associated with pre-competition fatigue, whilst statistically significant, provide little to no indication of substantial impairment regarding player running performance during critical, high-speed scenarios such as those observed prior to goal-scoring moments [35, 36].

Our results suggest that measures of lower-body muscle soreness are associated with changes in subsequent running performance during competition. For example, a one-point change in player lower-body muscle-soreness (e.g., 'normal' to 'increase in soreness/tightness') elicits a decrease in peak very high-speed running of 6 m/min. Practically, this means a three-point change in a player's lower-body muscle-soreness would result in a decrease of 18 m/min in a 1-minute epoch. A decrease of 6 m/min over the course of 1 minute of match-play would unlikely hinder players in critical match situations. However, a decrease of 18 m/min at very high-speed across a 1-minute epoch would constitute a significant, meaningful change in running performance. Our results further highlight the need to consider the magnitude of change in perceived player wellbeing metrics prior to competition and its association with player's subsequent running performance. However, there was no association between lower-body muscle soreness and peak very high-speed running in 2-, 5-minutes rolling epochs and relative measures. Coaches and practitioners should therefore remain cautious when associating reported pre-competition perceived lower-body muscle soreness and subsequent running performance.

Although perceived player wellbeing measures from the 72-hour period following competition were not investigated in this study, it is important to consider these findings in relation to the practicality of utilising perceived player wellbeing throughout an entire training microcycle. For example, Evans et al., [37] reported that stress, sleep, and total wellness measurements five days prior (MD-5) to competition were indicative of the total number of accelerations and decelerations in the following match but not TD, HSRD (> 4.1 m/s) or VHSRD (> 5.2 m/s) in under-18 elite youth male soccer players. Other studies have found that players reported significant reductions in wellbeing during the 72-hours following competition [3, 5]. Malone et al., [3] reported that in elite senior (age: 25.3 ± 3.1) male soccer players reduction in wellbeing negatively impacted running performance in training environments. Notably, the lowest wellbeing Z-scores (Z-score of -2) were reported the day following competition (MD+1) with a steady increase throughout the microcycle with the greatest player wellbeing being reported on match day [3]. These findings suggest that player wellbeing observed in the 72-hour window following competition appear to have an influence on subsequent competition running performance of players [3, 37]. Therefore, the results observed in this study may be reflective of the exclusion of perceived player wellbeing in the 72-hours following competition and therefore not accounting for the greatest decrement in perceived player wellbeing during a typical training microcycle.

Whilst these findings suggest that pre-competition perceived player wellbeing measures are associated with subsequent player running outputs, the results of this study should be interpreted in accordance with several limitations. Firstly, menstrual cycle phase was only separated into follicular and luteal phases. Future investigations should seek to utilise the proposed definitions of 1) early follicular, 2) late follicular, 30) ovulatory and 4) midluteal in future investigations [11]. Furthermore, the use of hormonal contraception by players should be included as an additional covariate in future studies [11]. Finally, the influence of 'survey fatigue' has been reported when undertaking athlete wellbeing research and as such, results should be interpreted with this in mind [38].

CONCLUSIONS

This study is the first to investigate the association between pre-competition perceived player wellbeing, accounting for menstrual cycle phase, and the relative and peak running outputs of developmental youth female soccer players. Stress, fatigue, and lower-body muscle soreness appear to be the key metrics that are associated with subsequent changes in running performance in developmental youth female soccer players. Practically, coaches and practitioners could use changes in perceived player wellbeing metrics as indicators to proactively initiate targeted communication and gain more information regarding an athlete's state prior to competition. However, the scale of change must be considered, as small one-point changes of perceived player wellbeing may not provide a meaningful change in running performance. Alternatively, a three-point change will likely impact subsequent running performance and in this regard may be used as the foundation for a face-to-face conversation in the lead up to competition fixtures. Nonetheless, such considerations should be made in alignment with normal athlete response patterns and context of personal circumstances. Finally, the study design and data reported in this investigation provides the basis for coaches and practitioners to promote and continue the inclusion of menstrual cycle tracking into athlete monitoring practices to further understand the multifaceted nature of performance in female athletes.

Conflict of Interest

The authors declare no conflict of interest.

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Original Paper

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Application of arbitrary and individualized load quantification strategies over the weekly microcycle in professional soccer players

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ABSTRACT: The aims of this study were to: (a) determine the differences in external load quantification between arbitrary and individual speed thresholds over the weekly microcycle in professional soccer players, and (b) analyse the association between internal load and different external load quantification strategies (ELQSs). Ten professional outfield players were monitored during training sessions and official matches using 10 Hz GPS devices over a 6-week in-season period. The absolute and relative ("R" before the distance category) distances covered were calculated for the following external load variables: medium-intensity running distance (MIR), high-intensity running (HIR), sprint distance (SD), and very high-intensity running (VHIR). Individualized thresholds were determined based on maximal sprinting speed (MSS) and the last speed achieved during the 30–15 Intermittent Fitness Test (V_{IFT}) of each player. In terms of match-day workload, significant differences ($p < 0.05$) were observed between arbitrary and individualized strategies (i.e., MSS and V_{IFT}) for the distance covered in MIR, HIR, SD, VHIR, RHIR, RSD, and RVHIR. The MSS strategy compared to arbitrary thresholds revealed significant differences ($p < 0.05$) for distance covered in HIR, RHIR, and VHIR during all training sessions. The present results showed that arbitrary thresholds lead to underestimation of external load absolute and relative metrics compared to the MSS strategy throughout the microcycle. The V_{IFT} strategy mainly revealed differences in external load quantification regarding MD compared to arbitrary thresholds. Individualized speed threshold strategies did not achieve better associations with internal load measures in comparison with arbitrary thresholds in professional soccer players.

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Peak velocity
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INTRODUCTION

Time-motion analysis and physiological monitoring have frequently been used to analyse the movement patterns and workloads imposed by the match play and training sessions in soccer [1]. According to previous literature, the workload can be differentiated into internal and external loads [2]. In that sense, Global Positioning System (GPS) technology is commonly used to monitor and record external load in professional soccer [3]. The appropriate management of daily external load has been considered a central issue in optimizing microcycle programming [4, 5]. Recently, an expert panel belonging to teams from Big-5 European football leagues stated that high-intensity running (HIR) and sprinting-focused exercises were perceived as the most effective strategies for preventing lower-limb injuries [6]. Additionally, the ability to reproduce high-intensity actions during matches is a key element in gaining advantages during offensive and defensive tactical situations [7, 8]. In this regard, Beato et al. [9] established that implementing HIR and sprint training has a pivotal role in developing or maintaining the intermittent ability to execute high-intensity actions during a soccer match. Therefore, one might state that accurate monitoring and management of HIR and sprinting exposure across microcycles reduce the likelihood of non-contact injuries and optimize the ability to perform high-intensity actions during competitive scenarios [9, 10].

Despite the recognized relevance of external load monitoring, the player's locomotor demands are generally analysed using different running thresholds determined arbitrarily [3, 11]. Concerning HIR and sprinting, the implementation of the arbitrary threshold may mask the player's real efforts, leading to an inadequate interpretation of actual metabolic and neuromuscular demands during training or competition [12, 13]. In order to individualize speed thresholds, researchers have used different methods based on physiological laboratory and field tests [11, 12, 14, 15, 16]. However, the implementation of physiological tests comprising continuous or linear movements does not reflect the ability of soccer players to perform changes of direction and high-intensity actions [13]. Conversely, the action-specific field tests could be recognized as ecological, time-efficient, and cost-effective alternatives to determine the individual speed thresholds [17, 18]. Consequently, it seems necessary to develop field methods for quantifying the external load considering the individual physical capacity of soccer players [9].

Recent studies have established the possibility of individualizing speed thresholds by maximal sprinting speed (MSS) and functional fitness tests (e.g., the 30–15 Intermittent Fitness Test) [9, 12, 16, 19]. Regarding MSS, Kyprianou et al. [20] pointed out that it is a key metric for external load individualization since exposure to sprint (ranging from > 85% to > 95% of MSS) during training (i.e., match day minus 2) might be related to a reduction in hamstring injuries during matches [21]. Likewise, Massard et al. [22] showed that MSS could be easily defined with GPS data due to its strong association with the 40-m sprint test. In addition, to better prescribe and monitor HIR-related metrics, other studies have individualized the speed zones using the velocity reached during the last successful stage of the 30–15 Intermittent Fitness Test (V_{IFT}) [12, 16]. During the last few years, this test has been widely used to assess intermittent physiological capacities (i.e., maximal oxygen uptake (VO_{2max}), change of direction and inter-effort recovery ability, and to prescribe high-intensity interval training (HIIT) in soccer players [23]. In fact, the drills based on V_{IFT} have been recommended to provide a dose of weekly HIR in soccer players, especially for non-starter players [24]. Therefore, individualization of speed thresholds based on MSS and V_{IFT} could provide a more practical approach for training monitoring and for replicating match-equivalent HIR and sprinting load, while accounting for individual fitness levels.

To the best of our knowledge, there are limited previous comparisons of external load resulting from arbitrary and individualized speed thresholds within the typical microcycle in professional soccer players [25, 26]. Furthermore, no previous research has analysed possible discrepancies between arbitrary and individual speed thresholds, as determined using V_{IFT}. Therefore, the aim of this study was to determine the differences in external load quantification between arbitrary and individual speed thresholds based on MSS and V_{IFT} over the weekly microcycle in professional soccer players. Additionally, the secondary aim was to analyse the association between internal load (i.e., rating of perceived exertion (RPE) and session-RPE (sRPE) and distance covered in HIR and sprinting depending on the external load quantification strategy (ELQS). In line with previous research [16, 17], it is hypothesized that the arbitrary thresholds underestimate or overestimate the distance covered at HIR and sprinting depending on the player's physical fitness status.

MATERIALS AND METHODS

Participants

A total of 10 male outfield Spanish professional soccer players (mean ± SD; age = 26.52 ± 4.25 years; height = 178.0 ± 6.36 cm; body mass = 73.47 ± 3.24 kg) who belonged to the same squad during the season 2021–2022 participated in this study. According to the positional role, the distribution of players was as follows: central defenders (2), fullbacks (2), midfielders (4), and forwards (2). All participants had experience at the professional soccer level from a minimum of one year to a maximum of nine years. Players regularly trained 5 times per week and training sessions had a duration 45 to 80 min (average duration = 62.8 ± 9.66 min) depending on the day of the microcycle. In addition, the team competed in one match per week. The inclusion criteria were that the players completed 80% of all training sessions and played at least one full match during the monitoring period. Moreover, the goalkeepers were excluded from data collection due to the differences in external load demands. The research protocol was approved by the investigation review committee (code 10-0721). The study fulfilled the ethical requirements and principles of the Declaration of Helsinki.

TABLE 1. Training contents for each microcycle session.

Day	Description
MD-4	Strength training, small possession and position games, small-sided games, and repeat sprint training.
MD-3	Rondos, tactical drills, pressing tasks, physical-technical circuits based on V_{IFT}, medium-sided games, and partial time simulated 11 vs 11 matches.
MD-2	Rondos, control and passing tasks, and tactical drills.
MD-1	Activation drills, rondos, 11 vs 11 games (half pitch), and review of tactical keys regarding the match.
MD	Match day

MD: match day; MD-5: 5 days before match; MD-4: 4 days before match; MD-3: 3 days before match; MD-2: 2 days before match; MD-1: 1 day before match.

Experimental approach to the problem

A retrospective longitudinal observational research study was conducted on a Spanish professional soccer team during the 2021–2022 end-season period. External load data from 6 competitive microcycles were collected. Throughout the data collection period, players completed 3–5 on-field training sessions and one official match per week. In line with Akenhead et al. [27], the days of the microcycle were categorized in relation to the match day (MD): 4 days before the match (MD-4), 3 days before the match (MD-3), 2 days before the match (MD-2), and 1 day before the match (MD-1). The training contents of each session are described in Table 1. Only data from the principal training sessions of the team were recorded. Records from regeneration and compensatory sessions (i.e., 1 day after match sessions) were excluded. In reference to match analysis, only the files of players who participated for at least 80 min were retained for analyses [28]. The external load of each session and match was calculated using standardized (arbitrary), and individualized speed thresholds. Specifically, the individualized speed thresholds were calculated from the MSS of each player and the speed reached at the end of the 30–15 Intermittent Fitness Test (V_{IFT}). In total, 585 observations from 20 training sessions and 6 official matches were registered for the subsequent statistical analysis.

Procedures

During the intervention period, the external load of each session and match was gathered using a portable 10-Hz GPS device (Playertek, Catapult Innovations, Melbourne, Australia). According to Scott et al. [29], GPS units with a sampling rate of 10-Hz are the most valid and reliable for external load analysis in team sports. In order to avoid inter-unit variability error, all players used the same GPS unit during training sessions and matches. To increase the reliability of data collection, the GPS units were activated 15 minutes prior to each training session or match in an open area to acquire a minimum of 6 satellites avoiding weak connections and ensuring data quality [3, 30, 31]. Subsequently, players wore a custom-made vest with a small pocket between the shoulder blades, where the GPS unit was placed. After each session, the data were transferred using the manufacturer's software in order to calculate standardized and individualized external load variables. In this regard, each session was processed three times, applying different speed thresholds based on standardized, MSS, and V_{IFT} external load quantification strategies (Figure 1). Regardless of ELQS, all variables were analysed in terms of volume (i.e., absolute distance covered in metres) and intensity (i.e., distance covered relative to session or match duration), considering each speed threshold [4, 5]. In line with previous research, external load data were analysed from 6 competitive microcycles in order to reduce the effects of physical performance variations within the competitive season in MSS and V_{IFT} strategies [16, 32].

The arbitrary speed thresholds were established in accordance with previous research [4, 30]: medium-intensity running distance (MIR; 14.4–19.79 $km \cdot h^{-1}$), high-intensity running (HIR; 19.8–25.1 $km \cdot h^{-1}$), and sprint distance (SD; > 25.2 $km \cdot h^{-1}$). In addition, the distance covered above 19.8 $km \cdot h^{-1}$ was categorized as very high-intensity running (VHIR).

The 30–15 Intermittent Fitness Test ($30\text{–}15_{IFT}$) was performed as previously described [33, 34]. The $30\text{–}15_{IFT}$ consisted of 30-s shuttle runs interspersed with 15-s passive recovery periods. The initial running velocity was set at 8 $km \cdot h^{-1}$ for the first 30-s shuttle run and increased by 0.5 $km \cdot h^{-1}$ until the end of the protocol. The players ran back and forth between two lines set 40 m apart. The pace of shuttle runs was governed by audio beeps, allowing players to adjust their running velocity to each stage. During the 15-s recovery period, the players walked forward until the nearest 3-m zone located in the middle or at one end of the running area, awaiting the beginning of the next running stage. Players were instructed to complete as many stages as possible. The test was considered finished when players were unable to maintain the running pace established by audio beeps or when they were unable to reach the 3-m zone around each line at the moment of the audio signal, 3 consecutive times. The velocity reached during the last successful stage of $30\text{–}15_{IFT}$ was used for individualizing the speed threshold of each player. Previous research determined high validity and reliability for the $30\text{–}15_{IFT}$ outcomes in team sports athletes [35, 36]. Players presented an average V_{IFT} of 21.30 ± 0.82 $km \cdot h^{-1}$. Individualized speed thresholds based on the V_{IFT} strategy were established as follows [16, 37]: MIR (68–86.99% V_{IFT}), HIR (86.99–110% V_{IFT}), and SD (> 110% V_{IFT}). For this strategy, the distance covered above 86.99% V_{IFT} was classified as VHIR. All players conducted the $30\text{–}15_{IFT}$ during the week before the data collection period.

Regarding the MSS strategy, the peak speed was retrospectively established by analysing the speed obtained in training sessions and matches throughout the competitive season [38]. Recent research has established that 10 Hz GPS technology can provide valid and reliable related to a player's peak speed [22]. Likewise, the data referring to sprint and repeated sprint ability training were included to establish peak speed. The average peak speed was 31.90 ± 1.92 $km \cdot h^{-1}$. In accordance with Murray et al. [15], the MSS thresholds were categorized as follows: MIR (34–54.99% MSS), HIR (55–74.99% MSS), and SD (> 75% MSS). For this strategy, the distance covered above 54.99% MSS was classified as VHIR.

The 0–10 Foster's RPE was registered to quantify the internal load of each player [39]. All participants recorded individually their RPE 30 minutes after the end of the training sessions to avoid potential bias [40]. Players were familiar with the use of the RPE scale because they used it as a part of their regular training routine. Additionally, the S-RPE was calculated by multiplying the RPE score provided for each player during training sessions by the training duration.

Statistical analyses

The results were presented as means and standard deviations (mean ± SD). All analyses were performed using the statistical software R version 4.2.1 (R Core Team, 2020) for Macintosh. A linear

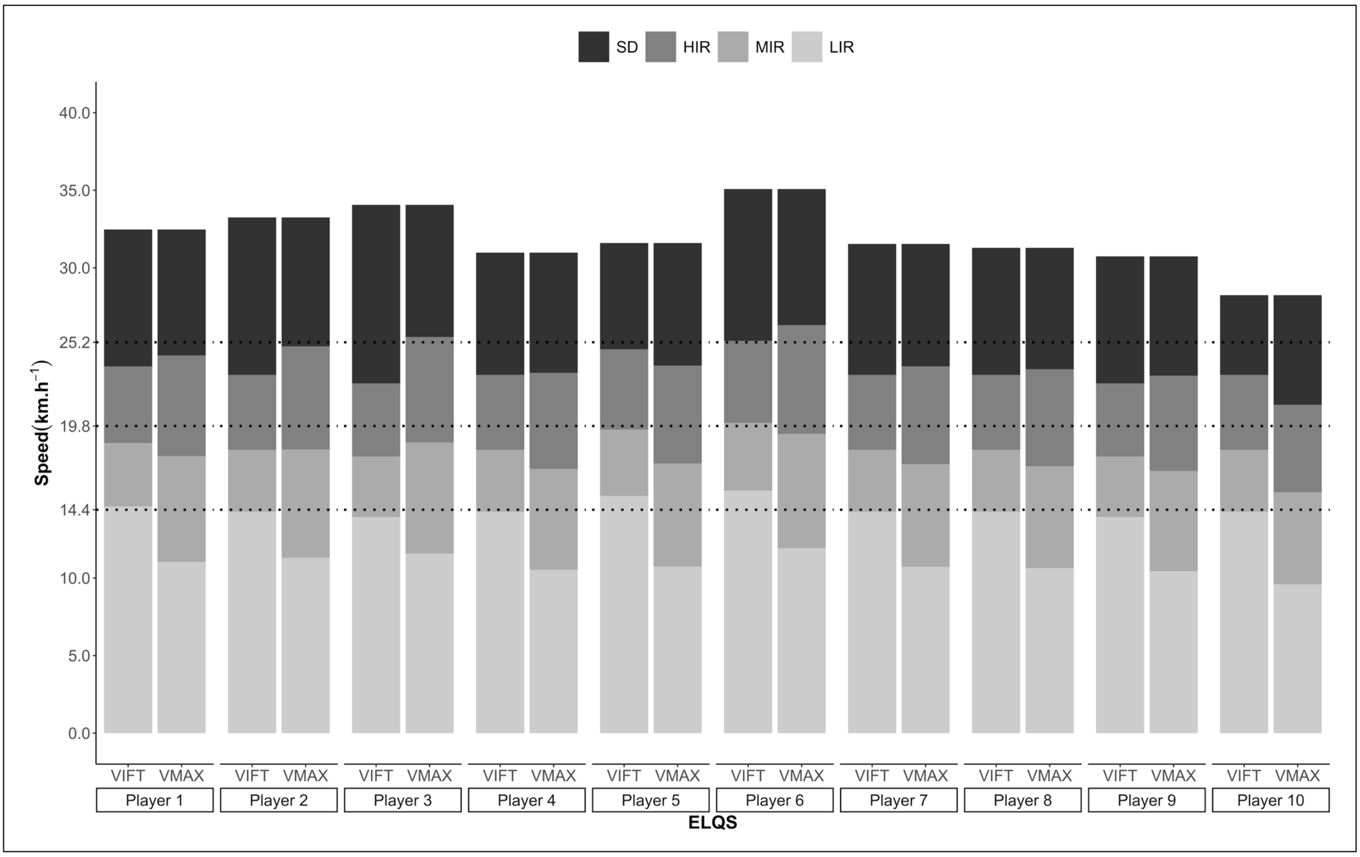

FIG. 1. Displays the arbitrary and individualized (i.e., MSS and V_{IFT} strategies) speed thresholds for each player.

mixed model was adjusted using the R package "lm4" [41] to analyse the differences in external load quantification strategies (i.e., "standard" arbitrary strategy, and individualization ones using V_{IFT} and MSS as references) for the different speed thresholds (i.e., MIR, HIR, SD), according to the microcycle session (i.e., MD-4, MD-3, MD-2, MD-1, MD). Player identity was determined as a random effect to account for the repeated measures. In this regard, the following model was adjusted for all running variables (y):

$$y = \text{ELQS} \cdot \text{Session} + (1|\ \text{Player ID})$$

Where ELQS = external load quantification strategy; ID = identity

For each model, the assumptions of homogeneity and normal distribution of the residuals were checked. The models' residuals fulfilled the assumption of homogeneity and normal distribution. The R package "*emmeans*" [42] was used to perform pairwise comparisons via the Bonferroni post-hoc test between external load quantification strategies. Additionally, effect sizes were determined using Cohen's d with the following formula: $d = (M_2 - M_1)/SD_{pooled}$. According to Hopkins et al. [43], effect sizes were classified as trivial (0.0–0.2), small (0.2–0.6), moderate (0.6– 1.2), large (1.2–2.0), and very large (> 2.0). Repeated measures correlations between RPE and external load quantification strategies using the different speed thresholds were examined using the R package "*rmcorr*" [44]. The magnitude of correlation was categorized using the following criteria [39]: < 0.10, trivial; 0.10 to 0.29, small; 0.30 to 0.49, moderate; 0.50 to 0.69, large; 0.70 to 0.89, very large; and > 0.90, nearly perfect. The significance value was established for all statistical analyses at $p < 0.05$.

RESULTS

Effects of external load quantification strategies on the training and match day's workload.

Table 2 displays the absolute and relative ("R" before the distance category) values of workload as well as the significant differences observed between ELQSs during a weekly microcycle. In terms of MD workload, the MSS and V_{IFT} strategies presented significantly greater distance covered in HIR (ES: 1.49 and 0.64, large and moderate), SD (ES: 0.63 and 0.97, moderate), VHIR (ES: 1.35 and 0.85, large and moderate), RHIR (ES: 1.38 and 0.60, large and moderate), RSD (ES: 0.60 and 0.93, moderate), and RVHIR (ES: 1.26 and 0.81, large and moderate) than the arbitrary strategy. For the speed threshold of MIR, the MSS (ES: 3.76, very large) and arbitrary (ES: 0.95, moderate) strategies displayed significantly greater distance covered in comparison with V_{IFT}. In addition, the MSS strategy displayed significantly greater distances in HIR (ES: 1.11, moderate), VHIR (ES:

0.75, moderate), RHIR (1.01, moderate), and RVHIR (ES: 0.70, moderate) compared to V_{IFT}. Regarding MD-4, the MSS strategy resulted in significantly greater distance in MIR (ES: 3.82, very large), HIR (ES: 1.13, moderate), SD (ES: 0.25, small), VHIR (ES: 0.75, moderate), RMIR (ES: 3.21, very large), RHIR (ES: 1.18, moderate), and RVHIR (ES: 0.84, moderate) compared to the arbitrary strategy. Additionally, the MSS strategy exhibited a greater distance covered in MIR (ES: 4.47, very large) and RMIR (ES: 3.68, very large) than V_{IFT}, while V_{IFT} showed a significantly greater distance covered in RSD (ES: 0.38, small) than the arbitrary strategy. In reference to MD-3, the workload quantified with the MSS strategy resulted in significantly greater MIR (ES: 2.75, very large), HIR (ES: 1.52, large), SD (ES: 0.80, moderate), VHIR (ES: 0.81, moderate), RMIR (ES: 2.50, very large), RHIR (ES: 1.56, large), and RVHIR (ES: 1.51, large) distance compared to the arbitrary strategy. In addition, the MSS presented higher values in MIR (ES: 3.20, very large), HIR (ES: 1.10, moderate), VHIR (ES: 0.74, moderate), RMIR (ES: 2.89, very large), RHIR (ES: 1.16, moderate), and RVHIR (ES: 0.78, moderate) compared to V_{IFT}, while V_{IFT} revealed greater distance covered in SD (ES: 0.98, moderate) and RSD (ES: 1.00, moderate) than the arbitrary strategy. For

TABLE 2. Differences (mean ± SD) in the distance covered in different speed zones according to arbitrary and individualized thresholds during competitive microcycle.

Variable	ELQS	MD-4 (mean ± SD)	MD-3 (mean ± SD)	MD-2 (mean ± SD)	MD-1 (mean ± SD)	MD (mean ± SD)
MIR (m)	ARB	381.30 ± 82.95	622.64 ± 131.69	256.74 ± 77.99	331.71 ± 94.45	1754.97 ± 415.21
	V_{IFT}	318.69 ± 67.37	508.70 ± 84.63	255.74 ± 152.26	273.94 ± 73.11	1415.87 ± 284.88*
	MSS	878.40 ± 163.75*#	1470.92 ± 415.48*#	610.24 ± 177.21*#	829.76 ± 270.99*#	3286.87 ± 642.64*#
HIR (m)	ARB	122.56 ± 69.51	223.71 ± 94.16	119.50 ± 53.13	85.67 ± 34.31	650.47 ± 199.02
	V_{IFT}	148.26 ± 64.98	268.05 ± 86.18	156.04 ± 78.31	117.14 ± 40.68	771.84 ± 180.10*
	MSS	211.00 ± 85.32†	385.23 ± 122.97*#	214.29 ± 121.99†	167.51 ± 67.78†	1097.43 ± 373.55*#
SD (m)	ARB	68.45 ± 87.06	44.80 ± 33.39	19.27 ± 16.65	8.69 ± 10.04	194.25 ± 118.50
	V_{IFT}	105.42 ± 118.93	89.60 ± 55.22†	49.35 ± 31.99	23.30 ± 18.35	312.09 ± 125.14*
	MSS	92.74 ± 107.81	76.18 ± 43.50	38.63 ± 27.59	17.71 ± 16.70	265.15 ± 104.45*✦
VHIR	ARB	191.01 ± 145.22	268.52 ± 114.43	138.77 ± 60.69	94.37 ± 38.44	844.71 ± 294.62
	V_{IFT}	253.69 ± 168.14	357.65 ± 125.69	205.40 ± 100.29	140.44 ± 48.99	1083.94 ± 264.41*
	MSS	308.05 ± 164.41†	461.42 ± 151.97*✦	252.92 ± 141.59†	185.23 ± 76.74	1362.59 ± 453.49*#
RMIR (m/min)	ARB	5.76 ± 1.26	8.54 ± 1.86	4.76 ± 1.07	5.58 ± 1.57	18.57 ± 4.91
	V_{IFT}	4.82 ± 1.03	6.98 ± 1.23	4.65 ± 2.32	4.61 ± 1.22	14.97 ± 3.44*
	MSS	13.43 ± 3.14*#	20.30 ± 6.39*#	11.40 ± 2.66*#	14.00 ± 4.76*#	34.58 ± 6.98*#
RHIR (m/min)	ARB	1.81 ± 1.01	3.04 ± 1.19	2.18 ± 0.78	1.44 ± 0.58	6.87 ± 2.20
	V_{IFT}	2.20 ± 0.93	3.65 ± 1.09	2.83 ± 1.16	1.98 ± 0.70	8.16 ± 2.08*
	MSS	3.16 ± 1.27*	5.26 ± 1.63*#	3.87 ± 1.85*✦	2.83 ± 1.17*	11.58 ± 4.29*#
RSD (m/min)	ARB	0.94 ± 1.15	0.61 ± 0.45	0.36 ± 0.31	0.14 ± 0.17	2.06 ± 1.30
	V_{IFT}	1.47 ± 1.60†	1.22 ± 0.74†	0.90 ± 0.55†	0.39 ± 0.31	3.29 ± 1.34*
	MSS	1.29 ± 1.44	1.04 ± 0.58	0.71 ± 0.47	0.30 ± 0.28	2.79 ± 1.14*
RVHIR (m/min)	ARB	2.75 ± 1.98	3.65 ± 1.46	2.54 ± 0.92	1.60 ± 0.66	8.93 ± 3.25
	V_{IFT}	3.67 ± 2.26	4.88 ± 1.62†	3.74 ± 1.50	2.38 ± 0.86	11.44 ± 2.95*
	MSS	4.52 ± 2.22*	6.30 ± 1.99*✦	4.58 ± 2.15*	3.13 ± 1.33*	14.38 ± 5.18*#

Abbreviations: MIR: medium-intensity running distance; HIR: high-intensity running; SD: sprint distance; VHIR: very high-intensity running; RMIR: relative medium-intensity running distance; RHIR: relative high-intensity running distance; RSD: relative sprint distance; RVHIR: relative very high-intensity running; ARB; arbitrary running threshold; MSS: individualized threshold based on maximal sprint speed; V_{IFT}: individualized threshold based on final speed reached at the end of 30–15 Intermittent Fitness Test; MD: match day; MD-5: 5 days before match; MD-4: 4 days before match; MD-3: 3 days before match; MD-2: 2 days before match; MD-1: 1 day before match; ELQS: external load quantification strategy. *Significant differences ($p < 0.01$) with arbitrary external load quantification strategy. #Significant differences ($p < 0.01$) with V_{IFT} external load quantification strategy. ‡Significant differences ($p < 0.01$) with MSS external load quantification strategy. †Significant differences ($p < 0.05$) with arbitrary external load quantification strategy. ✦Significant differences ($p < 0.05$) with V_{IFT} external load quantification strategy.

TABLE 3. Within-player correlation coefficients for the relationship between RPE, sRPE and external load according to different methods.

		Arb			VIFT			MSS		
		r	95% CI	Magnitude	*r*	95% CI	Magnitude	*r*	95% CI	Magnitude
sRPE	MIR (m)	0.68**	0.58–0.75	Moderate	0.59**	0.48–0.69	Moderate	0.47**	0.33–0.59	Small
	VHIR (m)	0.59**	0.47–0.68	Moderate	0.60**	0.48–0.69	Moderate	0.63**	0.51–0.71	Moderate
RPE	RMIR (m/min)	0.51**	0.38–0.62	Moderate	0.38**	0.23–0.51	Small	0.16*	0.01–0.31	Trivial
	RVHIR (m/min)	0.39**	0.25–0.52	Small	0.38**	0.23–0.51	Small	0.41**	0.27–0.53	Small

Abbreviations: ARB; arbitrary running threshold; MSS: individualized threshold based on maximal sprint speed; V_{IFT}: individualized threshold based on final speed reached at the end of 30–15 Intermittent Fitness Test; MIR: medium-intensity running distance; VHIR: high-intensity running; RMIR: relative medium-intensity running distance; RVHIR: relative very high-intensity running **p-value < 0.01; *p-value < 0.05.

MD-2 and MD-1, the MSS external load quantification strategy displayed significantly greater distance covered in MIR (ES: 2.58 and 2.45, very large), HIR (ES: 1.00 and 1.52, moderate and large), RMIR (ES: 3.27 and 2.45, very large), RHIR (ES: 1.19 and 1.51, moderate and large), and RVHIR (ES: 1.23 and 1.45, large) in comparison with the arbitrary strategy. However, the MSS strategy exhibited significantly greater distance in VHIR (ES: 1.05, moderate) on MD-2 but not on MD-1 ($p > 0.05$). Additionally, the V_{IFT} strategy revealed higher values in RSD (ES: 1.21, large) than the arbitrary strategy on MD-2.

Relationship between RPE and external load according to quantification strategy.

Table 3 presents repeated measures correlation coefficients for RPE and sRPE with workload calculated through different quantification strategies. The sRPE was associated with some absolute values of workload. VHIR showed moderate associations (r_{rm} = 0.59 to 0.63) with sRPE regardless of the strategy used. Similarly, the MIR had moderate correlations with sRPE for arbitrary (r_{rm} = 0.68) and V_{IFT} strategies (r_{rm} = 0.59), while MSS presented a small correlation (r_{rm} = 0.47). Additionally, the RPE was associated with some relative values. For RVHIR, all external load quantification strategies showed small associations with RPE (r_{rm} = 0.38 to 0.41). There was a moderate association between RMIR and RPE in the arbitrary strategy (r_{rm} = 0.51), while the correlations were classified as small-to-trivial for V_{IFT} and MSS strategies, respectively.

DISCUSSION

This study analysed the differences in external load quantification between arbitrary and individualized thresholds based on MSS and V_{IFT} across the microcycle, and associations between internal load and distance covered in MIR and HIR depending on the ELQS in professional soccer players. To the authors' knowledge, this is the first study to examine the differences in external load quantification using individualized thresholds based on the V_{IFT} and MSS across the microcycle days. The main findings of the study are that (a) arbitrary thresholds underestimated the distance covered in all absolute and relative speed thresholds compared to the MSS external load strategy, whilst (b) the V_{IFT} strategy showed similar values to the arbitrary threshold for all training sessions, although underestimating the external load for all variables in MD, except for MIR and RMIR. Additionally, the associations between internal and external load metrics (i.e., MIR and HIR) showed similar relationships independently of the ELQS used.

From a physical performance perspective, the distance covered in HIR has been considered a crucial metric for attaining successful participation in competitive soccer scenarios [9]. Moreover, several studies determined the relationship between distance covered in HIR and injury occurrence in high-intensity intermittent team sports [10, 45]. Because of inappropriate HIR load monitoring, the coaches and practitioners could miss the possibility of providing an efficient physiological stimulus and reducing the likelihood of non-contact injuries in professional soccer [6, 9]. In the current study, our results revealed that distance covered in HIR, RHIR, and VHIR was higher in all training sessions and MD (~50–60%) when speed zones were individualized using MSS compared to arbitrary thresholds. Similarly, Hunter et al. [11] observed differences of 39% to 61% in total high-speed running and total very high-speed running when adjusting speed bands based on MSS compared to arbitrary thresholds in U18 elite soccer players. More recently, Rago et al. [26] analysed the differences in external load quantification in professional soccer players using individualized speed thresholds considering maximal aerobic speed (MAS), ASR, and MSS. In line with our results, these authors found likely moderate differences (ES: 0.86) in the distance covered in HIR when speed thresholds were individualized in comparison with arbitrary thresholds over the microcycle. Conversely, in reference to the V_{IFT} strategy, the distance covered in HIR solely showed a significantly greater distance covered in HIR, RHIR, and VHIR in MD. Thus, the lack of differences observed between the V_{IFT} strategy and arbitrary thresholds across the microcycle could be explained by a reduced HIR bandwidth compared to the MSS strategy. However, implementing the V_{IFT} strategy could contribute to better monitoring and management of the HIR weekly dose in professional soccer players, taking into account their metabolic characteristics to reproduce high-intensity intermittent efforts, and avoid exposure to large and abrupt spikes in HIR distance [9, 46].

Sprinting is considered a critical element due to its potential to concurrently increase performance and reduce injury risk in team sports athletes [6, 47, 48]. In fact, hamstring injury incidence could be reduced when elite soccer players were exposed to running bouts at near-to-maximal speed during training sessions [21, 49]. However, the implementation of arbitrary thresholds (i.e., $> 25\ km \cdot h^{-1}$) to monitor sprint weekly dose could lead to load error because of the lack of specificity in relation to the player's MSS [3, 13, 50]. In this study, the results showed that arbitrary thresholds underestimated the SD and RSD compared to MSS and V_{IFT} strategies on MD. Both individualized ELQS presented higher values in the distances covered in SD and RSD according to the player's individual locomotor profile. However, the V_{IFT} strategy could lead to an error (i.e., mainly overestimation) in SD quantification. Specifically, the V_{IFT} strategy would not allow proper monitoring of speeds considered protective (i.e., 85–95% MSS), when soccer players display a low value of V_{IFT} during $30–15_{IFT}$ and their MSS values are high [21, 47]. In this regard, the SD thresholds individualized based on MSS could ensure that players are monitored regarding their own sprint ability, avoiding under- or overestimation in SD exposure [51]. Further research is needed to elucidate the benefits of monitoring SD using different percentages of MSS (i.e., 85–95%) over the microcycle, and its association with injury risk.

To obtain an accurate dose-response relationship, it is necessary to monitor internal and external loads during training sessions or matches in team sports [2, 52]. Currently, there is limited evidence from analyses of the associations between speed thresholds individualized in accordance with players' physical characteristics and fitness and internal load in soccer players [53, 54]. Our results showed small to moderate within-individual correlations between sRPE and MIR, and moderate correlations with the VHIR metric for the different ELQSs. Regarding RPE, our results revealed small correlations for RVHIR in all ELQSs, but small to moderate in the RMIR metric for arbitrary and V_{IFT} strategies. Previously, Scott et al. [53] examined the associations between speed thresholds individualized according to different physiological measures (i.e., MSS, MAS heart rate deflection point, or final speed achieved during the Yo-Yo intermittent recovery test) and internal load (i.e., RPE, TRIMP (TRaining IMPulse), minutes spent above 80% maximal heart rate) in international female soccer players. In accordance with our data, these authors found that individualized speed thresholds did not show stronger associations with internal load variables than arbitrary thresholds. Likewise, Sparks et al. [54] reported that non-significant correlations ($r = 0.10$, trivial) were found between HIR individualized by MSS and heart rate responses in university-level soccer players. In the present study, it is noteworthy that only RPE and sRPE were analysed as a reflection of the player's internal load. Perhaps the presence of similar associations between arbitrary and individualized time-motion analysis strategies with the internal load measures could be explained by the low variability of RPE response (CV: ~5%) and the high variability in HIR and SD across the microcycle (CV: > 80%) and competition (CV range: 19.8–53%) in soccer [4, 55, 56, 57]. Future studies should consider the inclusion of more internal load variables (e.g., heart rate, blood lactate, perceived tissue damage, self-reported wellness measures) in order to investigate the relationships with external load individualized speed thresholds in professional soccer players.

The findings of this research should be interpreted with caution due to some specific limitations. Firstly, the sample is composed of only one professional team. The results could not be generalized to other soccer backgrounds, leagues, or competitive levels (i.e., amateur or semi-professional squads), due to the differences in competitive demands [58]. Secondly, we examined a total of 6 microcycles, which could be considered a relatively small sample size. However, this sample size was similar to other studies that analysed the differences between different ELQSs [17, 26]. Thirdly, the physiological cut-off points of $30–15_{IFT}$ were determined in line with previous research [16, 59] due to the complexity of applying laboratory assessments in large team sports squads. Lastly, the individualized speed thresholds were established according to specific physical attributes (i.e., MSS, V_{IFT}). In this regard, it has been suggested [11] that a combined approach (i.e., two different physical measures) could contribute to establishing locomotor profiles accurately, improving the quantification of external load. In line with Clemente et al. [25], further studies should attempt to implement a combined approach with V_{IFT} and MSS in order to provide better management of the dose-response relationship in soccer players.

CONCLUSIONS

Workload monitoring is a relevant piece of the puzzle to appropriately programme training sessions, recovery strategies, and training drills during the microcycle. The application of arbitrary thresholds might lead to an external load quantification misconception by soccer coaches and sports scientists. This study showed that arbitrary thresholds lead to underestimation of external load absolute (i.e., MIR, HIR, and VHIR) and relative (i.e., RMIR, RHIR, and RVHIR) metrics compared to the MSS strategy throughout the microcycle. The V_{IFT} strategy mainly revealed differences in external load quantification regarding MD compared to arbitrary thresholds. Likewise, both individualized strategies led to different results in terms of external load quantification across microcycle days. Finally, the individualized speed threshold strategies did not achieve better associations with internal load measures (i.e., RPE, sRPE) in comparison with arbitrary thresholds in professional soccer players.

Conflict of interest

The auuthor declared no conflict of interest.

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Do players with superior physiological attributes outwork their less-conditioned counterparts? A study in Gaelic football

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ABSTRACT: This study investigated the association of physiological attributes with in-game workload measures during competitive Gaelic football match-play. Fifty-two male developmental level Gaelic football players (mean ± SD; age: 22.9 ± 3.8 years) underwent measurements of anthropometric characteristics, running speed, muscular strength and power, blood lactate (BLa), running economy and aerobic capacity during two separate testing visits. Global Positioning System units (18-Hz) were used to record players in-game workloads during a competitive match 1-week following the baseline physiological assessments. Results indicated that players body fat percentage, drop jump height (DJ) and running velocity at 4 $mmol \cdot L^{-1}$ BLa were significantly associated with the number of high-speed runs completed (Adjusted R^2 26.8% to 39.5%; $p < 0.05$) while 20 m running speed, running velocity at 2 $mmol \cdot L^{-1}$ BLa and DJ were significantly associated with the number of accelerations completed (Adjusted R^2 17.2% to 22.0%; $p < 0.05$) during match-play. Additionally, aerobic capacity and body fat percentage were significantly associated with total distance (Adjusted R^2 14.4% to 22.4%; $p < 0.05$) while body fat percentage, DJ and 20 m running speed were significantly associated with high-speed distance (Adjusted R^2 17.8% to 22.0%; $p < 0.05$). Players were also divided into higher-standard and lower-standard groups using a median split of these physiological attributes. Players in the higher-standard groups completed significantly more high-speed runs and accelerations and covered significantly larger total and high-speed distances (+10.4% to +36.8%; ES = 0.67 to 0.88; $p < 0.05$) when compared to the lower-standard groups. This study demonstrates that superior levels of physical conditioning are associated with larger in-game workloads during Gaelic football match-play.

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INTRODUCTION

Gaelic football is a field-based team sport predominantly characterised by low to moderate intensity activity interspersed with critical bouts of high-intensity actions, which can often influence a games result [1, 2]. To support these demands, a large aerobic capacity, well-developed blood lactate responses and efficient running economy (RE) may be necessary to generate and maintain the considerable workloads (≈ 100 to 130 $m \cdot min^{-1}$) observed during match-play [1, 2]. On the other hand, neuromuscular-related performance characteristics such as short distance running speed, power and relative strength likely underpin the performance of numerous high-speed running and power-based tasks [2, 3]. Notwithstanding the significant tactical organisation and technical skill proficiency necessary for a team sport such as Gaelic football, possessing the physical capacity to undertake a greater volume and intensity of work than the opposition is suggested to be a key requisite to successful match-play [2, 4, 5].

Whilst components of fitness are anecdotally thought to influence players in-game workloads during Gaelic football match-play [1, 3], empirical data exploring these interactions are limited. In contrast, a body of research exists assessing relationships between physical conditioning, playing standard, coaches' perceptions of performance and in-game workload measures in team sports similar to Gaelic football [6–8]. For instance, evidence suggests that players with superior levels of aerobic-based performance attributes undertake more sprints and accelerations, cover larger total and high-speed distances and participate in more ball involvements than their less aerobically proficient counterparts in rugby union [6] and soccer [8, 9]. Although this data does not currently exist within Gaelic football, the ability to frequently express high levels of power, speed and changes of pace/direction during match-play necessitates the rapid regeneration of anaerobic substrates [10] which is a process heavily reliant on aerobic metabolism [11, 12]. In Gaelic football, inter-county players (national level; tier 3) are reported to exhibit significantly higher estimated $\dot{V}O_{2max}$ values than club players (developmental level; tier 2) [13], possibly reflecting the importance of aerobic fitness in high-level performance [4]. While it may be likely that well-developed aerobic capabilities are necessary to cope with the physiological stressors of Gaelic football match-play [1], this is yet to be investigated directly.

Similar to markers of aerobic function, body composition has also been identified as an important indicator of Gaelic football performance through its impact on players capacity to run, jump and change direction/pace [3, 14, 15]. In soccer for example, players body fat levels have been negatively associated with high-speed running performance [14]. Despite the implications of these reports, an absence of applied data in Gaelic football makes it difficult to accurately surmise the extent with which body composition and other relevant components of fitness influence the unpredictable and multivariate in-game workload demands players face during competition [1].

Given the strenuous mechanical loads players are subject to during Gaelic football match-play, such as frequent accelerations/decelerations, sharp changes of direction and landing from jumps [2, 16]; it is reasonable to assume that strength, power and running speed facilitate players capacity for work [5, 17]. In team sports comparable to Gaelic football, lower body strength, power and running speed have been positively associated with acceleration and sprint number, distances covered at varying speeds and a number of key performance indicators such as effective turnovers and ball possessions during match-play [5, 6, 9]. Supporting the relevance of these markers in a team sport performance-specific setting, research in soccer reported that the number of high-intensity accelerations ($> 3\ m \cdot s^{-2}$) and decelerations ($< -3\ m \cdot s^{-2}$) recorded during elite match-play presented a significant dose-response relationship with match outcome; whereby outputs were highest during wins and lowest during draws or losses [7]. Similar findings were reported in Gaelic football specifically, where competitive workloads (total and high-speed distance [$\geq 4.7\ m \cdot s^{-1}$]) were observed to be higher during wins or draws when compared with losses [18].

Successfully undertaking these tasks in a fast-paced contact environment necessitates the rapid application of high force levels accompanied by the repeated performance of quick and powerful muscular contractions [5]. Thus, corresponding relationships between neuromuscular performance characteristics and workloads may exist in Gaelic football, wherein players undertake large volumes of stretch shortening cycle based movements comprising high eccentric loads [7, 19]. Indeed, when comparing playing standards in Gaelic football elite level players display significantly greater vertical and broad jump scores than their sub-elite counterparts, possibly highlighting a key role of lower-body power in successful competitive performances [4].

In summary, the above studies have detailed how various components of fitness positively impact in-game workload measures, playing standard and match outcome in team sports similar to Gaelic football [5, 6, 9]. Nevertheless, this research has yet to be replicated in Gaelic football, where many considerations unique to the sport may limit the applicability of training or match-based decisions derived from data collected in other team sport codes. Consequential to this lack of research, pivotal assumptions as to the importance of different components of fitness in relation to game-specific work capacity are rooted in data from other sporting populations. As such, in order to provide objective data for coaches to design effective training programmes with the goal of increasing competitive workloads, it may be necessary to address these interactions in an ecologically valid context [19]. Therefore, this study aims to investigate the association of players components of fitness on in-game workload measures in Gaelic football.

MATERIALS AND METHODS

Subjects

Fifty-two male developmental level Gaelic football players currently representing a senior club level Gaelic football team volunteered to partake in this study. Players' anthropometric, physiological and performance characteristics can be seen in table 1. Players were

TABLE 1. Descriptive overview of players' anthropometric, physiological and performance characteristics.

Baseline characteristics	Value
Anthropometrics and body composition	
Height (cm)	179.2 ± 7.6
Body mass (kg)	81.4 ± 9.0
Body fat (%)	14.5 ± 2.0
Running speed	
Running speed (5 m) (s)	1.1 ± 0.1
Running speed (20 m) (s)	3.1 ± 0.1
Muscular power and reactive strength	
DJ (cm)	33.6 ± 5.0
CT (s)	0.3 ± 0.1
DJ (RSI)	1.1 ± 0.4
CMJ (cm)	34.3 ± 5.2
Muscular strength	
1RM squat (kg)	107.4 ± 12.9
Relative 1RM squat (1RM/BM)	1.3 ± 0.2
1RM Hip thrust (kg)	127.9 ± 26.1
Relative 1RM hip thrust (1RM/BM)	1.6 ± 0.3
Aerobic endurance	
$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	51.4 ± 7.2
Maximal heart rate ($beats \cdot m^{-1}$)	199.6 ± 6.5
Running velocity at LT ($km \cdot h^{-1}$)	10.5 ± 1.0
Running velocity at 2 $mmol \cdot L^{-1}$ BLa ($km \cdot h^{-1}$)	9.7 ± 1.6
Running velocity at 4 $mmol \cdot L^{-1}$ BLa ($km \cdot h^{-1}$)	13.2 ± 1.2

Abbreviations; DJ: drop jump, $\dot{V}O_{2max}$: maximal aerobic capacity, LT: lactate threshold, 1RM: One repetition maximum, RSI: reactive strength index, BM: body mass, BLa: blood lactate, CT: contact time.

omitted from this study if they failed to pass a physical activity readiness questionnaire (PAR-Q) or had endured a lower body injury in the previous 8-weeks. Informed consent was obtained from each player and ethical approval was granted for this research by the Technological University of the Shannon Research Ethics Committee (code 20180501).

Experimental Outline

Previous research [5, 6, 9] and the physical demands of Gaelic football match-play [2, 19] guided the selection of physical conditioning measures to be assessed during baseline testing. The testing procedures were explained to the players during a familiarization session. During visit-1, players' anthropometric characteristics (body mass, height and body fat percentage (body fat [%]) one-repetition maximum (1RM) relative squat strength, blood lactate concentrations (BLa) (lactate threshold, running validity at 2 and 4 mmol $\cdot$ L^{-1}), RE and maximal aerobic capacity ($\dot{V}O_{2max}$) were assessed. Players' countermovement jump height (CMJ), drop jump height (DJ), contact time (CT), reactive strength index (RSI), 5 m and 20 m running speed (running speed [5 m] and [20 m]) and 1RM relative hip thrust strength were measured during the second visit to our lab. Both testing sessions were completed at the same time of day. Players were instructed to arrive hydrated and well rested. One week after the baseline testing, players' in-game workload measures were recorded during a competitive match using global positioning system (GPS) units (Figure 1). To facilitate a high level of ecological validity, a maximum of four players were tested per game. Data was collected in 18 competitive matches spanning 2 seasons and players were recruited from 5 different teams.

Procedures

Body mass and height were measured to the nearest 0.1 cm and 0.1 kg respectively, using a portable scales and stadiometer (Seca 707 Scales, Hamburg, Germany). Players' skinfold thickness was measured at seven anatomical sites using a skinfold callipers (Baty, UK) as described in previous methods [19]. Here, three measurements for each skinfold on the right side of the body were obtained to the nearest 0.2 mm using the International Society for the Advancement of Kinanthropometry (ISAK) protocols [19]. Pilot testing was undertaken in order to verify the reliability of the anthropometrical measurements performed as the investigator was not ISAK accredited [20, 21]. Following intra-rater reliability assessments, the technical error of measurement of 4 repeated skinfold trials was lower than 5%, which is in line with recommendations [20]. To calculate players' body fat (%), the equation of Withers and colleagues [22] (% BF $= 495/(1.0988 - 0.0004 \times$ [sum of seven skinfolds]) $- 450$) was used. This equation has previously demonstrated the low bias and high agreement (r = 0.88) with criterion dual energy absorptiometry (DEXA) measurements [23].

Players' 1 repetition maximum (1RM) squat values were assessed using the incremental protocol described previously by Baechle and Earle [24]. Briefly, players completed a general 10-minute warm up including stationary cycling, dynamic stretching of the lower body and 10 repetitions of an empty Olympic bar (20 kg). After 2-minutes rest, an incremental warm up of 5–8 repetitions at 40% to 60% of their estimated 1RM (E1RM) followed by 3–5 repetitions at 60% to 80% of E1RM with 3–5 minutes rest between sets. Next, the lead researcher issued 1–10 kg weight increments for single repetition attempts. The players rested 3–5 minutes following each attempt and

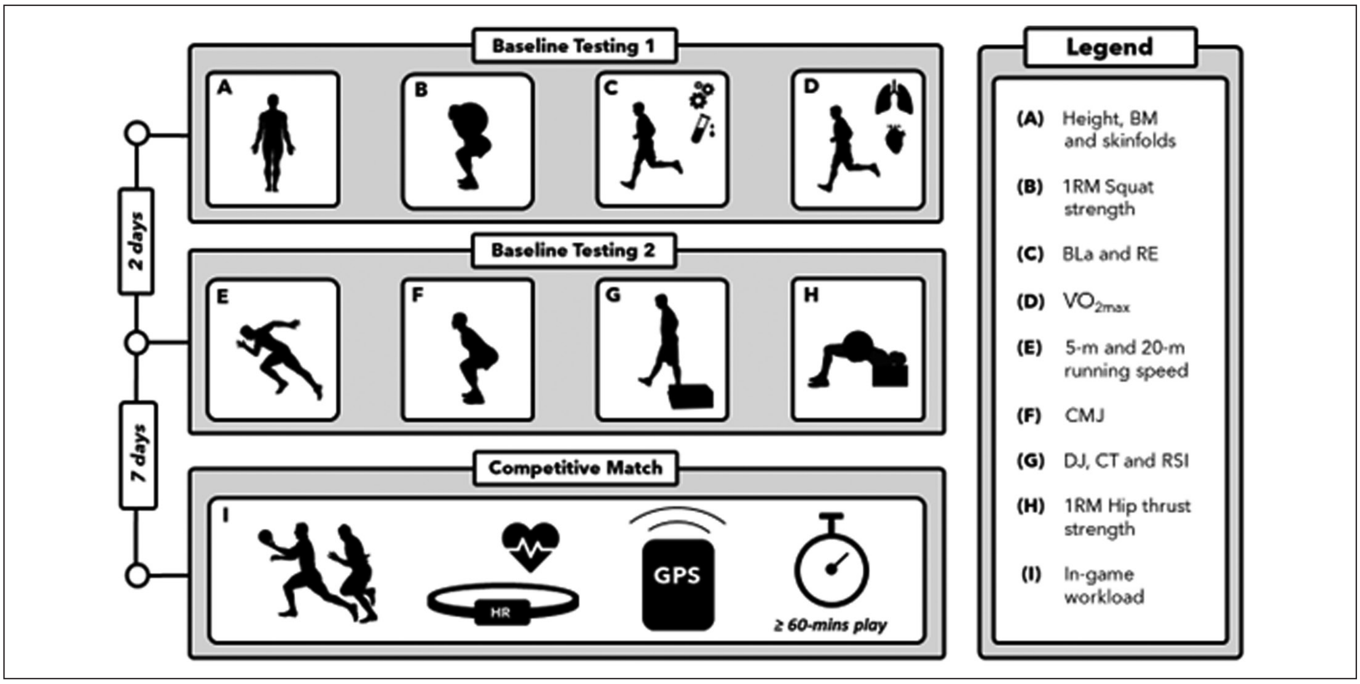

FIG. 1. Schematic overview of study methodology.

repeated as necessary until a 1RM was established. Players' 1RM was recorded as the greatest resistance (kg) lifted successfully through a full range of motion as assessed by the lead investigator. Players' relative strength measures were calculated by dividing 1RM values (kg) by their body mass (kg).

Players' $\dot{V}O_{2max}$ and RE were measured using a Moxus metabolic cart (AEI Technologies, PA, USA) on a motorized treadmill (Quasar, HP Cosmos, Germany) using an incremental incline ramp protocol [3, 25]. Subsequent to a 3-minute warm-up at $8 km \cdot h^{-1}$ on a 1% gradient, the speed of the treadmill incrementally increased by $1 km \cdot h^{-1}$ every 3-minutes until the players' blood lactate concentrations reached $4 mmol \cdot L^{-1}$ or higher. To collect lactate samples, the base of the earlobe was first wiped with an alcohol wipe and allowed to dry, before being pierced with a lancet (AccuChek; Softclix, Roche, Germany). The first drop of blood was then swabbed away with another alcohol wipe and pressure was then applied with the thumb and forefinger to draw a 5-μl capillary blood sample. The sample was automatically aspirated (via capillary action) into an enzyme-coated electrode test strip and analysed using a portable amperometric microvolume lactate analyser (Lactate Pro 2, Arkray, Japan) to determine whole BLa concentration. In order to collect the sample, players stepped to the side and straddled the treadmill for approximately 20 seconds following completion of the previous stage, and the speed and/or incline was changed accordingly before the subsequent stage. The lactate analyser used has previously demonstrated high levels of validity (intraclass correlation coefficient [ICC] = 0.87) and reliability (ICC = 0.99) [26]. Applying methods previously described elsewhere [3, 25], plots of BLa, $\dot{V}O_2$ and running speed were generated with an exponential trendline and provided to two independent reviews. Lactate threshold (LT) was identified as the first sustained increase in BLa above the baseline values. Markers of 2 and $4 mmol \cdot L^{-1}$ were also identified on these plots. Once $4 mmol \cdot L^{-1}$ or greater was recorded, a constant speed of $10 km \cdot h^{-1}$ was set on a 4% gradient, increasing the gradient by 1% each minute until volitional exhaustion [25, 27]. Players' heart rate (HR) was measured using a watch and chest strap (Polar Vantage, Polar Electro, Finland) at the end of each stage. During the test, expired CO_2, expired O_2, ventilatory volume/rate, HR and rate of perceived exertion were continuously monitored. RE and $\dot{V}O_{2max}$ were reported in $ml \cdot kg^{-1} \cdot min^{-1}$ using the average of the final two 30 s values [25].

Players' running speed was recorded over 5 m and 20 m using photoelectric cells (Brower Timing Systems, UT, USA). These photoelectric cells have been reported as valid (standard error of measurement = 0.1 s) and reliable (coefficient of variation = 0.1%) [28]. The players were instructed to start by placing forward their dominant foot on a mark 50 cm behind the starting line. Timing gates were placed at the starting line, 5 m line and the 20 m line. Players completed three runs, with the best time recorded as their result. Players rested 4–5 minutes between each trial.

Players' CMJ and DJ were evaluated using a photoelectric optical device (Optojump, Microgate, Italy). This measurement system has previously displayed low random errors (± 2.8 cm) and coefficients of variation (2.7%) [29]. Players performed the CMJ whilst standing on a standardised surface between two photoelectric measurement bars with hands placed on their hips. Next, a countermovement action was undertaken by the players using self-selected ankle, knee and hip flexion angles before jumping vertically as high as possible. When performing the DJ, players began the jump standing on a 30 cm high step with their hands placed on their hips before stepping off and immediately jumping vertically as high as possible when contacting the ground. Here, players were instructed to jump to a maximal height while simultaneously minimising ground contact time. The players' 1RM hip thrust was assessed using the same incremental protocol as the squat test [24].

Players' in-game workloads were recorded using 18 Hz GPS units (Apex, STATSports, UK). This model of GPS unit has previously demonstrated good levels of validity (Bias $< 5.0\%$) [30]. Players were fitted with an appropriately sized vest to hold the GPS receiver. Each GPS unit was powered on 15-minutes before throw-in and inserted into a slot towards the top of the fitted vest sitting in the upper back. A HR telemetry system (Polar Vantage, Polar Electro, Finland) with an accompanying strap was placed around the chest to collect HR data. The workload and HR data were then extracted from the GPS devices and downloaded using the STATSports analysis platform [19]. Total distance (m), total accelerations (*n*) ($\geq 3 m \cdot s^{-2}$), total high-speed runs (*n*) ($\geq 5 \cdot 5 m \cdot s^{-1}$), and high-speed distance ($\geq 5.5 m \cdot s^{-1}$) were the metrics used to quantify in-game workloads in the current analysis. These metrics were specifically selected as they have been commonly used in the literature and may subsequently help translate current results into applied and research settings [2, 16, 31, 32].

Statistical Analyses

Descriptive statistics using means and standard deviations (± SD) were calculated for all anthropometric characteristics, components of fitness and in-game workload measures. All data were normally distributed as assessed by Shapiro-wilk tests. Standard multiple regression analysis was performed to examine possible relationships between components of fitness and in-game workload measures [33]. These tests were selected in order to provide a statistical summary of the associations (or lack thereof) between the various independent variables whilst accounting for potential between-variable interdependence [33]. An *a priori* power analysis was conducted to estimate the sample requirements for the multiple regression analysis using G*Power (version 3.1.9.7). Power was set at 0.95 in conjunction with a significance level of 0.05 and an effect size (ES) of 0.3, which yielded a minimum sample size of 38 players [33]. Additional players were requited to account for possible drop out. A median split divided players into higher-standard (HS) and lower-standard (LS) groups for each component of fitness significantly contributing to the multiple regression analysis, similar to previous work in the domain [5, 34]. Independent samples t tests and Cohen's ES statistic were used to examine differences between-group differences. Effect sizes of > 0.20, 0.20–0.60, 0.61–1.19, and > 1.20 were considered trivial, small, moderate, and large respectively [35]. Data were analysed using Statistical Package for Social Sciences (SPSS Version 27, Chicago, USA). Statistical significance was accepted at an alpha level of $p < 0.05$.

RESULTS

Results of the multiple regression analysis are summarised in table 2 and the plots of actual versus predicted residuals are depicted in figure 2 and 3.

Table 3 shows the HS and LS descriptive variables for each component of fitness.

The differences between HS and LS groups based off each component of fitness are shown in figure 3 and 4. When players were dichotomized into HS and LS running velocity at 2 mmol·L^{-1} groups, the HS group performed significantly more 1st half accelerations (ES = 0.76; p = 0.008), 2nd half accelerations (ES = 0.64; p = 0.027) and total accelerations (ES = 0.76; p = 0.009) than the LS group. Additionally, the HS running velocity at 2 mmol·L^{-1} group covered significantly larger 1st half high-speed distance (HSD) (ES = 0.62; p = 0.031) and performed significantly more 1st half high-speed runs (HSR) (ES = 0.88; p = 0.003), 2nd half HSR (ES = 0.86; p = 0.003) and total HSR (ES = 0.95; $p < 0.001$) when compared to the LS group. When players were divided into HS and LS running velocity at 4 mmol·L^{-1} groups the HS group performed significantly more total HSR (ES = 0.68; p = 0.015) than the LS group. When players were divided into HS and LS $\dot{V}O_{2max}$ groups the HS group covered significantly greater 1st half distances (ES = 0.56; p = 0.048) and total distances (ES = 0.57; p = 0.045) when compared to the LS group.

When players were divided into HS and LS body fat (%) groups, the HS group covered significantly greater 2nd half distances (ES = 0.75; p = 0.038), total distances (ES = 0.67; p = 0.20), 1st half HSD (ES = 0.58; p = 0.042) and total HSD (ES = 0.59;

TABLE 2. Summary of Multiple regression analysis.

Model predictors	Dependant variable	Adj. R^2 (%)	p value
Body fat (%), DJ and running velocity at 4 mmol·L^{-1}	HSR (n) (≥ 5.5 m·s^{-1}) (1st half)	27.5	< 0.001
	HSR (n) (≥ 5.5 m·s^{-1}) (2nd half)	26.8	< 0.001
	HSR (n) (≥ 5.5 m·s^{-1}) (Match)	39.8	< 0.001
Relative squat strength and DJ	Total accelerations (n) (≥ 3 m·s^{-2}) (1st half)	17.2	0.007
	Total accelerations (n) (≥ 3 m·s^{-2}) (2nd half)	22.0	0.002
	Total accelerations (n) (≥ 3 m·s^{-2}) (Match)	21.2	0.002
$\dot{V}O_{2max}$ and body fat (%)	Total distance covered (m) (1st half)	14.4	0.009
	Total distance covered (m) (2nd half)	21.3	0.001
	Total distance covered (m) (Match)	22.4	0.001
Running speed (20 m), running velocity at 2 mmol·L^{-1} and DJ	HSD (m) (≥ 5.5 m·s^{-1}) (1st half)	17.8	0.006
	HSD (m) (≥ 5.5 m·s^{-1}) (2nd half)	21.2	0.002
	HSD (m) (≥ 5.5 m·s^{-1}) (Match)	27.0	< 0.001

Abbreviations; Adj: Adjusted, DJ: drop jump, HSD: high-speed distance, HSR: high-speed runs, $\dot{V}O_{2max}$: maximal aerobic capacity, 1st half: first half of a match, 2nd half: second half of match; Match: full match.

TABLE 3. Descriptive results for each higher-standard and lower-standard group.

Component of Fitness	Higher standard	Lower standard
Body fat (%)	11.5 ± 2.0	17.5 ± 4.1
$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	57.4 ± 4.2	45.3 ± 3.8
Running velocity at 2 mmol·L^{-1} (km·h^{-1})	11.2 ± 0.8	8.2 ± 0.4
Running velocity at 4 mmol·L^{-1} (km·h^{-1})	14.4 ± 0.7	12.5 ± 0.8
Running speed (20 m) (s)	3.04 ± 0.04	3.18 ± 0.05
DJ (cm)	37.6 ± 2.5	29.7 ± 3.6

Abbreviations; DJ: drop jump, $\dot{V}O_{2max}$: maximal aerobic capacity.

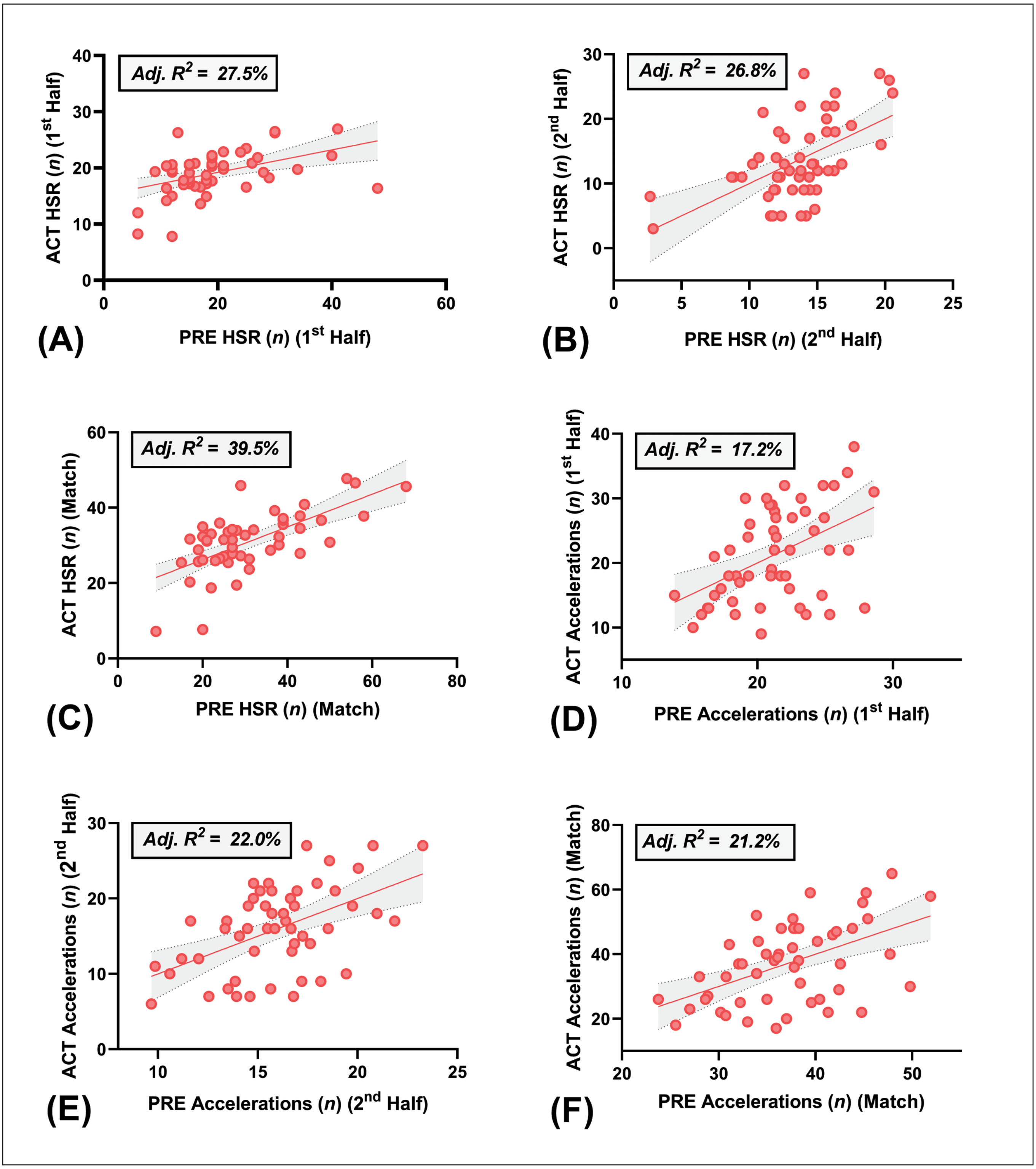

FIG. 2. Plot of actual (ACT) vs. predicted (PRE) values for the number of **(A)** 1st half high-speed runs (HSR), **(B)** 2nd half HSR, **(C)** full match HSR, **(D)** 1st half accelerations, **(E)** 2nd half accelerations and **(F)** full match accelerations completed during match-play. Dependant variables for total HSR (*n*) (≥ 5.5 $m \cdot s^{-1}$): body fat (%), drop jump and running velocity at 4 $mmol \cdot L^{-1}$. Dependant variables for total accelerations (*n*) (≥ 3 $m \cdot s^{-2}$): running speed (20 m), running velocity at 2 $mmol \cdot L^{-1}$ and DJ). Shading represents 95% confidence intervals.

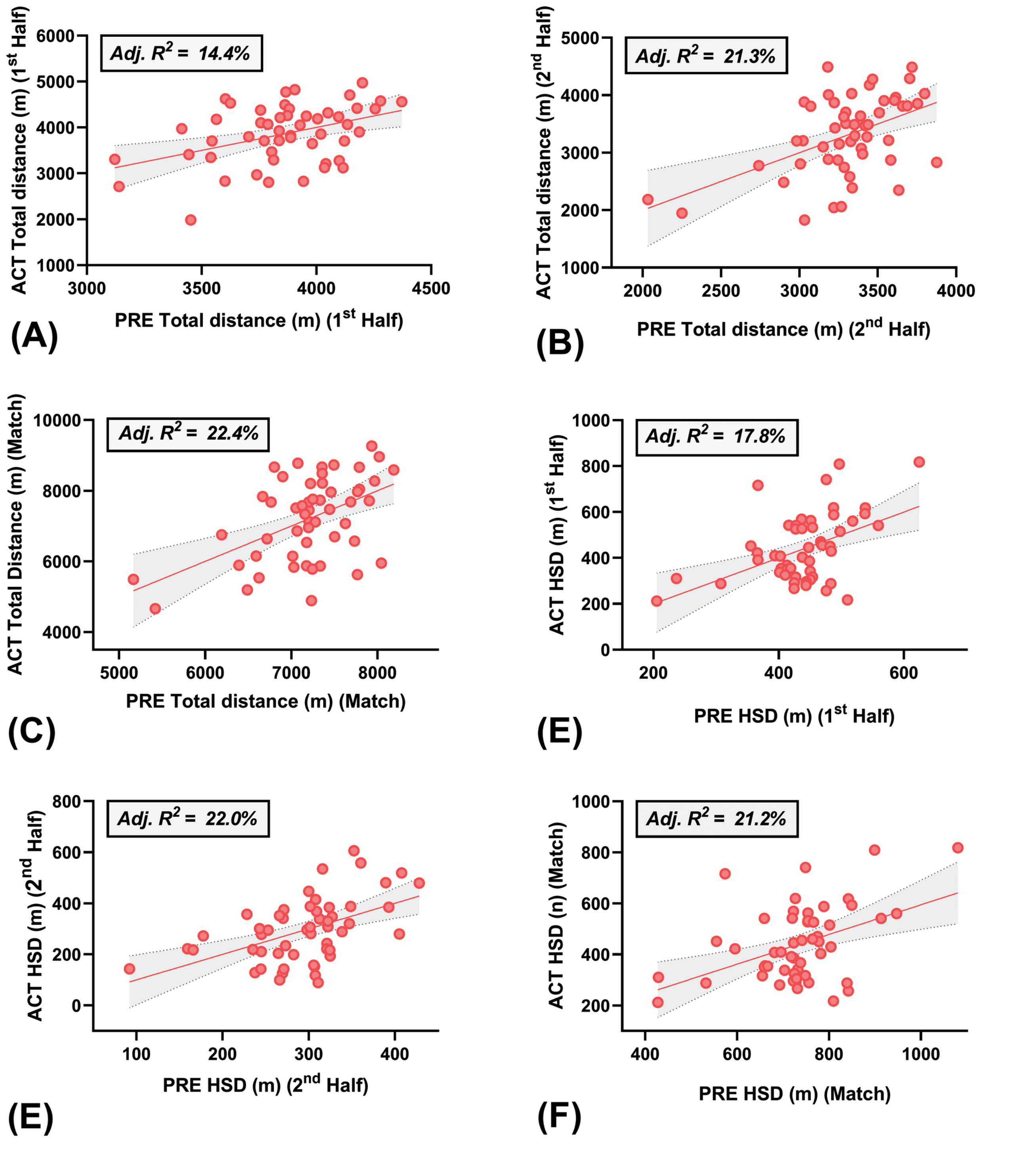

FIG. 3. Plot of actual (ACT) vs. predicted (PRE) values for **(A)** 1st half distance, **(B)** 2nd half distance, **(C)** full match distance, **(D)** 1st half high-speed distance (HSD), **(E)** 2nd half HSD and **(F)** full match HSD covered during match-play. Total distance (m) dependant variables: $\dot{V}O_{2max}$ and body fat (%). HSD (≥ 5.5 m·s $^{-1}$) (m) dependent variables: body fat (%), drop jump and 20 m running speed. Shading represents 95% confidence intervals.

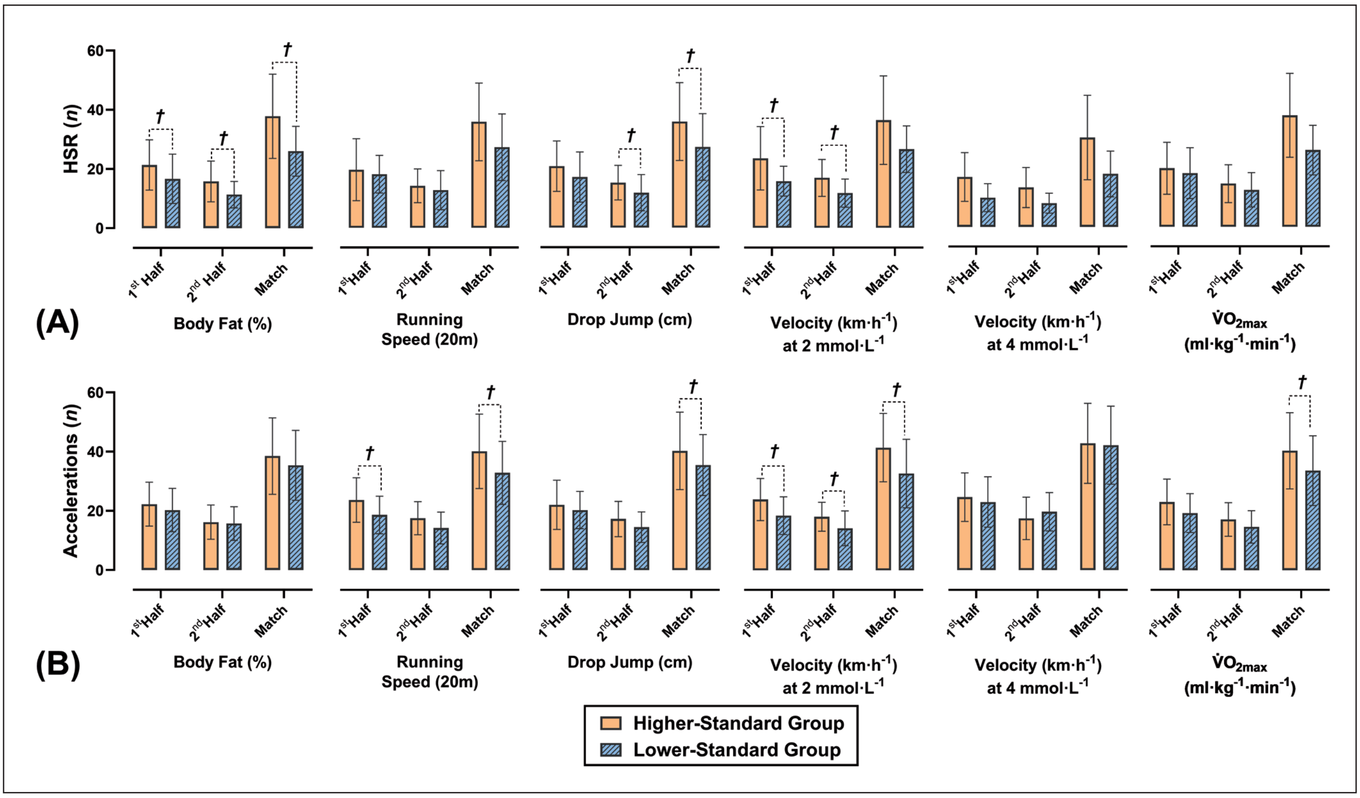

FIG. 4. Differences in the number of accelerations **(A)** and high-speed runs (HSR) **(B)** completed during match-play between higher-standard (HS) and lower-standard (LS) component of fitness groups. † Denotes a significant difference between HS and HS groups.

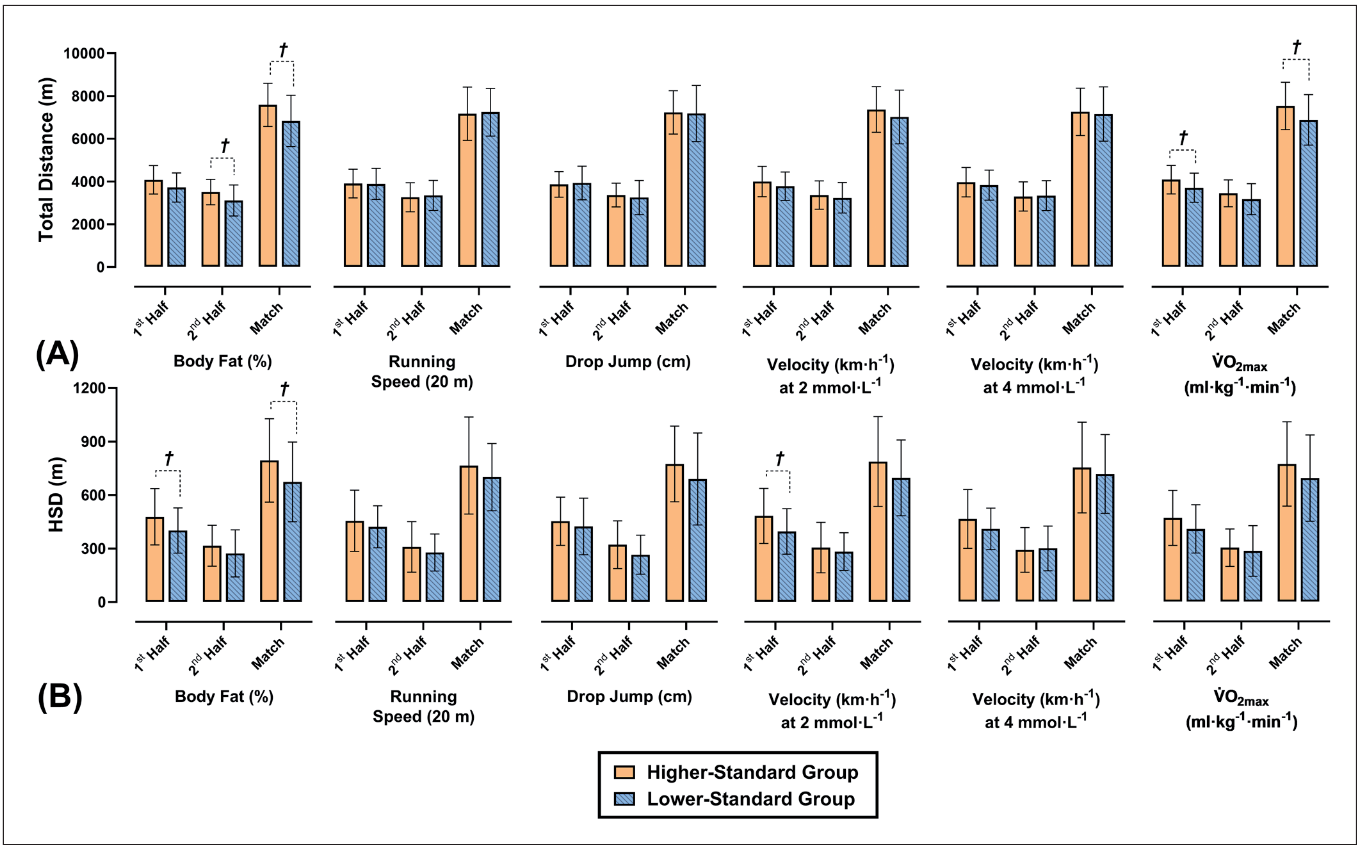

FIG. 5. Differences in total distance covered **(A)** and high-speed distance (HSD) covered **(B)** during match-play between higher-standard (HS) and lower-standard (LS) component of fitness groups. † Denotes a significant difference between HS and HS groups.

$p = 0.038$) when compared to the LS group. Additionally, players in the HS body fat (%) group performed significantly more 2nd half HSR (ES = 0.77; $p = 0.008$) and total HSR (ES = 0.71; $p = 0.014$) when compared to the LS group. Furthermore, when players were split into HS and LS 20 m running speed groups, the HS group performed significantly more accelerations during the 1st half (ES = 0.74; $p = 0.011$), 2nd half (ES = 0.60; $p = 0.035$) and full game (ES = 0.72; $p = 0.013$) when compared to the LS group. Finally, when players were dichotomized into HS and LS DJ groups, players in the HS group performed significantly more 2nd half HSR (ES = 0.57; $p = 0.047$) than the LS group.

DISCUSSION

This study aimed to investigate the association of Gaelic football players body composition and markers of physical conditioning with in-game workload measures. Some of the physiological attributes measured are the first to be reported in Gaelic football, and the markers may be used by practitioners as benchmark scores for training and profiling purposes (Table 2). Additionally, the workload data reported is similar to prior analysis in developmental Gaelic football players [2] and may be used by practitioners to structure and monitor training sessions and inform return to play protocols (figure 4 and 5). The current data demonstrates that a wide range of components of fitness significantly associate with external load measures during competitive match-play, complimenting research in similar team sports [8, 9, 34].

Similar to previous results in soccer [36], blood lactate responses were significantly associated with the number of accelerations/HSR completed and the HSD covered during competitive match-play (table 1). Capacity to perform these high-intensity tasks are often crucial for team sport performance; possibly serving as a surrogate measure of successful contests for possession, entering space during scoring opportunities, defensively tracking opposition players movements and coping with fast-paced and potentially evolving tactical requirements [2, 37, 38]. Moreover, when players were divided into HS and LS groups based on running running velocity at 2 $mmol \cdot L^{-1}$, the HS groups performed significantly more accelerations and HSR during match-play than the LS groups, which corresponds with previous work in ice hockey [39]. Equivalent associations were also reported in female soccer players, where lactate responses were significantly correlated with high-intensity running distances during simulated [40] and competitive match-play [36].

Other markers of aerobic function displayed comparable trends in the present analysis, whereby well-developed $\dot{V}O_{2max}$ (in combination with body fat [%]) significantly contributed to a regression model associated with total distance covered during match-play. Furthermore, when players were dichotomised into groups using higher and lower $\dot{V}O_{2max}$ scores, the HS $\dot{V}O_{2max}$ group covered significantly greater total distances when compared to their LS group counterparts, which is consistent with work in rugby league [5]. These collective observations present evidence that aerobic capacity plays a fundamental role in the considerable running demands undertaken during team sport match-play. In line with this premise, aerobic capacity was positively associated with total distance, high speed running distance and high-intensity efforts during rugby league [5], Australian rules football [41] and soccer [9] match-play respectively. Furthermore, well-developed aerobic conditioning and blood lactate response have been reported to accelerate metabolite clearance, improve phosphocreatine resynthesis and reduce the metabolic and cardiovascular strain associated with recurrent high-intensity running [10, 25] possibly helping to explain current findings. Specifically, energy for these high-intensity actions is supplied by anaerobic metabolism resulting in lactate formation, hydrogen ion accumulation, pH reduction and the depletion of adenosine triphosphate phosphocreatine stores paralleled with inorganic phosphate increases [11, 12, 25]. In response to these disruptions, oxidative phosphorylation is a necessary process to achieve adequate recovery prior to the next bout of intense work during match-play and this mechanism is enhanced in aerobically fitter athletes [10, 11]. Overall, many possible adaptations associated with well-developed aerobic function and/or blood lactate responses, such as increased muscle capillarization, mitochondrial volume and density and oxidative enzyme activity could have possibly contributed to the present results [3, 10, 12].

Similar to research in soccer [14], body fat percentage was negatively associated with the number of HSR and accelerations completed and the total and HSD covered. Body composition exerts an important influence on players game-specific work capacity, as excess adipose tissue can increase mechanical and metabolic strain by adding unnecessary resistance against the forces of gravity during movements such as jumping, running or changes of direction [14, 15, 23]. In addition to the energy cost of bearing a larger body mass over the course of a match, it is possible that excessive adipose tissue in Gaelic football players could impair thermoregulatory function by impeding capacity to transport and dissipate metabolically generated body heat, thereby potentially disrupting thermal balance [14, 42]. In support of this premise, it is commonly reported that elite level players possess lower body fat percentages then their sub-elite counterparts within Gaelic football [4] and other team sports [43]. Considering the potential overlap in training adaptations associated with improving body composition, blood lactate responses and aerobic conditioning; programming strategies to increase these attributes in tandem with the goal of improving players work capacity may possibly be employed with relatively minimal physiological interference [44]. That being said, the multifaceted physical demands of Gaelic football match-play imply that other components of fitness such as strength, power and running speed may also moderate players external match-play loads as has been reported previously in other team sports [5, 9, 17].

Although movement patterns during invasive team sports such as Gaelic football are predominantly low-intensity in nature, explosive stretch shortening cycle actions imposing high mechanical tension regularly occur at pivotal moments of a game [1, 2]. As a consequence of such taxing neuromuscular demands, muscular strength and power are commonly acknowledged as important attributes for team sport performance [5, 27, 45]. Indeed, measures of maximal force and power generating capacity have been previously related to in-game workload measures such as running speed and the number of sprints/accelerations completed in rugby league [5]. Our data supports these findings, whereby DJ was significantly associated with the number of HSR and accelerations completed. Therefore, coaches may select the development of players lower body power as a potentially effective means to increase high intensity running indices and the capacity to perform numerous accelerations during competitive matches. In agreement with prior work [46], the current analysis reported that players in the HS 20 m running speed group performed significantly more accelerations during match-play than their LS group counterparts. Based on this data, it is possible that the number of HSR and accelerations recorded during competitive Gaelic football match-play may be modulated by players baseline DJ and 20 m running speed values. If this is the case, it may be possible that implementing training processes to develop these performance attributes may deliver a high transfer efficacy for Gaelic football specific tasks and subsequently promote players external workloads, and ultimately performance. Of note, caution should be exercised when interpreting data such as accelerations or decelerations during match-play, given variance in approach demands (e.g., walking vs. sprinting) will greatly alter the physiological demands imposed by a change of pace, yet will be reflected in the same net increase or decrease in speed [47, 48].

The current findings provide evidence that Gaelic football players competitive running and acceleration profiles are associated with their physical conditioning attributes. Specifically, lower body power, running speed, body composition, aerobic capacity and blood lactate responses display significant associations, which is complementary to findings in other team sports [9, 36, 39]. Furthermore, when players were dichotomised into HS and LS groups based off these conditioning markers, the HS groups almost always performed more external work than the LS groups. In combination with prior research [27], these findings suggest that players with well-developed components of fitness express comparatively lower fatigue and muscle damage responses, even despite undertaking larger external loads during competition than their less physically conditioned counterparts. This data may improve coaches understanding of the complex interactions between physical conditioning and in-game workload measures, thereby providing relevant guidance for effective training programme design intent on increasing sport-specific work capacity. Despite promising findings as to the role of physical conditioning in the determination of game-based workloads, this data is most relevant to the population studied and limitations may exist applying this research in female players or in other team sport athletes. Finally, future research assessing relationships between players physical conditioning attitudes and coaches subjective scoring of match performance would provide beneficial information for a more sport-specific outlook when viewed in conjunction with the current work. Whilst the current findings demonstrate that various physiological attributes coincide with superior match-specific work capacity, it is difficult to surmise whether improvements in these physiological parameters would elicit meaningful increases in these outcomes. To the best of the authors knowledge, this has yet to be examined in any team sport population, as the contemporary work in the area exclusively employs cross-sectional and observational study designs [6, 8, 9, 39]. Hence, as highlighted by Steel and colleagues [49], causality may not be assumed from the present work or many previous analyses, and future research should seek to investigate if the further development of physical conditioning measures provides additional benefits for increasing in-game workloads. Furthermore, if the links are indeed reported to be causative, it would be useful for practitioners to understand: (1) does the magnitude of enhanced responses reflect the magnitude of physiological improvements? or (2) is there a ceiling effect, whereby increases in physical conditioning beyond a certain point may present diminishing returns? Critically, studies utilising appropriate methods to infer causation are needed to explore this complex and mediator-entangled area [49, 50].

CONCLUSIONS

In this study, Gaelic football players with superior neuromuscular and aerobic characteristics demonstrated larger workloads during competitive match-play. Our results reflect the multifaceted physical and metabolic loads players face during match-play, highlighting a significant association between competitive workload measures and body composition, running speed, muscular power, reactive strength and aerobic conditioning. The data herein provide potentially useful information for coaches and practitioners who seek to increase players' external loads during competition. An important avenue for future exploration is to characterise the dose-response relationship between physical conditioning and workload using controlled inference methods.

Practical applications

The numerous physical, tactical and technical components that govern successful Gaelic football match-play make effective preparation for the sport's demands a complex challenge. Whilst directionally associated, physical conditioning appears to represent a clouded predictor of in-game workload at best, and this finding emphasises the premise that many moderators collectively bear an influence upon match-play locomotor profiles (e.g., score line, opposition, technical-tactical and psycho-social factors). Nevertheless, the novel findings presented support the contention that developing players metabolic, mechanical and neuromuscular properties may translate into the performance of larger total and high intensity external loads. Therefore, adopting periodised concurrent training approaches that appropriately integrate strength and/or power training with endurance training may improve on-field work capacity [3, 17, 50].

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Match demands of female team sports: a scoping review

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ABSTRACT: This scoping review aimed to characterize and quantify the external load demands of professional female team sports, in terms of total distance [TD], moderate-speed [MSR] and high-speed running [HSR], sprint, accelerations [ACC], and decelerations [DEC]. A search was conducted in PubMed, Scopus, and Web of Science until 15/04/2023. The Risk of Bias Assessment Tool for Nonrandomized Studies (RoBANS) was used. Eighty-six articles were eligible for inclusion in this review, with 40 in soccer, 23 in rugby (6 rugby union, 3 rugby league, and 14 rugby sevens), 8 in field hockey, 8 in basketball, 6 in handball, and 1 in futsal. Soccer is the most investigated sport, and players perform ~9500 m TD, of which ~580 m is performed in HSR, and with a great number of ACC, DEC, and sprints. Rugby league and union players cover a greater distance (~5450 m) when compared to rugby sevens (~1550 m); however, rugby sevens is more demanding in terms of high-intensity actions. Field hockey players perform ~5400 m TD with high-intensity and sprint actions. Women's indoor sports are less studied, and basketball players cover ~5300 m TD, of which 7% is performed in MSR. Handball players perform ~3500 m TD and cover ~423 m in MSR and ~141 m in HSR, and futsal players perform ~5 m $\times$ min^{-1} in HSR and they do a great number of high-intensity activities (HSR, ACC, and DEC). Considering the high physical demands experienced by female athletes, professionals could use the present results for training and return to competition schedules.

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INTRODUCTION

Female team sports' participation and popularity have increased considerably in the last decade [1]. This increase has attracted more sports scientists, strength and conditioning coaches, and medical staff into the field [1–4]. However, a recent scoping review [5] about external load monitoring with wearable technology from 2015 to 2020 reported that only 16.2% of the investigations were carried out with female athletes, compared to 80.6% with male counterparts. Moreover, current sports performance methods and strategies in female team sports are often supported by evidence derived from male athletes [3, 4]. Consequently, sport practitioners should understand better the physiological and mechanical demands during match play in female team sports [6].

The external load represents the basic measurement of a monitoring system [7] and expresses the activities performed by an athlete [8] independently of its internal characteristics (i.e., internal load) [9]. The consensus statement of the International Olympic Committee on load in sports and risk of injury states that a successful training load monitoring system is fundamental to ensure the adaptation to stress, maximize physical performance, and possibly minimize the risk of injury [10]. In team sports, physical activity can be registered by different tracking systems, such as global positioning systems (GPS), local positioning systems (LPS), inertial measurement units (IMU), and time-motion analysis (TMA) [11–16]. Each system has its limitations; therefore a pragmatic and systematic approach to data collection, analysis, and interpretation is necessary [11]. Total distance (TD) is generally used as an indicator of overall training volume [11, 17], while high-speed running (HSR), acceleration (ACC) and deceleration (DEC) actions refer to a neuromuscular type of loading, which is likely more related to injury risk [18–20], and lastly Player Load (Pload) provides an estimate of the total cost of movement actions [17, 21].

The analysis of the physical demands during matches is an essential element for broadening knowledge of the stress that players experience at this level [22]. This information may help professionals to design appropriate training and return to play programme sessions regarding the match [16, 22]. For example, Taylor et al. [16] analysed the demands of athletes in both men and women in different team sports (soccer, basketball, handball, futsal, and field hockey) and categories (elite, sub-elite and junior), where only 10 studies were found in elite female players (soccer = 5, basketball = 2, handball = 2, field hockey = 1). Therefore, more research, characterizing the match demands in female team sports, to implement further evidence-based practices, is warranted.

To the authors' knowledge, this is the first study to review the professional female athletes' match demands, collected by external load from six different team sports (soccer, rugby, field hockey, basketball, handball, and futsal). The aim of this scoping review was to characterize and quantify the demands of external load (i.e., TD, moderate-speed running [MSR], HSR, sprint, ACC, DEC, and Pload) in professional female multi-directional team sports and highlight the importance of research on female sport [4, 23].

MATERIALS AND METHODS

Protocol and registration

The scoping review protocol was preliminarily submitted and published on the Open Science Framework, with the registration number 10.17605/OSF.IO/E4H9M on 29th April 2023.

Study design

The present study is a scoping review focused on the match demands of professional women's team sports (i.e., soccer, rugby, field hockey, basketball, handball, and futsal) measured with a tracking system. The review was carried out in accordance with the recommendations for Systematic Reviews and Meta-Analyses (PRISMA) [24] and did not require institutional review board approval.

Data sources and searches

A scoping review of the literature was performed using three different online databases – PubMed, Scopus, and Web of Science – until April 15th, 2023. In order to ensure that all research related to this topic was identified, a broad and general search was carried out, searching for the following terms: [("match analysis" OR "GPS" OR "demands" OR "external load") AND ("basketball"/ "field hockey"/ "football OR soccer"/ "handball"/ "rugby"/ "futsal") AND ("female" OR "women") NOT "male"], to ensure that all studies related to this topic were identified, and the search was repeated for each sport individually. This search was performed by two authors (MLPA and KS), and search results were uploaded to reference management software (Zotero) where duplicates were automatically removed. All titles and abstracts of all remaining studies were screened by two authors (MLPA and KS) using the eligibility criteria below. Any disagreements about study inclusion/ exclusion that could not be resolved between the two authors were decided by a third party (PEA).

Eligibility criteria

Studies were eligible for inclusion if they met the following criteria: 1) a sample of highly trained and competitive/professional female athletes according to classification of levels of competition adapted from Russell et al. [25], aged > 18 years; 2) competing in soccer, rugby, field hockey, basketball, handball, and futsal; and lastly 3) incorporating tracking systems (i.e., GPS, LPS, TMA or IMU) and analysing some external load variables (i.e., TD, distance per zone, ACC, DEC, Pload).

Studies were excluded if they: 1) did not include original data; 2) were not available in English and full text; 3) reported simulated games and/or drills; and 4) scored < 8 in methodological quality assessment.

Study selection

The initial search was carried out by two researchers (MLPA and KS). After the elimination of duplicates, an intensive review of all titles and abstracts obtained was completed and those not related to the review's topic were discarded. The full version of the remaining articles was read. All studies not meeting the inclusion criteria were excluded.

Data extraction

Data were extracted into a custom-made Microsoft Excel sheet (2007) by one author (MLPA), with two other authors (KS and PEA) checking for the accuracy. The results were selected with the following order: participant's information (i.e., sample size, age, height, weight), number of matches, country, equipment used (i.e., device brand, model details, sampling frequency (Hz), according to recommendations for the collecting, processing and reporting of data from GPS devices [26] external load metrics (i.e., TD, distance at MSR [12.6–19.8 $km \cdot h^{-1}$], HSR [19.8–25.2 $km \cdot h^{-1}$], and sprinting [≥ 25.2 $km \cdot h^{-1}$], ACC, DEC, Pload). The mean and standard deviation (SD) were extracted for all the variables, and presented as full match-play. Intensity thresholds for ACC and DEC were presented. A meta-analysis was not performed due to the heterogeneous nature of sport specific study designs and inability to pool data.

Risk of bias

The risk of bias was evaluated independently by two authors (MLPA and KS), who reanalysed the process in cases of disagreement. If a consensus was not reached, a final decision was made by a third author (PEA). The Risk of Bias Assessment Tool for Nonrandomized Studies (RoBANS) was utilized to evaluate the included studies' risk of bias, as it has demonstrated moderate reliability and good feasibility and validity [27]. The tool comprises six domains, which are the selection of participants, confounding variables, measurement of exposure, blinding of outcome assessments, incomplete outcome data, and selective outcome reporting, and these domains are classified as 'low', 'high', or 'unclear' risk of bias [27].

Methodological quality assessment

The methodological quality of the included studies was assessed by two researchers (MLPA and KS) using the modified Downs & Black [28] evaluation scale. Of the total 27 criteria, 12 were used according to the study's design (i.e., descriptive), as observed in similar systematic reviews [13, 14, 29].

RESULTS

Search results

Figure 1 depicts the PRISMA flow diagram of the search and selection process. The initial databases yielded 1175 studies, and

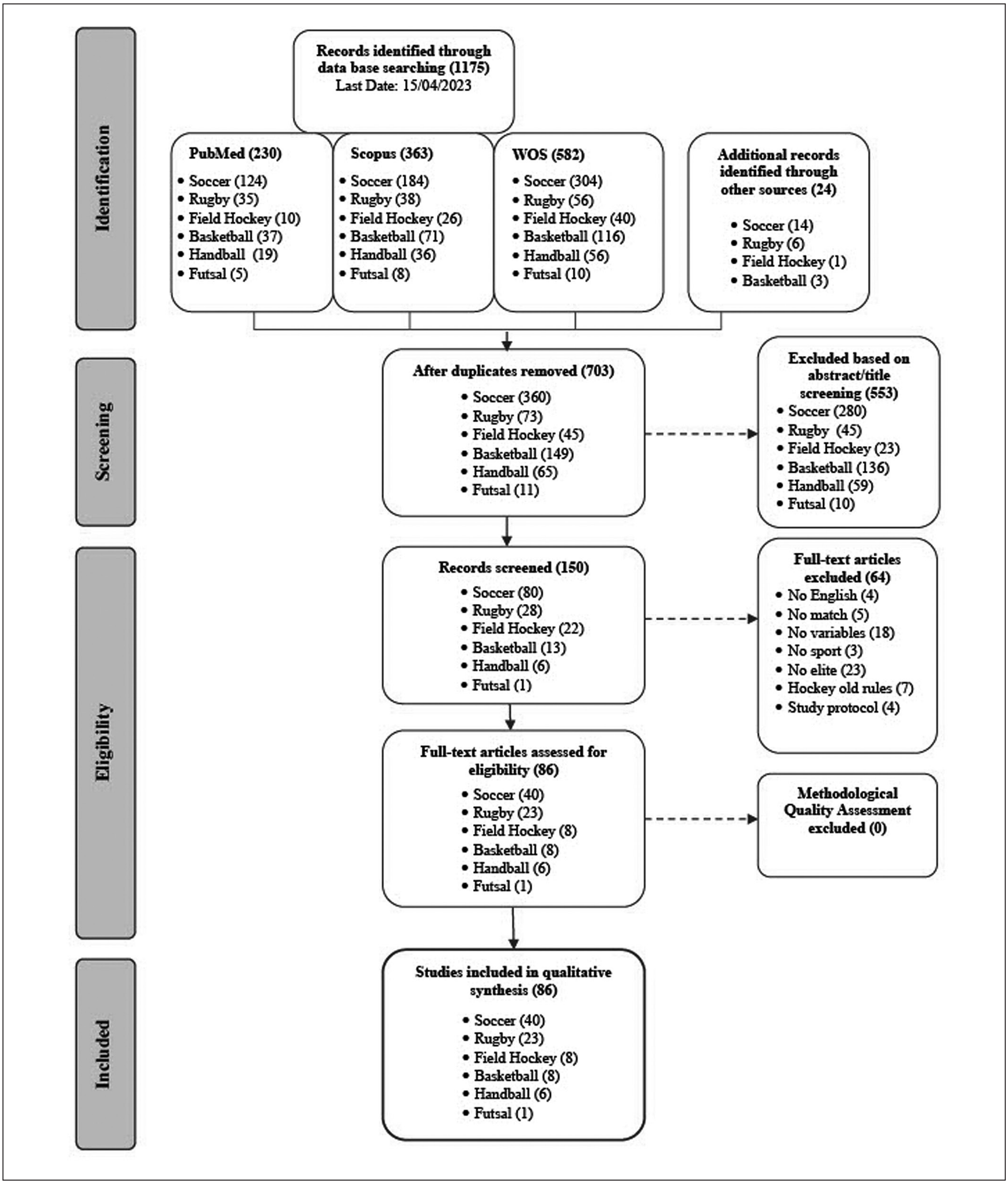

FIG. 1. Flow diagram.

24 additional records were added through other sources. After duplicate removal, 703 articles remained. Upon title and abstract screening, 150 were left for full-text review. Of the 150 articles reviewed, 86 met the inclusion criteria in this systematic review: 40 on soccer [30–70], 23 on rugby [71–93], 8 on field hockey [94–101], 8 on basketball [102–109], 6 on handball [110–115], and 1 on futsal [116].

Risk of bias

The results of the risk of bias assessment can be seen in Table 1. Overall the confounding variables were unclear in the majority (64%) of the articles. This is because contextual factors (e.g., sleep, nutrition, training, climate) were not reported or not controlled for. The risk of bias in the measurement of exposure was unclear in 16% of the articles and high in 13%, as assessments of demands were not conducted over a considerable period of time (> 4 matches) or in relation to the reliability of the measurement instrument. All included studies had a low risk of bias in the selection of participants.

Soccer

Table 2 presents the match demands, anthropometric data and origin of players in soccer. The match demands were collected by TMA (n = 9) and GPS devices (n = 31). Female players covered a total distance of 9556 ± 795 m and 103 ± 6 $m \times min^{-1}$ during matches [30–41, 43, 45, 48–63, 65–70]. Considering zones of intensity, women soccer players performed 1429 ± 702 m in MSR, 830 ± 1414 m in HSR and 267 ± 275 m in sprinting; other studies presented these variables relative to time (MSR = 15 ± 7 $m \times min^{-1}$; HSR = 4 ± 1 $m \times min^{-1}$; sprinting = 3 ± 2 $m \times min^{-1}$) [30, 33, 37, 47, 49, 55, 58, 66, 68–70]. Regarding the number of sprints, the players did a mean of 30 ± 19 sprint actions per match [34, 45, 5 3, 54, 58, 61, 67]. Moreover, studies [32–35, 41, 43, 46, 48, 54, 56, 63, 65, 67, 69, 70] reported that female players completed a total of 165 ± 129 ACC and 146 ± 141 DEC actions during the match. These actions were also presented in frequency per minute [30, 43, 48, 49, 54, 57, 66, 68], distance travelled [31, 36] and duration [38] (Table 2).

Rugby

Table 3 depicts the match demands, anthropometric data and origin of rugby, rugby sevens, and field hockey. Out of the 23 results found in rugby, 6 correspond to rugby union [71, 73, 74, 76, 92, 93], 3 to rugby league [72, 75, 87] and 14 to rugby sevens [76–82, 84–86, 88–91]. Regarding external match load, GPS devices were used. Players covered an average of 5351 ± 855 m, while only three studies reported the density of 70 ± 8 $m \times min^{-1}$ [71–73]. Rugby female players performed 916 ± 386 m in MSR and a mean of 135 ± 63 m HSR per match. Few studies presented the locomotive zones of intensity in terms of proportion (18 ± 9%) [73, 76] and density (21 ± 4 $m \times min^{-1}$) [75]. The authors reported that players did a mean of 8 ± 8 sprints per game [75]. Regarding ACC, one study [76] reported number (Nº = 19 ± 8) and two [71, 72] the frequency per minute (0.7 ± 0.4 $ACC \times min^{-1}$) (Table 3).

All rugby sevens studies used GPS devices to record external match load. Rugby sevens female players covered an average of 1549 ± 562 m and 94 ± 9 $m \times min^{-1}$. Regarding zones of intensity, female players performed 355 ± 168, 165 ± 129 and 108 ± 49 m in MSR, HSR, and sprinting respectively. Some studies [79, 83, 85, 86, 90] reported MSR and HSR in terms of proportion of TD (MSR = 28 ± 8%; HSR = 10 ± 4%; sprinting = 14 ± 3%). Regarding distance relative to time in MSR, HSR, and sprinting, players performed 19 ± 13, 10 ± 4, and 5 ± 3 $m \times min^{-1}$, respectively [77, 80, 81, 84]. Lastly, players performed 5 ± 1 sprints, 7 ± 6 ACC and 21 ± 1 DEC per match [77, 78, 82] (Table 3).

Field hockey

In field hockey, GPS devices were used to record external match load (Table 3). Female players covered an average of 5433 ± 265 m TD [94–99, 101, 117], while only two studies reported this variable relative to time 130 ± 24 $m \times min^{-1}$ [94, 100]. Players covered 823 ± 131 m in MSR [94–99], 466 ± 326 m in HSR [94, 95, 97, 99, 101] and 371 ± 9 m in sprinting [99]. Moreover, female field hockey players performed 39 ± 23 sprints, 26 ± 10 ACC and 32 ± 8 DEC per game (Table 3).

Basketball

Table 4 shows the results for basketball, handball and futsal. In basketball, the variables were recorded by TMA (n = 4) and LPS (n = 1). Female basketball players covered 5285 ± 2480 m per match (MSR = 459 ± 70 m; HSR = 1850 ± 12 m; sprint = 925 $\pm$ 184 m) [106, 109]. The minutes played were 27 ± 2 min, of which 16 ± 14%, 7 ± 4% and 7 ± 5% corresponded to MSR, HSR, and sprinting respectively [102–105, 107]. This metric was also reported in numbers of actions relative of time (MSR = 2 ± 0.6 $m \times min^{-1}$; HSR = 0.2 ± 0.5 $m \times min^{-1}$; sprint = 0.6 ± 0.6 $m \times min^{-1}$) [104, 108].

Handball

In handball, variables were extracted using IMU (n = 4) and TMA (n = 2) (Table 4). Handball female players competed an average of 37.6 ± 11.2 min [111, 113, 114] and covered 3442 ± 792 m TD [114, 115] during match-play. Regarding the intensity of the matches (Pload), three studies reported that a mean of 9 ± 0.5 $au \cdot min^{-1}$ was performed [110–113]. Female handball players covered 423 ± 466 m in MSR and 141 ± 185 m in sprinting, which correspond to 16 ± 19% and 5 ± 7% respectively of TD [114, 115]. During the competition, the players performed 8.7 ± 11 $ACC \times min^{-1}$ and 2.3 $\pm$ 0.9 $DEC \times min^{-1}$ [111, 115] (Table 4).

Futsal

In futsal, only one study met the inclusion criteria [116]. Five matches were monitored using LPS. The players covered a mean of

TABLE. Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	175
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	175
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	175–176
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	176
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	176
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	176
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	176
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	176
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	176
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	176
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	176
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	176
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	176
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	176–178
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	176–178
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	178
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	176–194

TABLE. Continue.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	176–194
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	193–194
Limitations	20	Discuss the limitations of the scoping review process.	194
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	194–195
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	195

Note: JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

TABLE 1. Risk of bias assessment of non-randomized studies.

Author (year)	Selection of participants	Confounding variables	Measurement of exposure	Blinding of outcome assessments	Incomplete outcome data	Selective outcome reporting
Andersson et al. (2010) [51]	*Low*	*Unclear*	*Unclear*	*Low*	*Low*	*Low*
Bradley et al. (2014) [60]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Busbridge et al. (2020) [92]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Callanan et al. (2021) [73]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Choi et al. (2020) [96]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Choi et al. (2022) [67]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Clarke et al. (2014a) [88]	*Low*	*Low*	*High*	*Low*	*Low*	*Low*
Clarke et al. (2014b) [86]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Clarke et al. (2015) [85]	*Low*	*Unclear*	*Low*	*Low*	*Unclear*	*Low*
Clarke et al. (2017) [90]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Conte et al. (2015) [105]	*Low*	*Unclear*	*High*	*Low*	*Low*	*Low*
Conte et al. (2022) [77]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Datson et al. (2017) [47]	*Low*	*Unclear*	*Unclear*	*Low*	*Low*	*Low*
Datson et al. (2019) [61]	*Low*	*Unclear*	*High*	*Low*	*Low*	*Low*
Del coso et al. (2013) [89]	*Low*	*Low*	*Unclear*	*Low*	*Low*	*Low*
Delextrat et al. (2017) [104]	*Low*	*Unclear*	*Unclear*	*Low*	*Low*	*Low*
Delextrat et al. (2012) [108]	*Low*	*Low*	*High*	*Low*	*Low*	*Low*
Delves et al. (2021) [101]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
DeWitt et al. (2018) [45]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Diaz-Seradilla et al. (2022) [58]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Doeven et al. (2019) [91]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Emmonds et al. (2020) [75]	*Low*	*Unclear*	*Unclear*	*Low*	*Low*	*Low*
Fernandes et al. (2022) [56]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Gabbett et al. (2008) [62]	*Low*	*Unclear*	*Unclear*	*Low*	*Low*	*Low*
García-Ceberino et al. (2022) [57]	*Low*	*Low*	*Unclear*	*Low*	*Low*	*Low*
Gonçalves et al. (2021) [54]	*Low*	*Unclear*	*Low*	*Unclear*	*Low*	*Low*
Goodale et al. (2006) [84]	*Low*	*Unclear*	*Unclear*	*Low*	*Low*	*Low*
Griffin et al. (2021) [38]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Hewitt et al. (2014) [50]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Julian et al. (2021) [37]	*Low*	*Low*	*Unclear*	*Low*	*Low*	*Low*
Kapteijns et al. (2021) [94]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Kim et al. (2016) [99]	*Low*	*Unclear*	*High*	*Low*	*Low*	*Low*
Kniubaite et al. (2019) [110]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Kobal et al. (2022a) [69]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Kobal et al. (2022b) [68]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Krustrup et al. (2005) [53]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Krustrup et al. (2021) [36]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Luteberget et al. (2016) [111]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Luteberget et al. (2017) [112]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Malone et al. (2020) [78]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Manchado et al. (2013) [115]	*Low*	*Unclear*	*High*	*Low*	*Low*	*Low*
Mara et al. (2016) [63]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Mara et al. (2017) [46]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
McGuinness et al. (2018) [100]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*

TABLE 1. Continue.

Author (year)	Selection of participants	Confounding variables	Measurement of exposure	Blinding of outcome assessments	Incomplete outcome data	Selective outcome reporting
McMahon et al. (2019) [98]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Meylan et al. (2016) [49]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Michalsik et al. (2014) [114]	*Low*	*Low*	*Unclear*	*Low*	*Low*	*Low*
Misseldine et al. (2018) [79]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Mohr et al. (2008) [52]	*Low*	*Unclear*	*High*	*Low*	*Low*	*Low*
Morencos et al. (2019) [97]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Nakamura et al. (2017) [64]	*Low*	*Unclear*	*Unclear*	*Low*	*Low*	*Low*
Newans et al. (2021) [72]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Nolan et al. (2023) [93]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Oliva Lozano et al. (2021) [116]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Palmer et al. (2021) [102]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Palmer et al. (2022) [107]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Panduro et al. (2021) [34]	*Low*	*Unclear*	*Unclear*	*Low*	*Low*	*Low*
Park et al. (2018) [42]	*Low*	*Low*	*Low*	*Low*	*Low*	*Unclear*
Portillo et al. (2014) [82]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Principe et al. (2021) [35]	*Low*	*Unclear*	*Low*	*Unclear*	*Low*	*Low*
Quinn et al. (2019) [87]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Ramos et al. (2017) [65]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Ramos et al. (2019a) [41]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Ramos et al. (2019b) [66]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Reina et al. (2022) [109]	*Low*	*Low*	*Low*	*High*	*Low*	*Low*
Reyneke et al. (2018) [80]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Romero-Moraleda et al. (2021) [33]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Sánchez-Migallón et al. (2020) [95]	*Low*	*Low*	*High*	*Low*	*Low*	*Low*
Scanlan et al. (2012) [106]	*Low*	*Low*	*High*	*Low*	*Low*	*Low*
Scott et al. (2020a) [39]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Scott et al. (2020b) [40]	*Low*	*Unclear*	*Unclear*	*Low*	*Low*	*Low*
Sheppy et al. (2020) [74]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Stauton et al. (2018) [103]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Suarez-Arrones et al. (2014) [76]	*Low*	*Low*	*High*	*Low*	*Low*	*Low*
Suarez-Arrones et al. (2012) [83]	*Low*	*Low*	*High*	*Low*	*Low*	*Low*
Trewin et al. (2017) [43]	*Low*	*Low*	*Unclear*	*Low*	*Low*	*Low*
Trewin et al. (2018) [48]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Vescovi et al. (2012) [44]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Vescovi et al. (2015) [81]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Vescovi et al. (2019) [55]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Villaseca-Vicuña et al. (2021) [32]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Villaseca-Vicuña et al. (2023) [70]	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Wik et al. (2016) [113]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Winther et al. (2021) [31]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Woodhouse et al. (2021) [71]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*
Yousefian et al. (2021) [30]	*Low*	*Unclear*	*Low*	*Low*	*Low*	*Low*

TABLE 2. Summary of the match demands in soccer.

Study (year)	Sport	Country	Players (n)	Age (years) Height (cm) Mass (kg)	Match (n)	Device	TD (m)	TD ($m \cdot min^{-1}$)	MSR (m) 12.6–19.8 $km \cdot h^{-1}$	HSR (m) 19.8–25.2 $km \cdot h^{-1}$	Sprint (m) ≥ 25.2 $km \cdot h^{-1}$	ACC (n)	DEC (n)
Andersson et al. (2010) [51]	Soccer	Sweden-Denmark	17	27 ± 1 168 ± 2 61 ± 1	6	TMA (Canon DM-MV 600, Canon Inc.)	9800 ± 141	N-R	N-R	1430 ± 141 (≥ 18 $km \cdot h^{-1}$)	239 ± 25 (≥ 25 $km \cdot h^{-1}$)	N-R	N-R
Bradley et al. (2014) [60]	Soccer	N-R	59	N-R	N-R	TMA (Multiple-camera system, Amisco Pro) 25 Hz	10754 ± 150	N-R	2374 ± 70 (12–18 $km \cdot h^{-1}$)	718 ± 34 (18–25 $km \cdot h^{-1}$)	N° 59 ± 9 (≥ 25 $km \cdot h^{-1}$)	N-R	N-R
Choi et al. (2022) [67]	Soccer	South Korea	24	29 ± 4 166 ± 5 59 ± 6	21	GPS (APEX STATSports) 10 Hz	9520 ± 676		1685 ± 395 (13–19 $km \cdot h^{-1}$)	371 ± 82 (19–23 $km \cdot h^{-1}$)	129 ± 81 Nº 16 ± 5 (≥ 23 $km \cdot h^{-1}$)	75 ± 13 (N-R)	85 ± 15 (N-R)
Datson et al. (2017) [47]	Soccer	N-R	107	N-R	1–4	TMA (Prozone Sports Ltd., Leeds)	10321 ± 859	N-R	2520 ± 580 (14–19.8 $km \cdot h^{-1}$)	776 ± 247 (≥ 19.8 $km \cdot h^{-1}$)	168 ± 82 (≥ 25 $km \cdot h^{-1}$)	N-R	N-R
Datson et al. (2019) [61]	Soccer	N-R	107	N-R	2–4	TMA (Semi-automated multi-camera image recognition system, STATS)	N-R	N-R	N-R	N° 169 ± 50 (≥ 19.8 $km \cdot h^{-1}$)	N° 33 ± 13 (≥ 25 $km \cdot h^{-1}$)	N-R	N-R
DeWitt et al. (2018) [45]	Soccer	USA	18	25 ± 3 168 ± 5 61 ± 5	20	GPS (Optimeye S5, Catapult Innovations) 10 Hz	8883 ± 877	99 ± 22	570 ± 407 (≥ 17.8 $km \cdot h^{-1}$)	N-R	N° 9 ± 11 (≥ 22.7 $km \cdot h^{-1}$)	N-R	N-R
Diaz-Seradilla et al. (2022) [58]	Soccer	Spain	17	23 ± 5 166 ± 6 60 ± 7	1	GPS (WIMU PRO, Real rack Systems) 10 Hz	9347 ± 1013	96 ± 9	1110 ± 332 12 ± 4 $m \cdot min^{-1}$ (≥ 16 $km \cdot h^{-1}$)	N-R	235 ± 21 N° 1 3 ± 4 3 ± 2 $m \cdot min^{-1}$ (≥ 21 $km \cdot h^{-1}$)	32 ± 2 $m \cdot min^{-1}$ (N-R)	32 ± 1 $m \cdot min^{-1}$ (N-R)
Fernandes et al. (2022) [56]	Soccer	Portugal	10	24 ± 2 165 ± 6 58 ± 9	15	GPS (PlayerTeck, Catapult) 10 Hz	7616 ± 395	90 ± 5	880 ± 102 (≥ 15 $km \cdot h^{-1}$)	N-R	N-R	177 ± 8 (2–3 $m \cdot s^{-2}$)	169 ± 5 (-2–3 $m \cdot s^{-2}$)
Gabbett et al. (2008) [62]	Soccer	Australia	30	21 ± 2 N-R N-R	12	TMA (37-mm digital video cameras, Sony, DCR-TRV 950E)	9967 ± 610 5618 ± 67 s	N-R	1484 ± 402 266 ± 71 s 15 ± 3% ^{B} (N-R)	N-R	995 ± 182 159 ± 35 s 10 ± 2% ^{B} (N-R)	N-R	N-R
García-Ceberino et al. (2022) [57]	Soccer	Spain	10	26 ± 4 166 ± 1 61 ± 7	3	GPS (SPRO, RealTrack Systems) 18 Hz	N-R	91 ± 12	2 ± 2 $N° \cdot min^{-1}$ (N-R)	N-R	7 ± 15 $n \cdot min^{-1}$ (N-R)	31 ± 3 $n \cdot min^{-1}$ (N-R)	32 ± 3 $n \cdot min^{-1}$ (N-R)

TABLE 2. Continue.

Study (year)	Sport	Country	Players (n)	Age (years) Height (cm) Mass (kg)	Match (n)	Device	TD (m)	TD (m·min^{-1})	MSR (m) 12.6–19.8 km·h^{-1}	HSR (m) 19.8–25.2 km·h^{-1}	Sprint (m) ≥ 25.2 km·h^{-1}	ACC (n)	DEC (n)
Gonçalves et al. (2021) [54]	Soccer	Portugal	22	25 ± 6 162 ± 7 59 ± 9	10	GPS (SPI HPU, GPSports) 15 Hz	8237 ± 206	100 ± 1	758 ± 50 9 ± 0.2 m·min^{-1} (14–18 km·h^{-1})	306 ± 46 4 ± 0.4 m·min^{-1} (18–24 km·h^{-1})	N° 15 ± 0.1 22 ± 3 (≥ 24 km·h^{-1})	41 ± 0.6 0.5 ± 0.02 n·min^{-1} (2–3 m·s^{-2})	44 ± 0.2 0.5 ± 0.03 n·min^{-1} (-2–3 m·s^{-2})
Griffin et al. (2021) [38]	Soccer	Australia	33	NAT = 15 26 ± 3 167 ± 8 61 ± 6 INT = 18 26 ± 4 167 ± 8 60 ± 7	36	GPS (SPI HPU, GPSports) 10 Hz	9080 ± 499	N-R	687 ± 112 (16–20 km·h^{-1})	335 ± 40 (≥ 20 km·h^{-1})	N-R	176 ± 17 s (2–3 m·s^{-2})	172 ± 13 s (2–3 m·s^{-2})
Hewitt et al. (2014) [50]	Soccer	Austalia	15	23 ± 1 170 ± 1 65 ± 1	13	GPS (MinimaxX v2.5, Catapult Innovations) 5 Hz	9631 ± 175	N-R	2407 ± 125 (12–19 km·h^{-1})	338 ± 30 (≥ 19 km·h^{-1})	N-R	N-R	N-R
Julian et al. (2021) [37]	Soccer	Germany	15	23 ± 4 169 ± 1 64 ± 8	4–7	GPS (Tracktics TT01) 5 Hz	N-R	103 ± 1	18 ± 2 m·min^{-1} (13–20 km·h^{-1})	4 ± 0.2 m·min^{-1} N° 24 ± 13 (≥ 20 km·h^{-1})	N-R	N-R	N-R
Kobal et al. (2022a) [69]	Soccer	Brazil	24	28 ± 5 164 ± 5 59 ± 8	38	GPS (Catapult Innovations) 10 Hz	9830 ± 42	104 ± 3	N-R	7234 ± 327 8 ± 0.4 m·min^{-1} (≥ 18 km·h^{-1})	N-R	726 ± 15 (≥ 3 m·s^{-2})	912 ± 2 (≥ 3 m·s^{-2})
Kobal et al. (2022b) [68]	Soccer	Brazil	23	28 ± 5 165 ± 5 59 ± 5	14	GPS (Catapult Innovations) 10 Hz	N-R	96 ± 14	N-R	8 ± 3 m·min^{-1} (≥ 18 km·h^{-1})	N-R	1 ± 0.2 n·min^{-1} (≥ 3 m·s^{-2})	1 ± 0.2 n·min^{-1} (≤ -3 m·s^{-2})
Krustrup et al. (2005) [53]	Soccer	Denmark	14	24 ± 8 167 ± 17 58 ± 22	4	TMA (VHS movie camera NV-M50, Panasonic)	10300 (9700–1300)	N-R	N-R	1310 (700–1700) 4.8% * (2.8–6.1) (≥ 18 km·h^{-1})	160 (50–280) N° 26 (9–43) (≥ 25 km·h^{-1})	N-R	N-R
Krustrup et al. (2021) [36]	Soccer	N-R	17	23 ± 4 166 ± 5 60 ± 7	1	GPS (S5, Catapult Innovations) 10 Hz	8500 ± 1200	N-R	903 ± 275 (16–20 km·h^{-1})	N-R	N-R	233 ± 52 m (≥ 2 m·s^{-2})	172 ± 40 m (≤ -2 m·s^{-2})
Mara et al. (2016) [63]	Soccer	Australia	12	24 ± 4 172 ± 5 65 ± 5	7	TMA (High-definition video cameras, Legria HF R38, Canon) 25 Hz	N-R	N-R	N-R	N-R	N-R	423 ± 126 (≥ 2 m·s^{-2})	430 ± 125 (≤ -2 m·s^{-2})
Mara et al. (2017) [46]	Soccer	Australia	12	24 ± 4 172 ± 5 65 ± 5	7	TMA (8 stationary high-definition video cameras Legria HF R38; Canon)	10025 ± 775	N-R	2452 ± 36 (12–19 km·h^{-1})	615 ± 258 N° 70 ± 29 (≥ 19 km·h^{-1})	N-R	N-R	N-R

TABLE 2. Continue.

Study (year)	Sport	Country	Players (n)	Age (years) Height (cm) Mass (kg)	Match (n)	Device	TD (m)	TD (m·min⁻¹)	MSR (m) 12.6–19.8 km·h⁻¹	HSR (m) 19.8–25.2 km·h⁻¹	Sprint (m) ≥ 25.2 km·h⁻¹	ACC (n)	DEC (n)
Meylan et al. (2016) [49]	Soccer	N-R	13	27 ± 5 170 ± 6 66 ± 5	34	GPS (MinimaX S4, Catapult Innovations) 10 Hz	N-R	107 ± 16	6 ± 2 m·min^{-1} (16–20 km·h^{-1})	3 ± 1 m·min^{-1} (≥ 20 km·h^{-1})	N-R	2 ± 1 n·min^{-1} (≥ 2.26 m·s^{-2})	N-R
Mohr et al. (2008) [52]	Soccer	Sweden-Denmark	34	N-R	1–2	TMA (VHS movie cameras NV-M50)	10385 ± 150	N-R	N-R	1490 ± 95 (≥ 18 km·h^{-1})	420 ± 35 (≥ 25 km·h^{-1})	N-R	N-R
Nakamura et al. (2017) [64]	Soccer	Brazil	11	21 ± 3 164 ± 4 60 ± 8	10	GPS (SPI 119 Elite, GPSports Systems). 5 Hz	N-R	N-R	N-R	285 ± 164 N° 18 ± 9 3 ± 0.5 s (≥ 20 km·h^{-1})	N-R	N-R	N-R
Panduro et al. (2021) [34]	Soccer	Denmark	94	23 ± 4 170 ± 6 64 ± 6	2–4	GPS (Polar Team Pro Electro Oy) 10 Hz	10033 ± 454	N-R	1496 ± 256 (≥ 15 km·h^{-1})	676 ± 156 (≥ 18 km·h^{-1})	N° 49 ± 27 (≥ 25 km·h^{-1})	8 ± 5 (3–5 m·s^{-2})	15 ± 4 (-3–5 m·s^{-2})
Park et al. (2018) [42]	Soccer	N-R	27	25 ± 4 169 ± 5 63 ± 4	52	GPS (MinimaX S4, Catapult Innovations) 10 Hz	N-R	N-R	843 (812–876) (12–20 km·h^{-1})	101 (96–107) (≥ 20 km·h^{-1})	N-R	N-R	N-R
Principe et al. (2021) [35]	Soccer	Brazil	23	28 ± 5 165 ± 6 61 ± 5	22	GPS (Polar Team Pro Electro Oy) 10 Hz	8017 ± 360	N-R	2025 ± 224 (12–20 km·h^{-1})	306 ± 35 (≥ 20 km·h^{-1})	N-R	240 ± 18 (≥ 2 m·s^{-2})	242 ± 17 (≤ -2 m·s^{-2})
Ramos et al. (2017) [65]	Soccer	Brazil	12	18 ± 1 167 ± 6 62 ± 6	7	GPS (MinimaxX S5, Catapult Innovations) 10 Hz	8704 ± 432	N-R	688 ± 183 (16–20 km·h^{-1})	223 ± 120 (≥ 20 km·h^{-1})	N-R	15 ± 2 (≥ 2 m·s^{-2})	17 ± 6 (≤ -2 m·s^{-2})
Ramos et al. (2019a) [41]	Soccer	Brazil	17	27 ± 4 187 ± 5 61 ± 4	6	GPS (MinimaxX S5, Catapult Innovations) 10 Hz	10110 ± 245	N-R	736 ± 153 (16–20 km·h^{-1})	307 ± 80 (≥ 20 km·h^{-1})	N-R	214 ± 3 (≥ 1 m·s^{-2})	174 ± 4 (≤ -1 m·s^{-2})
Ramos et al. (2019b) [66]	Soccer	Brazil	21	26 ± 4 167 ± 6 N-R	6	GPS (MinimaxX S5, Catapult Innovations) 10 Hz	N-R	109 ± 4	22 ± 2 m·min^{-1} (12–20 km·h^{-1})	3 ± 1 m·min^{-1} (≥ 20 km·h^{-1})	N-R	0.05 ± 0.01 n·min^{-1} (≥ 2.5 m·s^{-2})	0.12 ± 0.03 n·min^{-1} (≤ -2.5 m·s^{-2})
Romero-Moraleda et al. (2021) [33]	Soccer	Spain	18	26 ± 6 164 ± 5 59 ± 6	94	GPS (SPI Pro X, GPSports Systems) 5 Hz	9040 ± 938	95 ± 9	1108 ± 294 12 ± 2 m·min^{-1} (≥ 15 km·h^{-1})	N-R	N-R	255 ± 40 (≥ 1 m·s^{-2})	78 ± 16 (≤ -1 m·s^{-2})

TABLE 2. Continue.

Study (year)	Sport	Country	Players (n)	Age (years) Height (cm) Mass (kg)	Match (n)	Device	TD (m)	TD (m·min^{-1})	MSR (m) 12.6–19.8 km·h^{-1}	HSR (m) 19.8–25.2 km·h^{-1}	Sprint (m) ≥ 25.2 km·h^{-1}	ACC (n)	DEC (n)
Scott et al. (2020a) [39]	Soccer	USA	36	24 ± 4 168 ± 6 63 ± 5	220	GPS (Optimeye S5, Catapult Innovations) 10 Hz	10068 ± 615	N-R	2401 ± 454 (≥ 12.5 km·h^{-1})	398 ± 153 (≥ 19 km·h^{-1})	162 ± 69 (≥ 22.5 km·h^{-1})	N-R	N-R
Scott et al. (2020b) [40]	Soccer	USA	220	25 ± 3 167 ± 6 64 ± 6	N-R	GPS (Optimeye S5, Catapult Innovations) 10 Hz	10073 ± 425	N-R	2409 ± 263 (≥ 12.5 km·h^{-1})	479 ± 114 (≥ 19 km·h^{-1})	139 ± 32 (≥ 22.5 km·h^{-1})	N-R	N-R
Trewin et al. (2017) [43]	Soccer	N-R	45	N-R	7 ± 6	GPS (MinimaX S4, Catapult Innovations) 10 Hz	10368 ± 952	108 ± 10	930 ± 348 10 ± 4 m·min^{-1} (≥ 16 km·h^{-1})	0.2 ± 0.1 N°·min^{-1} N° 20 ± 9 (≥ 20 km·h^{-1})	N-R	174 ± 33 1.8 ± 0.3 n·min^{-1} (≥ 2 m·s^{-2})	N-R
Trewin et al. (2018) [48]	Soccer	N-R	45	24 ± 13 N-R N-R	47	GPS (MinimaX S4, Catapult Innovations) 10 Hz	N-R	107 ± 10	10 ± 3 m·min^{-1} (≥ 16 km·h^{-1})	0.2 ± 0.1 N°·min^{-1} N° 20 ± 9 (≥ 20 km·h^{-1})	N-R	1.8 ± 0.3 n·min^{-1} (≥ 2 m·s^{-2})	N-R
Vescovi et al. (2012) [44]	Soccer	USA	71	N-R	12	GPS (SPI Pro, GPSports) 5 Hz	N-R	N-R	N-R	550 ± 186 (18–21 km·h^{-1})	N-R	N-R	N-R
Vescovi et al. (2019) [55]	Soccer	N-R	28	N-R	2	GPS (SPI Pro, GPSports) 5 Hz	N-R	111 ± 12	27 ± 1 m·min^{-1} (12–20 km·h^{-1})	4 ± 1 m·min^{-1} (≥ 20 km·h^{-1})	N-R	N-R	N-R
Villaseca-Vicuña et al. (2021) [32]	Soccer	Chile	26	27 ± 3 158 ± 21 59 ± 5	26	GPS (Optimeye S5, Catapult Innovations) 10 Hz	9415 ± 766	108 ± 7	N-R	515 ± 162 N° 35 ± 11 (≥ 18 km·h^{-1})	N-R	102 ± 28 (≥ 2 m·s^{-2})	N-R
Villaseca-Vicuña et al. (2023) [70]	Soccer	Chile	10	27 ± 3 163 ± 4 60 ± 5	6	GPS (Optimeye S5, Catapult Innovations) 10 Hz	9737 ± 448	108 ± 4	N-R	566 ± 49 6 ± 1 m·min^{-1} Nº 42 ± 4 (≥ 18 km·h^{-1})	N-R	N-R	N-R
Winther et al. (2021) [31]	Soccer	Norway	108	22 ± 4 N-R N-R	60	GPS (APEX STATSports) 10 Hz	9603 ± 480	N-R	1499 ± 300 (≥ 16 km·h^{-1})	369 ± 116 (≥ 20 km·h^{-1})	N-R	486 ± 62 m (≥ 2 m·s^{-2})	389 ± 69 m (≤ -2 m·s^{-2})
Yousefian et al. (2021) [30]	Soccer	Sweden	21	27 ± 4 172 ± 5 65 ± 4	7	GPS (S5, Catapult Innovation) 10 Hz	N-R	99 ± 4	22 ± 3 m·min^{-1} (12–19 km·h^{-1})	4 ± 0.5 m·min^{-1} (≥ 19 km·h^{-1})	N-R	0.2 ± 0.04 n·min^{-1}	0.2 ± 0.04 n·min^{-1}

*Percentage of total time. [B] Percentage of total distance. ACC: accelerations; DEC: decelerations; GPS: global positions system; HSR: high-speed running; MSR: moderate-speed running; N-R: no reported; TD: total distance; TMA: time-motion analysis; USA: United States of America.

TABLE 3. Summary of the match demands of rugby union and sevens and field hockey.

Study (year)	Sport	Country	Players (n)	Age (years) Height (cm) Mass (kg)	Match (n)	Device	TD (m)	TD (m·min⁻¹)	MSR (m) 12.6–19.8 km·h⁻¹	HSR (m) 19.8–25.2 km·h⁻¹	Sprint (m) ≥ 25.2 km·h⁻¹	ACC (n)	DEC (n)
Busbridge et al. (2020) [92]	Rugby Union	New Zealand	20	24 ± 4 170 ± 6 79 ± 11	7	GPS (VX Log 340b, Firmware V1.62-03, VX Sport) 10 Hz	5812 ± 470	N-R	483 ± 276 7 ± 4 m·min⁻¹ (≥ 16 km·h⁻¹)	N-R	N-R	N-R	N-R
Callanan et al. (2021) [73]	Rugby Union	Ireland	128	Forwards 26 ± 4 172 ± 7 80 ± 8 Backs 25 ± 4 167 ± 5 70 ± 6	12	Triaxial magnetometer (PlayerTek, Catapult Innovations) 10 Hz	5696 ± 822	68 ± 7	1380 ± 383 24%* (10–18 km·h⁻¹)	220 ± 156 4%* (≥ 18 km·h⁻¹)	N-R	N-R	N-R
Nolan et al. (2023) [93]	Rugby Union	N-R	53	N-R	12	GPS (STATSports Apex; STATSports) 10 Hz	4177 ± 206	60 ± 9	1254 ± 637 18 ± 6 m·min⁻¹ (10–19.5 km·h⁻¹)	106 ± 126 1 ± 2 m·min⁻¹ (≥ 19.5 km·h⁻¹)	N-R	N-R	N-R
Sheppy et al. (2020) [74]	Rugby Union	Wales	29	24 ± 3 167 ± 1 75 ± 11	8	GPS (Optimeye S5, Catapult Innovations) 10 Hz	5784 ± 569	N-R	N-R	N-R	N-R	N-R	N-R
Suarez -Arrones et al. (2014) [76]	Rugby Union	Spain	8	Backs = 4 27 ± 3 170 ± 2 68 ± 4 Forwards = 4 27 ± 2 174 ± 6 77 ± 10	1	GPS (SPI Pro X; GPSports) 5 Hz	5820 ± 512	N-R	658 ± 264 11.3%* (14–20 km·h⁻¹)	73 ± 107 N° 5 ± 5 1.2%* (≥ 20 km·h⁻¹)	N-R	19 ± 8 (≥ 3 m·s⁻²)	N-R
Woodhouse et al. (2021) [71]	Rugby Union	England	78	25 ± 4 171 ± 6 77 ± 10	53	GPS (Viper, STATSports) 18 Hz	4271 ± 814	66 ± 4	1314 ± 367 21 ± 4 m·min⁻¹ (11–20 km·h⁻¹)	N° 8 ± 5 0.1 ± 0.07 N·min⁻¹ (≥ 20 km·h⁻¹)	N-R	1 ± 0.1 n·min⁻¹ (2–3 m·s⁻²)	1 ± 0.1 n·min⁻¹ (-2 to -3 m·s⁻²)
Emmonds et al. (2020) [75]	Rugby League	N-R	58	N-R	9	GPS (Optimeye S5, Catapult Innovations) 10 Hz	5383 ± 780	75 ± 2	N-R	140 ± 90 2 ± 1 m·min⁻¹ (≥ 18 km·h⁻¹)	N° 8 ± 8 0.1 ± 0.1 m·min⁻¹ (≥ 25 km·h⁻¹)	N-R	N-R
Quinn et al. (2019) [87]	Rugby League	Australia	18	26 ± 4 N-R N-R	7	GPS (SPI Pro X, GPSports) 10 Hz	6712 (6203–6951)	N-R	542 (368–644) (≥ 15 km·h⁻¹)	N-R	N-R	N-R	N-R
Newans et al. (2021) [72]	Rugby League	Australia	117	26 ± 5 170 ± 1 77 ± 12	4 ± 2	GPS (Optimeye S5, Catapult Innovations) 10 Hz	4504 ± 1029	79 ± 2	774 ± 210 (≥ 12 km·h⁻¹)	N-R	N-R	0.4 ± 0.02 n·min⁻¹ (N-R)	N-R

TABLE 3. Continue.

Study (year)	Sport	Country	Players (n)	Age (years) Height (cm) Mass (kg)	Match (n)	Device	TD (m)	TD (m·min⁻¹)	MSR (m) 12.6–19.8 km·h⁻¹	HSR (m) 19.8–25.2 km·h⁻¹	Sprint (m) ≥ 25.2 km·h⁻¹	ACC (n)	DEC (n)
Clarke et al. (2014a) [88]	Rugby sevens	Australia	12	25 ± 5 168 ± 1 69 ± 7	N-R	GPS (SPI Pro X; GPSports) 5 Hz	N-R	86 ± 7	N-R	N-R	N-R	N-R	N-R
Clarke et al. (2014b) [86]	Rugby sevens	Australia	12	23 ± 5 168 ± 1 68 ± 8	6	GPS (SPI HPU, GPSports) 5 Hz	1164 ± 255	106 ± 7	36 ± 2%* (≥ 12.6 km·h⁻¹)	13 ± 2%* (≥ 18 km·h⁻¹)	N-R	N-R	N-R
Clarke et al. (2015) [85]	Rugby sevens	Australia	12	22 ± 2 167 ± 4 66 ± 5	4–6	GPS (SPI HPU, GPSports) 5 Hz	3142 ± 879	95 ± 10	629 19%* (12–18 km·h⁻¹)	482 ± 14 13%* (≥ 18 km·h⁻¹)	N-R	N-R	N-R
Clarke et al. (2017) [90]	Rugby sevens	Australia	11	(N-R) 169 ± 2 69 ± 4	12	GPS (SPI HPU, GPSports) 5 Hz	1078 ± 197	86 ± 4	323 ± 87 30 ± 4%* (12–18 km·h⁻¹)	120 ± 41 11 ± 3%* (≥ 18 km·h⁻¹)	149 ± 39 14 ± 3%* (N-R)	N-R	N-R
Conte et al. (2022) [77]	Rugby sevens	Brazil	14	Backs = 6 24 ± 3 161 ± 7 59 ± 5 Forwards = 8 22 ± 3 167 ± 5 71 ± 6	12	GPS (OptimEye X4, Catapult Innovations) 10 Hz	1119 ± 416	92 ± 1	66 ± 4 5 ± 0.2 m·min⁻¹ (18–20 km·h⁻¹)	97 ± 25 8 ± 2 m·min⁻¹ (≥ 20 km·h⁻¹)	N-R	14 ± 2 1 ± 0.1 n·min⁻¹ (≥ 1.8 m·s⁻²)	21 ± 1 1 ± 0.4 n·min⁻¹ (≤ -1.8 m·s⁻²)
Del coso et al. (2013) [89]	Rugby sevens	Spain-Netherlands	8	23 ± 2 166 ± 7 66 ± 7	3	GPS (SPI Pro X, GPSports) 5 Hz	N-R	87 ± 8	N-R	N-R	N-R	N-R	N-R
Doeven et al. (2019) [91]	Rugby sevens	N-R	10	25 ± 4 169 ± 4 64 ± 5	5	GPS (JOHAN Sports) 10 Hz	1466 ± 120	N-R	366 ± 45 (≥ 12 km·h⁻¹)	N-R	N-R	N-R	N-R
Goodale et al. (2006) [84]	Rugby sevens	N-R	20	24 ± 4 168 ± 6 69 ± 5	N-R	GPS (Minimax S4, Catapult Innovations) 10 Hz	1352 ± 306	87 ± 11	255 ± 94 16 ± 5 m·min⁻¹ (12–18 km·h⁻¹)	112 ± 51 7 ± 3 m·min⁻¹ (18–23 km·h⁻¹)	38 ± 31 2 ± 2 m·min⁻¹ (≥ 23 km·h⁻¹)	N-R	N-R
Malone et al. (2020) [78]	Rugby sevens	N-R	27	24 ± 2 168 ± 7 68 ± 4	36	GPS (Viper; STATSports) 10 Hz	1625 ± 132	116 ± 9	N-R	199 ± 44 14 ± 3 m·min⁻¹ (16–20 km·h⁻¹)	118 ± 45 N° 3.5 ± 1 (≥ 20 km·h⁻¹)	2 ± 1 (≥ 2.5 m·s⁻²)	N-R
Misseldine et al. (2018) [79]	Rugby sevens	N-R	12	Fowards = 5 27 ± 2 170 ± 3 70 ± 2 Backs = 7 24 ± 5 167 ± 5 62 ± 4	6	GPS (JOHAN trackers, JOHAN Sports) 5 Hz	1564 ± 52	98 ± 1	255 ± 30 17 ± 1%* (14–20 km·h⁻¹)	86 ± 37 N° 6 ± 1 6 ± 3%* (≥ 20 km·h⁻¹)	N-R	N-R	N-R

TABLE 3. Continue.

Study (year)	Sport	Country	Players (n)	Age (years) Height (cm) Mass (kg)	Match (n)	Device	TD (m)	TD ($m \cdot min^{-1}$)	MSR (m) 12.6–19.8 $km \cdot h^{-1}$	HSR (m) 19.8–25.2 $km \cdot h^{-1}$	Sprint (m) ≥ 25.2 $km \cdot h^{-1}$	ACC (n)	DEC (n)
Portillo et al. (2014) [82]	Rugby sevens	Spain	20	INT = 10 26 ± 4 167 ± 7 65 ± 5 NAT = 10 32 ± 6 167 ± 3 66 ± 5	4	GPS (SPI HPU, GPSports) 5 Hz	1503 ± 197	N-R	312 ± 94 (14–20 $km \cdot h^{-1}$)	83 ± 51 N° 4 ± 3 (≥ 20 $km \cdot h^{-1}$)	N-R	4 ± 1 (≥ 2 $m \cdot s^{-2}$)	N-R
Reyneke et al. (2018) [80]	Rugby sevens	N-R	15	24 ± 4 168 ± 7 67 ± 6	15	GPS (VX sport 220,Visuallex Sport International) 4 Hz	N-R	90 ± 3	18 ± 1 $m \cdot min^{-1}$ (12–18 $km \cdot h^{-1}$)	6 ± 3 $m \cdot min^{-1}$ (18–21 $km \cdot h^{-1}$)	4 ± 1 $m \cdot min^{-1}$ (≥ 21 $km \cdot h^{-1}$)	N-R	N-R
Suarez-Arrones et al. (2012) [83]	Rugby sevens	N-R	12	28 ± 4 165 ± 6. 64 ± 5	5	GPS (SPI Elite, GPSports) 1 Hz	1556 ± 189	N-R	437 ± 149 28%* (12–20 $km \cdot h^{-1}$)	84 ± 65 5.4%* (≥ 20 $km \cdot h^{-1}$)	N-R	N-R	N-R
Vescovi et al. (2015) [81]	Rugby sevens	Canada	16	N-R	5	GPS (SPI Pro 5, GPSports) 5 Hz	1468 ± 88	95 ± 5	552 ± 76 36 ± 5 $m \cdot min^{-1}$ (8–16 $km \cdot h^{-1}$)	224 ± 55 14 ± 3 $m \cdot min^{-1}$ (16–20 $km \cdot h^{-1}$)	128 ± 67 8 ± 4 $m \cdot min^{-1}$ (20–32 $km \cdot h^{-1}$)	N-R	N-R
Choi et al. (2020) [96]	Field hockey	Korea	52	26 ± 3 165 ± 4 59 ± 5	65	GPS (SPI-HPU, GPSports) 15 Hz	5760 ± 88	N-R	859 ± 90 (≥ 15 $km \cdot h^{-1}$)	N-R	N-R	16 ± 1 (≥ 3 $m \cdot s^{-2}$)	32 ± 2 (≤ -3 $m \cdot s^{-2}$)
Delves et al. (2021) [101]	Field hockey	Australia	11	22 ± 2 167 ± 6 62 ± 7	14	GPS Catapult (OptimEye X4, Catapult Innovations) 10 Hz	5310 ± 50	N-R	N-R	325 ± 109 (≥ 18 $km \cdot h^{-1}$)	N-R	N-R	N-R
Kapteijns et al. (2021) [94]	Field hockey	N-R	20	23 ± 4 169 ± 5 62 ± 5	26	GPS (APEX, County Down, STATSports) 18 Hz	5384 ± 835	147 ± 16	796 ± 221 (15–19 $km \cdot h^{-1}$)	274 ± 105 (≥ 19 $km \cdot h^{-1}$)	N-R	27 ± 12 (≥ 3 $m \cdot s^{-2}$)	40 ± 15 (≤ -3 $m \cdot s^{-2}$)
Kim et al. (2016) [99]	Field hockey	N-R	32	28 ± 3 165 ± 4 60 ± 4	N-R	GPS (SPI-HPU, GPSports) 5 Hz	5268 ± 77	N-R	580 ± 11 (12–14 $km \cdot h^{-1}$)	775 ± 19 (18–24 $km \cdot h^{-1}$)	371 ± 9 n: 28 ± 1 (≥ 24 $km \cdot h^{-1}$)	N-R	N-R
McGuinness et al. (2018) [100]	Field hockey	N-R	16	23 ± 3 163 ± 13 66 ± 6	7	GPS (S5, Catapult Innovations) 10 Hz	5147 ± 628	113 ± 9	16 ± 5 $m \cdot min^{-1}$ (≥ 16 $km \cdot h^{-1}$)	N-R	N-R	N-R	N-R
McMahon et al. (2019) [98]	Field hockey	Ireland	19	23 ± 4 (N-R) 64 ± 6	13	GPS Catapult (OptimEye S5, Catapult Innovations) 10 Hz	5167 ± 1030	N-R	959 ± 294 298 ± 7 $m \cdot min^{-1}$ (11–19 $km \cdot h^{-1}$)	N-R	N-R	N-R	N-R

TABLE 3. Continue.

Study (year)	Sport	Country	Players (n)	Age (years) Height (cm) Mass (kg)	Match (n)	Device	TD (m)	TD ($m \cdot min^{-1}$)	MSR (m) 12.6–19.8 $km \cdot h^{-1}$	HSR (m) 19.8–25.2 $km \cdot h^{-1}$	Sprint (m) ≥ 25.2 $km \cdot h^{-1}$	ACC (n)	DEC (n)
Morencos et al. (2019) [97]	Field hockey	Spain	16	25 ± 3 165 ± 5 58 ± 6	5	GPS (SPI ELITE, GPSport) 10 Hz	5834 ± 931	N-R	892 ± 41 (≥ 15 $km \cdot h^{-1}$)	848 ± 45 N° 65 ± 1 (≥ 21 $km \cdot h^{-1}$)	N-R	35 ± 5 3 ± 0.5 $n \cdot min^{-1}$ (2–3 $m \cdot s^{-2}$)	24 ± 3 2 ± 1 $n \cdot min^{-1}$ (2–3 $m \cdot s^{-2}$)
Sánchez-Migallón et al. (2020) [95]	Field hockey	N-R	30	23 ± 4 160 ± 1 60 ± 7	1	GPS (RealTrack Systems, WimuProTM) 10 Hz	5456 ± 699	N-R	852 ± 282 16 ± 5%* (12–18 $km \cdot h^{-1}$)	108 ± 76 1.98 ± 1.40%* (18–21 $km \cdot h^{-1}$)	n: 24 ± 29 0.5 ± 0.5%* (21–24 $km \cdot h^{-1}$)	N-R	N-R

[B]Percentage of total distance. ACC: accelerations; DEC: decelerations; GPS: global positions system; HSR: high-speed running; MSR: moderate-speed running; N-R: no reported; TD: total distance; TMA: time-motion analysis.

TABLE 4. Summary of the match demands of basketball, handball, and futsal.

Study (year)	Sport	Country	Players (n)	Age (years) Height (cm) Mass (kg)	Match (n)	Device	TD (m)	Pload ($AU \cdot min^{-1}$)	MSR (m) 12.6–19.8 $km \cdot h^{-1}$	HSR (m) 19.8–25.2 $km \cdot h^{-1}$	Sprint (m) ≥ 25.2 $km \cdot h^{-1}$	ACC (n)	DEC (n)
Conte et al. (2015) [105]	Basketball	Italy	12	27 ± 4 184 ± 1 77 ± 15	5	TMA (Dartfish 6.0 hfixed camera, Sony HD AVCHD HDR-CX115)	N-R	N-R	N° 56 ± 16 9.6 ± 2.5%* (N-R)	N°63 ± 16 11 ± 1.8%* (N-R)	n: 44 ± 15 7.8 ± 2.2%* (N-R)	N-R	N-R
Delextrat et al. (2012) [108]	Basketball	England	9	24 ± 4 173 ± 8 65 ± 11	1	TMA (JVC-x400)	N-R	N-R	N-R	N° 40 ± 14 02 ± 0.5 $N° \times min^{-1}$ (N-R)	n: 26 ± 16 1 ± 0.5 $N° \times min^{-1}$ (N-R)	N-R	N-R
Delextrat et al. (2017) [104]	Basketball	Spain	42	26 ± 4 183 ± 9 (N-R)	3	TMA (LINCE multiplatform sport analysis software Observesport) 25 Hz	N-R	N-R	1.2 ± 0.6 $n \times min^{-1}$ 4.9 ± 2.6%* (≥ 9 $km \cdot h^{-1}$)	N-R	0.2 ± 0.2 $n \times min^{-1}$ 0.6 ± 0.6%*	N-R	N-R
Palmer et al. (2021) [102]	Basketball	Australia	12	25 ± 6 180 ± 11 79 ± 17	20	Triaxial accelerometer (GT9X Actigraph) 100 Hz	N-R	N-R	16.7%* (15.7–17.4) (≥ 40–90% VO_2)◊	3.3%* (1.1–3.8) (90–100% VO_2)◊	3.8%* (2.5–5.3) (≥ 100% VO_2)◊	N-R	N-R
Palmer et al. (2022) [107]	Basketball	Australia	13	25 ± 6 181 ± 11 79 ± 17	21	Triaxial accelerometer (GT9X Actigraph) 100 Hz	N-R	N-R	40.2%* (35.9–49.1) (40–90% VO_2 reserve)◊	10.7%* (9.8–12.0) (90–100% VO_2 reserve)◊	15.1%* (9.7–25.0) (≥ 100% VO_2 reserve)◊	N-R	N-R
Reina et al. (2022) [109]	Basketball	Spain	10	24 ± 3 195 ± 1 93 ± 16	1	LPS (WIMU PROTM systems RealTrack Systems)	3531 ± 310 69 ± 3 m $\times min^{-1}$	1 ± 0.15	459 ± 70 9 ± 1 m $\times min^{-1}$ (≥ 15 $km \cdot h^{-1}$)	N-R	N-R	18 ± 1 n $\times min^{-1}$	18 ± 1 n $\times min^{-1}$
Scanlan et al. (2012) [106]	Basketball	Australia	12	22 ± 4 174 ± 7 73 ± 14	1	TMA (Labviewsoftware, National Instruments) 7.5 Hz	7039 ± 446	N-R	N-R	1850 ± 13 (11 –25 $km \cdot h^{-1}$)	925 ± 184 (≥ 25 $km \cdot h^{-1}$)	N-R	N-R
Stauton et al. (2018) [103]	Basketball	Australia	10	27 ± 5 182 ± 8 81 ± 12	18	Triaxial accelerometer (Link; Actigraph) 100 Hz	N-R	N-R	11 ± 0.5%* (60–90% VO_2)◊	4 ± 1%* (90–100% VO_2)◊	6 ± 5%* (100% VO_2)◊	N-R	N-R
Kniubaite et al. (2019) [110]	Handball	Lithuania	8	23 ± 2 173 ± 5 68 ± 7	14	Triaxial accelerometer (IMU; Optimeye S5 Catapult Innovations) 100 Hz	N-R	9	N-R	N-R	N-R	N-R	N-R

TABLE 4. Continue.

Study (year)	Sport	Country	Players (n)	Age (years) Height (cm) Mass (kg)	Match (n)	Device	TD (m)	Pload (AU·min^{-1})	MSR (m) 12.6–19.8 km·h^{-1}	HSR (m) 19.8–25.2 km·h^{-1}	Sprint (m) ≥ 25.2 km·h^{-1}	ACC (n)	DEC (n)
Luteberget et al. (2016) [111]	Handball	Norway	20	25 ± 4 175 ± 4	9	Triaxial accelerometer (IMU; Optimeye S5 Catapult Innovations) 100 Hz	N-R	8.8 ± 2.1	N-R	N-R	N-R	0.7 ± 0.4 n × min^{-1} (≥ 2.5 m × s^{-2})	2.3 ± 0.9 n × min^{-1} (≤ -2.5 m × s^{-2})
Luteberget et al. (2017) [112]	Handball	Norway	31	22 ± 3 171 ± 6 68 ± 7	9	Triaxial accelerometer (IMU; Optimeye S5 Catapult Innovations) 100 Hz	N-R	9.85 ± 0.36	N-R	N-R	N-R	N-R	N-R
Manchado et al. (2013) [115]	Handball	Germany-Norway	25	25 ± 3 175 ± 6 68 ± 5	N-R	TMA (camera 25 Hz)	2882 ± 1506	N-R	752 ± 484 m 29.7 ± 3.9%[B] 3.4 ± 0.6 n × min^{-1} (11–20 km·h^{-1})	272 ± 224 m 10.5 ± 4.1%[B] 0.8 ± 0.4 n × min^{-1} (≥ 20 km·h^{-1})	N-R	16.7 ± 6.7 n × min^{-1} (1.5–3 m × s^{-2})	N-R
Michalsik et al. (2014) [114]	Handball	Denmark	24	26 ± 4 174 ± 6 70 ± 7	1–8	TMA (No reported)	4002 ± 551	N-R	93 ± 67 m 0.8 ± 0.5% [*] 2.5 ± 1.8% [B] (≥ 15.5 km·h^{-1})	10 ± 11 m 0.1%[*] 0.2% [B] (≥ 22 km·h^{-1})	N-R	N-R	N-R
Wik et al. (2016) [113]	Handball	Norway	18	25 ± 4	9	Triaxial accelerometer (IMU; Optimeye S5 Catapult Innovations) 100 Hz	N-R	9.5 ± 1.1	N-R	N-R	N-R	N-R	N-R
Oliva Lozano et al. (2021) [116]	Futsal	Spain	14	24 ± 4 165 ± 6 63 ± 6	5	LPS (WIMU PROTM systems RealTrack Systems) 33 Hz	N-R	N-R	N-R	5 ± 0.4 m·min (≥ 20 km·h^{-1})	N-R	0.4 ± 0.3 m × min^{-1} (4–5 m × s−2) 28 ± 0.2 m × min^{-1} 240 ± 55 m × min^{-1}	28 ± 0.2 m × min^{-1}

[*]Percentage of total time; [B]Percentage of total distance. ACC: accelerations; DEC: decelerations; GPS: global positions system; HSR: high-speed running; MSR: moderate-speed running; N-R: no reported; TD: total distance; TMA: time-motion analysis.

5 ± 0.4 m × min^{-1} in HSR. The maximum ACC was 6 ± 0.2 m × s^{-2}; a total of 240 ± 55 m × min^{-1} in ACC was recorded, with a total of 28 ± 0.3 ACC × min^{-1}, of which 0.4 ± 0.3 ACC × min^{-1} was performed above 4–5 m × s^{-2}. The maximum DEC was 6 ± 2 m × s^{-2} and an average of 28 ± 0.2 per minute [116] (Table 4).

DISCUSSION

This scoping review provides an overview of research on the physical demands of female athletes in elite team sports. Football was the most researched sport. In contrast, women's indoor sports have been less researched. In particular, GPS have emerged as the main devices used to monitor the physical demands of outdoor team sports (i.e., soccer, rugby, field hockey) and, on the other hand, accelerometers and TMA have been more commonly used to measure the physical demands of indoor sports (i.e., basketball, handball, futsal). It should be noted that the demands of matches vary significantly between sports, as each sport has its own characteristics and requirements. Therefore, a thorough understanding of the physical demands of different team sports is crucial to optimise training and performance, reduce the risk of injury and improve player well-being.

Considering female soccer, TD covered were ~9556 m and 103 ± 6 m × min^{-1} when considered in relative distance. Similar results were obtained in a previous meta-analysis [118] but with male players. Regarding intensity zones, there was observed high variability in MSR (range: 570–2520 m), HSR (range: 101–1490 m), and sprinting (range: 22–995 m). This could be explained by the differences in devices (TMA vs. GPS), sampling frequencies (i.e. 1–15 Hz) or ranges of velocity used. The same was observed when relative distance in MSR (6–27 m × min^{-1}) was analysed. Although the number of sprints was reported, no previous consensus was established about the velocity that should be considered (e.g. > 21 km × h^{-1} – > 25 km × h^{-1}); this phenomenon could explain the differences in results (9–70 number of sprint), and it was repeated in male studies as well [16]. In relation to the ACC and DEC actions, these variables can be strongly influenced by the device used and its sensitivity, as well as the duration of the action to be considered as ACC or DEC (i.e. 2–3 seconds) [119]. Studies [32–35, 41, 43, 54, 56, 63, 65] revealed that players performed a range of 8–423 and 15–430 in ACC-DEC actions per match respectively, while male soccer players performed about 64 ACC and 58 DEC actions per match (2–3 m × s^{-1}) [120]. Knowledge of the demands of elite women's soccer matches can be very useful for coaches, physical trainers, and physiotherapists to plan tailor-made training and return-to-play sessions.

In rugby league and union very similar TD were reported, with a mean of ~5533 m [72, 75, 87] and ~5458 m [71, 73, 74, 76] respectively. Considering TD performed per minute, the rugby league players performed ~77 m × min^{-1} and the rugby union players about ~65 m × min^{-1}. In rugby sevens TD was ~1549 m [76–79, 81, 82, 84–86, 90, 91], ~72% lower than rugby league and union; however, when reported relative to time it was slightly higher at 94 m × min^{-1}. Considering distances, female rugby league and union players covered 934 m and 114 m in MSR and HSR, respectively, whilst sevens elite female players performed 355 m in MSR, 165 m in HSR, and 108 m in sprinting. A recent meta-analysis [121] found that male sevens players covered 1100–2486 m of TD, 77–121 m × min^{-1}, ~449 m in MSR and ~190 m in HSR – greater distance than women players, especially at high speeds. The same was observed in rugby league and union male players, who performed greater distances [122, 123]. Female rugby players completed a mean of 7 and 5 sprints per match in rugby league/union and rugby sevens respectively. The variability of results may be explained by positional differences of rugby demands (i.e., backs, forwards) and the differences in the sports' rules and discipline. Therefore, reference values from different rugby disciplines are important, especially when players interchange within rugby sports, or return to play following a long-term injury or illness.

In field hockey, TD covered was similar in studies, ~5403 m [94–99, 101], of which ~823 m were in MSR, ~466 m in HSR and ~371 m in sprinting. Slightly lower results were found by James et al. [124] in male players (TD = ~4861 m; > 14.5 km × h^{-1} = ~1193 m; > 19 km × h^{-1} = ~402 m). Elite female field hockey players performed a mean of ~39 sprints, ~26 ACC and ~32 DEC actions; however, male field hockey players [124] reported that they performed ~21 sprints, ~50 ACC and ~60 DEC actions per match. Coaches and physical trainers may know the demands that competition requires, and in consequence these values can help to better understand the efforts that hockey players make during the competition. This would make it possible to compare the physical level with elite hockey reference values and draw the lines of work for both conditioning and recovery; however, more research is needed.

In female basketball, the TD covered was 7039 m, using TMA [82], and similar results were obtained for male players in a systematic review [125] (TD = ~7558 m) when the same system was used. Reina et al. [109] used LPS and found that women players covered 3531 m. The studies indicated that the proportion of movement performed by female basketball players was: MSR ~16%, HSR ~7%, and sprinting ~7%; while male players covered ~40% in MSR, ~25% in HSR, and ~0.4% in sprinting [125]. Also, elite female basketball players did ~35 sprint actions per match [105, 108]. Although few studies are available, these values can help to better understand the demands of elite women's basketball, and further investigation is warranted.

Regarding handball demands, studies that used TMA analysis reported that TD ranged between 2882 and 4002 m [114, 115]. Similar results were found in male players (i.e., ~3.5 km) [126, 127]. Elite female handball players covered ~423 m in MSR and ~141 m in HSR; similarly, during professional men's matches, players covered 356–670 m in MSR and 133–153 m in HSR. Moreover, the range of Pload was 8.8–10.6 au × min^{-1} [110–113] and women players performed 8.7–2.3 ACC and DEC per minute respectively.

Considering futsal, only one study [116] recorded female futsal match demands, using LPS. Players ran an average of ~5 m × min in HSR, with a threshold close to 20 km × h^{-1}. In addition, approximately ~0.4 ACC per minute of play (> 4–5 m × s^{-2}) were performed, the maximum ACC was 6 m × s^{-2} and 240 m × min^{-1} were covered in ACC, which corresponds to a total of ~28 ACC × min^{-1}. The maximum DEC was ~-6 m × s^{-2} and ~28 DEC × min^{-1} was performed. However, male futsal players presented higher match demands when compared to female futsal players [29]. Given that, methods and strategies in female's team sports should not be supported by evidence derived from male athletes.

There is limited evidence available regarding external load monitoring in indoor sports. This could be attributed to the fact that many indoor sports are practised in confined spaces, which makes it challenging to use tracking and monitoring devices compared to outdoor sports (due to e.g. high cost, complex installation, variables) [128, 129]. Each tracking technology has unique approaches to monitoring athletes, resulting in distinct advantages and disadvantages when tracking external load; therefore, it is essential to consider how the technology and its manufacturer process data within the context of the sport [11].

It should be noted that there are a number of contextual factors (i.e., team characteristics, style of play, opponent characteristics, moods, starter/non-starter, competition situations and venue) that may have influenced the variability of the data [130, 131]. The context can significantly affect the performance of the players and, therefore, the results obtained through the tracking system. It is important for staff to consider these variables when analysing the demands of competition and the variation that can occur from match to match. Therefore, it is recommended to avoid drawing absolute conclusions from a single measurement and instead analyse multiple data points to gain an overall understanding of the demands of competition.

On the other hand, this study established specific speed ranges for MSR, HSR, and sprinting to simplify the summary and comparison of results regarding the distance covered. However, the selection of speed thresholds lacks consensus, particularly regarding external load monitoring with wearable devices for female athletes. While most studies have focused on male athletes, some have suggested that speed thresholds set for men may not be applicable for women due to underestimation of efforts and inaccuracy of results [86, 132, 133]. Therefore, the authors recommend using relative thresholds in monitoring with wearable devices for better interpretation of results. Considering individual athlete performance and the use of absolute thresholds allows for a broader comparison and establishment of general goals [86, 134–136]. Consequently, further evidence is needed to determine whether female athletes require a different external load control approach than male athletes and whether it differs between sports.

Another point to consider is the definition of "elite" status in sports, which is a complex issue depending on several factors [137]. Generally, elite athletes are those who have achieved a high level of performance in their sport and compete at a professional level or in international competitions; criteria such as world ranking in a given sport discipline, history of achievement in major competitions, Olympic medal winning, or participation in national teams could be used [138, 139]. Nonetheless, defining elite status in sport can be challenging because it can vary depending on the sport and country in question [137]. Additionally, the level of performance required to be considered an elite athlete may change over time as sports evolve and athletes become stronger and faster [140, 141].

This study is limited by the lack of consistency of the devices (i.e., GPS, TMA, LPS), thresholds of different actions (i.e. zones of intensity, sprint, ACC, DEC), and sampling frequencies (1–15 Hz) that have been used. Lower sampling frequencies (e.g. 1 Hz, 5 Hz) have been shown to be less reliable than 10 Hz [119, 142], whereas with 10 Hz, the occurrence of high-intensity ACC and DEC actions can be obtained reliably, although distance and time-related variables are less reliable [119, 143]. The data filtering technique used by different software and upgrades can also influence the quality, reliability, and usefulness of the data [143, 144]. In addition, the minimum time that an ACC or DEC action must stabilize above the threshold to be determined as effort could generate inaccuracies in the frequencies of ACC and DEC of greater intensity [145]. Depending on the variables analysed, in elite female athletes, analysing between 3 and 9 matches, less than 10% error was found for profiling [146]. Finally, the present study did not consider positional differences or other variables (e.g., impacts, ACC and DEC zones, and peak velocity, among others) that might be of interest. Therefore, practitioners and researchers should carefully consider the methodology used and the criteria used to delineate the variables of interest.

CONCLUSIONS

In conclusion, this systematic review provides information regarding the match demands of elite female team sports. Soccer is the most investigated sport; female players perform ~9500 m TD; also they do ~580 m in HSR with a great number of ACC, DEC, and sprints. Rugby league and union players cover a greater distance (~5450 m) when compared to rugby sevens (~1550 m); however, rugby sevens is more demanding in terms of high-intensity actions. Women's field hockey players perform ~5400 m TD; also, it is a high-intensity sport, with high-speed and sprint actions. Women's indoor sports are less studied, which could be due to the difficulty and high cost of measuring the external load indoors. Female basketball players cover ~5300 m TD, of which 7% are in MSR. In handball, elite women's players perform ~3500 m TD; also, they cover ~423 m in MSR and ~141 m in HSR. Finally, female elite futsal players perform ~5 m × min^{-1} in HSR and they do a great number of high-intensity activities (i.e., HSR, ACC, and DEC actions). We consider that the results obtained from the existing research on the competitive demands of female athletes in team sports should be considered as a starting point, while keeping in mind the limitations discussed earlier. Additionally, it is important to customize the methods for external load monitoring based on the particular context and objectives of each sport. Lastly, we strongly recommend that researchers and professionals continue to explore and expand the knowledge on external load monitoring in female athletes.

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Competing interests
Authors declare that they have no competing interests.

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Snus use in football: the threat of a new addiction?

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ABSTRACT: The use of Snus, an oral nicotine pouch, is becoming increasingly common in English professional football. As a nicotine product, Snus raises important questions about health and performance for practitioners. The purpose of this short communication is to explain the current regulatory status of Snus, performance related-effects, and associated health outcomes. Further, based on player statements and evidence from the general public, we argue that Snus is used as a coping mechanism to deal with the stressors of professional football. Accordingly, the communication concludes with guidance for club-level multidisciplinary interventions to support player welfare, aimed at reducing Snus use as well as future research recommendations.

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Football medicine

INTRODUCTION

High performance expectations, employment insecurity, fatigue, injury, frequent travel, and intense media scrutiny are hallmark stressors of the professional men's football environment conducive to mental health issues [1]. Equally, strong socio-cultural and experiential barriers exist in football that often prevent players from seeking psychological help [2]. Accordingly, the prevalence of stress and mental health problems in male professional footballers (e.g., anxiety, distress, depression) are considerable, mirroring rates in the general population including mild to severe presentation [1]. Athletes may turn to a range of mood-altering substances such as alcohol, cigarettes, cannabis, and/or painkillers used recreationally to cope with the mental load/stress of a sporting career [3]. Mood-altering substances often negatively influence well-being [4], for example, cannabis use is becoming recognised as a modifiable risk factor for several adverse effects on human health, including mental illness [5].

Snus use is common in professional male football players, attracting negative attention from practitioners, clinicians and the popular press [6–10]. It is an oral, smokeless tobacco product containing nicotine that is placed between the gum and upper lip. Player testimony alongside journalistic investigations confirm Snus is predominantly used recreationally to relax [8, 10–12] and like smoking, is a substance commonly used to regulate mood [13]. However, whether Snus negatively affects player health or performance is not well established.

We provide a summary of the health and performance effects of Snus and nicotine, arguing that Snus use should not be considered an independent behaviour. Rather, a response to significant football-specific occupational stress warranting an interdisciplinary approach to reduce its widespread use, yet poorly understood effects, on player health and performance.

Is Snus legal?

Snus is not prohibited by the World Anti-Doping Agency (WADA) as a performance enhancing substance or controlled substance. Nicotine is however, on the WADA 2023 Monitoring Programme for in-competition use as a stimulant. Nicotine primarily acts as a neuroregulatory agent on neuronal nicotinic acetylcholine receptors in the central and peripheral nervous system, releasing dopamine via the mesolimbic pathway [14]. It has stimulatory effects in lower doses whilst depressing the central nervous system in higher doses leading to feelings of relaxation [15]. Analysis of 60,802 in-competition anti-doping urine samples taken in Italy from 2012–2020 reported that on average, 22.7% (15.2–32.5%) of all samples indicated nicotine intake, increasing to 29% (18.4–40.4%) in football [16]. The nicotine content in commercially available pouched Snus from Europe is comparable to a cigarette (approx. 15mg per product) [17]. However, it leads to significantly higher plasma nicotine concentration than smoking due to the longer use duration [17]. The nicotine content and carcinogen content of Snus products varies considerably between products [18]. Indeed, Swedish Snus has greater levels of unionized nicotine in comparison to US products meaning nicotine can be absorbed quicker across mucous membranes leading to a 'greater nicotine reward' [19].

It is not illegal to possess or consume Snus in the UK, but it is illegal to sell. Player testimonies suggest that purchasing Snus online through social media and illegal websites or from other players is common. This raises questions about substance propriety (e.g., contaminated products that may trigger anti-doping rule violations) alongside legal and employment implications for any players caught selling Snus to teammates [7]. Ultimately, whilst nicotine remains legal from an anti-doping perspective, there is no policy incentive for players to change their behaviour. Instead, Snus use should be treated as a matter of professionalism, like alcohol and smoking, with concern concentrated on player health and team performance.

Does Snus Impact Performance or Recovery?

A recent review of the limited studies concerning oral nicotine and Snus use in sport concluded that performance enhancement was unlikely and performance may even diminish [6]. A broader review of nicotine's impact on performance (aerobic, anaerobic and muscular) also concluded that ergogenic effects were unlikely, however, the available evidence quality for this conclusion was low [20]. Opposingly, meta-analytical findings support that nicotine can enhance some cognitive abilities on tasks involving fine motor skills, attention, and memory [21]. Further, the calming effects of high-dose nicotine described by users may offer short-term protection against the impact of stress on performance. Although, determining the impact of nicotine on performance is complex and often confounded by sampling of nicotine in naïve and chronic user participants. Indirectly, nicotine use is associated with sleep impairment [22] and the deleterious effects of limited sleep on athletic performance and recovery are well documented [23]. Equally, nicotine can lead to increased metabolic energy expenditure, reduced body weight, and appetite suppression [24] meaning Snus use may challenge optimal nutritional support for athletic performance and recovery. Therefore, chronic Snus use has the potential to undermine performance/recovery via impaired sleep and potentially diet.

Does Snus Impact Health?

Snus use has been associated with noteworthy short and long-term physiological health risks [6] linked to nicotine consumption (see Figure 1) including: (i) increased risk of periodontal disease; (ii) heat intolerance; (iii) impaired cardiovascular function; (iv) metabolic syndrome; and (v) increased mortality rates, caveated with the need for more robust studies in sport-specific populations. More broadly, meta-analytical results from military training studies indicate an association between smoking and increased injury risk [25] but there is little evidence to comment on any relationship between smokeless tobacco products, like Snus, and injury rates in high-performance athletic populations. Nicotine is a highly addictive compound and anecdotal reports suggest that dependence is becoming more common in football [8]. Like other addictions, nicotine dependence is associated with mental health issues and may lead to adverse physical and psychological withdrawal symptoms [26]. For example, short-term abstinence from nicotine can lead to intensified mood-related symptoms including anxiety and depression [27]. On balance, using Snus as a stress-coping method has the potential to cause social, physical, and mental harm undermining players' performance and recovery.

Reducing Snus Use

A central premise of this manuscript is that Snus use can be viewed as a maladaptive stress management strategy for football-related occupational stress. Smoking cessation, appetite suppression, and pre-match psychological reassurance have been cited as motivations for Snus use. Yet anecdotally the most frequently stated reason is for recreational relaxation as shown in Figure 1, aligning with research examining smokeless tobacco users in sporting samples [28] and Snus use in the general public [13].

Paradoxically, Snus use may enhance the risk of poor performance, injury and ill-health, a significant stressor for professional athletes. Yet instigating changes towards more positive health behaviours in athletes remains difficult and education alone is often insufficient [29]. In practice, an interdisciplinary approach that not only provides information concerning health risks but situates Snus use within broader strategies to improve athlete mental well-being is required. For example, psychologists can help footballers to cope with underlying mental health status and sport specific stressors by understanding player history, peer-pressure, social supports, motivation for use, and providing evidence-based interventions (e.g., cognitive behavioural therapy). It is important that when discussing Snus use and potential cessation strategies that conversation is framed against factors valued by players to promote engagement, such as any potential negative impact on their performance. Likewise, routine enquiry and education by medical staff, identification of at-risk players through daily well-being reporting by staff with frequent interaction (e.g., physiotherapists, S&C staff), and monitored pharmacotherapy for nicotine dependence, could all contribute to identifying, preventing, reducing, and hopefully stopping Snus use. Lastly, given that occupational stressors are inherent in a professional football career, ongoing work to promote mental health awareness and reduce barriers to seeking mental health support may encourage more adaptive methods for coping with stress at an individual and club level [30].

CONCLUSIONS

Recognising the inherent data limitations, the illustrative player testimonies presented in Figure 1 support a call for more research and systematic reviews examining Snus use in elite sport. We outline six future research avenues that could develop our understanding of

FIG. 1. Understanding the psychological and health impacts of Snus use in football. Please see commentary for the full reference list.

Snus use in football and other elite sporting populations as well as assisting sport medicine practitioners working with athletes. First, dedicated qualitative and quantitative analysis voicing the experience and motivations of Snus use in footballers that encompasses non-users to daily users should be prioritised to theorise behaviour and understand how to design behavioural interventions. Second, comprehensive prevalence surveys should be employed to accurately establish Snus use prevalence and patterns (e.g., when and how much is used). Third, as previously mentioned, the impact of nicotine use on performance is complicated warranting further studies into the impact of Snus use on physiological, cognitive, and match performance in elite samples [31]. Fourth, an objective focus on the wellbeing impacts of Snus use and dependence are essential. At present, there is scant evidence on the long-term consequences of Snus use in elite sporting populations to properly assess the behavioural risk. Epidemiological studies should therefore be undertaken to assess lifelong outcomes that include current and retired players. Fifth, staff experiences of athlete Snus use should be canvassed to ascertain field experience to guide research [32]. Finally, rigorously designed, long-term intervention studies utilising different psychological techniques can build an evidence base to support practitioners in reducing use. All of the above would inform policies and protocols for clinical decision-making aiming at supporting holistically healthy footballers.

Disclosure of Competing Interests

All authors declare that they have no competing interests.

Contributorship

All authors significantly contributed to the commentary and approved the final version. Research and manuscript drafting was collaboratively undertaken by all authors. SC produced the infographic.

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Top-class women's soccer performance: peak demands and distribution of the match activities relative to maximal intensities during official matches

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ABSTRACT: The aims of the current study were to determine the most demanding passages of match play (MDP) and the distribution of match activities relative to maximum intensities during official matches in top-class women soccer players. Twenty-eight women players competing in European championship and international UEFA competitions were monitored during 38 official matches (277 individual samples). Maximum relative ($m \cdot min^{-1}$) total distance (TD), high-speed running (HSRD), very high-speed running (VHSRD), sprint, acceleration and deceleration distances were calculated across different durations (1–5, 10, 15, 90 min) using a rolling average analysis. Maximum intensities (1-min_{peak}) were used as the reference value to determine the distribution of relative intensity across the whole-match demands (90-min_{avg}). Time and distance higher than 90-min_{avg} (> 90-min_{avg}) were also calculated. MDP showed *moderate* to *very large* [effect size (ES): 0.63/5.20] differences between 1-min_{peak} *vs* all durations for each parameter. The relative ($m \cdot min^{-1}$) 1-min_{peak} was greater than 90-min_{avg} of about +63% for TD, +358% for HSRD, +969% for VHSRD, +2785% for sprint, +1216% for acceleration, and +768% for deceleration. The total distance covered > 90-min_{avg} was ~66.6% of the total distance covered during the 90-min_{avg} for TD, ~84.8% for HSRD, ~97.4% for VHSRD, ~100% for sprint, ~99.1% for acceleration and ~98.2% for deceleration. The relative distance > 90-min_{avg} was higher ($P < 0.05$) than the 90-min_{avg} for each metric (ES: 2.22 to 7.58; *very large*). The present results may help coaches and sport scientists to replicate the peak demands during training routine in top-class women soccer players.

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INTRODUCTION

Nowadays, the popularity of women's soccer is growing, and the understanding of the official match-play demand is crucial for high-performance development through an evidence-based decision-making process [1]. Different tracking technologies (e.g. global positioning system, semi-automatic video-analysis, etc.) are currently utilized to quantify the total distance (TD), the distance covered at different running speeds [2] and the distance covered while accelerating/decelerating during both training and matches [3]. In practice, the locomotor activities recorded during the matches are used to plan the training workload and as a reference for soccer-specific drills (e.g., small-sided games), technical-tactical drills and/or individual positional exercises [4–6].

The relative whole-match running distance (90-min_{avg}) is usually utilized as a reference for player performance profiling and training prescriptions [6, 7]. Although match demands are affected by several factors such as playing position, the level of competition, the match-to-match variability and several others [8], it could be argued that top-class women players might cover a TD of ~9500 m to ~11200 m and a distance of ~800 m to ~1600 m between 15 and 20 $km \cdot h^{-1}$, ~500 m to ~900 m between 20 and 25 $km \cdot h^{-1}$, and ~190 m to ~250 m > 25 $km \cdot h^{-1}$ [9]. However, it has been previously reported that the 90-min_{avg} demands fail to fully account for the most demanding passages (MDP) of official match play [6 10, 11] determined across different time windows (e.g., 1, 2, 3, 5, 10 min periods) [11]. It may be responsible for underpreparing players for the MDP [11–13] during official matches. As such, the MDP analysis may help practitioners to contextualize the average [6] and peak [14] official match demands during the training routine [15]. The MDP during official matches were widely investigated in Serie A [11], French Ligue 1 [4], English Championship [16], reserve squad Spanish La Liga [3, 17] and Spanish La Liga 123 [18, 19] men soccer players. These highlighted that both 90-min_{avg} and the MDP across different durations should be considered as a reference for training prescriptions [20, 21]. The MDP across different durations may provide information to compare ball drills (e.g., small-sided games with or without goalkeepers, individual positional drills, etc.) of a different duration with the official match peak demands across a similar time window. As an example, it was recently shown how to replicate the 4-minute official match peak demands using ball drills in Italian Serie A men soccer players [14]. Unfortunately, in top-class women's soccer, information about MDP has been determined solely in the 5-min period [9], but research findings about MDP of a different duration are still lacking. These latter are challenging issues for the comparison of the official match peak demands and the ball drills' locomotor demands during training routine in women's top-class soccer. This information may be crucial for both performance development and injury prevention purposes in top-class women's soccer [14, 21].

Notwithstanding, the MDP theoretically occur only once or a few times during the game [10]. Therefore, conditioning for the MDP and whole match (90-min$_{avg}$) relative intensity should be only a part of the overall periodized training programmes [14, 21]. Although 90-min$_{avg}$, 1-min$_{peak}$ and MDP across different time windows (e.g., 1, 2, 3, 5, 10 min periods) could guide the training prescription [6, 11, 14], also the distribution of match activities relative to the maximum intensities has been recently reported [20] as a tool to reduce the gap between training and official match demands. The distribution analysis investigates the demands of each minute from the most demanding minute (i.e. 1-min$_{peak}$) to the less demanding minute during official matches and it may be used as a tool to have a more comprehensive analysis of the individual official match demands [21], as recently demonstrated in Australian soccer [22], rugby league [22], Italian Serie A [21] and Spanish La Liga men soccer players [20]. To the best of our knowledge, also the distribution of match activities regarding peak demands has not been previously investigated in top-class women's soccer.

Therefore, the current study aims to determine for the first time the 1-min$_{peak}$, the MDP across different time windows and the distribution of match activities relative to the maximum intensities in top-class women soccer players. Additionally, it aims to determine the match-to-match variability in 1-min$_{peak}$ *vs* 90-min$_{avg}$ during official matches [23]. Lastly, the time spent and the distance covered at different percentages relative to the maximal match-play demands were calculated.

MATERIALS AND METHODS

Participants

Twenty-eight (*n = 28*) top-class women soccer players competing in European championship and international UEFA competitions were monitored during official matches across the 2019–2020 and 2020–2021 seasons. Goalkeepers were not included in the analysis. A total of 277 individual observations were collected. The number of individual matches varied among players ($n = 9.9 \pm 5.3$, range: 2–18). The Ethics Committee of the University of Milan (protocol #102/14) approved the study. It was performed in accordance with the principles of the Declaration of Helsinki (1975).

Experimental design

Data were collected during 38 official home matches. A 18 Hz Global Positioning System unit (GPEXE Pro2, Exelio SRL, Italy, firmware version 0.13) was used to collect data during official matches [24]. Each device was turned on at least 15 min before each session to allow for acquisition of the satellite signal [6]. To reduce the inter-unit differences, each player wore the same unit for every match over the whole investigation [6]. The system has previously been shown to provide valid and reliable measurements of the match activity in soccer [24, 25].

Procedures

Following the completion of each match (~90 min), each file was trimmed so that only data recorded when the player was on the field for at least 85 min were included for further analysis [11]. Data were exported into a customized Microsoft Excel spreadsheet (Microsoft, Redmond, USA). A customized spreadsheet was used to allow analysis of relative distance covered ($m \cdot min^{-1}$) in the following categories: total distance (TD), high-speed running distance (HSRD, 15.1 to 20 $km \cdot h^{-1}$), very high-speed running distance (VHSRD, 20.1 to 24 $km \cdot h^{-1}$), sprint distance (sprint, > 24.1 $km \cdot h^{-1}$), distance with variations in running speed > 3 $m \cdot s^2$ (acceleration) and distance with variations in running speed < 3 $m \cdot s^2$ (deceleration) [6]. To assist in the development of velocity-based movement indicators, the rolling moving average was utilized to calculate the most demanding one-minute period (1-min$_{peak}$) and the maximal locomotor demands across six other durations (2, 3, 4, 5, 10 and 15 min) for each player across each match [11, 12, 17]. To compare with the traditional metrics analysis, the distance over the whole match demand (90-min$_{avg}$) was recorded and inserted into the data analysis. As previously proposed [20, 21], the 1-min$_{peak}$ was then used as the reference value to determine the distribution of relative intensity across the whole match for all other rolling 1-minute periods. The match-to-match variability in 1-min$_{peak}$ and 90-min$_{avg}$ were calculated for TD, HSRD, VHSRD, sprint, acceleration and deceleration [11]. The time and distance higher than 90-min$_{avg}$ (> 90-min$_{avg}$) were calculated as the minutes or distance covered at intensity higher than the percentage of 1-min$_{peak}$ corresponding to the average 90-min$_{avg}$ [21].

Statistical analysis

SPSS (version 26, IBM, USA) was used to perform the statistical analysis. A linear mixed model analysis was used to compare the effects of the duration of each period of match demands and the distribution of the match activities on the dependent parameter [11, 26]. The model used for each dependent parameter was with the duration of each period or with the distribution of match activities as independent fixed factors and random intercepts on the individual players. A log-likelihood ratio test was used to assess the goodness of fit of the models. Bonferroni's correction was used for multiple comparison analysis. Between-matches coefficient of variation (CV) values were calculated for 1-min$_{peak}$ and the 90-min$_{avg}$ demands for TD, HSRD, VHSRD, sprint, acceleration and deceleration. Cohen's *d* effect size (ES) with 95% confidence interval (CI) was used to describe the magnitude of the pairwise differences and interpreted as follows: < 0.20: *trivial*; 0.20–0.59: *small*; 0.60–1.19: *moderate*; 1.20–1.99: *large*; ≥ 2.00: *very large* [27]. Statistical significance was set at $\alpha < 0.05$. Unless otherwise stated, all values are presented as mean (SD) as reported using descriptive statistics.

RESULTS

The most demanding passages of play across different durations

Table 1 shows the maximal locomotor demands for each duration (1 to 5, 10, 15, 90 min). For each variable, as the time-dependent period decreases, an increase in maximal relative locomotor demand was found ($P < 0.05$). Descriptive results with differences across all durations for relative TD, HSRD, VHSRD, sprint, acceleration and deceleration are presented in Table 1.

As shown in Figure 1 (Panel A), the magnitudes of the percentage differences between 1-min$_{peak}$ and 90-min were sprint > acceleration = VHSRD > deceleration > HSRD > TD (ES: 2.11 to 28.2). As shown in Figure 1 (Panel B), the 1-min$_{peak}$ performance showed ~6% to ~48% match-to-match variability for TD and sprint, respectively. Sprint variability was higher for 90-min than 1-min$_{peak}$ (~61% *vs* 48%, respectively). No further difference in match-to-match variability between 1-min$_{peak}$ and 90-min was found (Figure 1, Panel B).

The distribution of the time spent at different percentages of 1-min$_{peak}$ for TD, HSRD, VHSRD, sprint, acceleration and deceleration are presented in Figure 2. Main effects for distribution of match activities were found for each dependent parameter ($P < 0.001$).

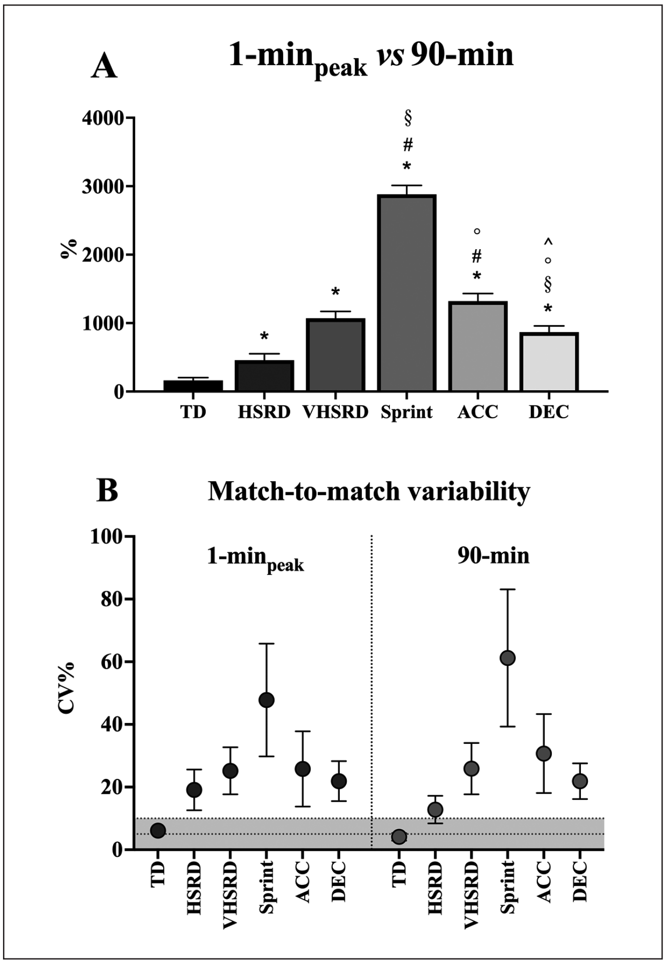

FIG. 1. The 1-min$_{peak}$ as percentage of the whole-match demands (90-min) (Panel A) and the match-to-match variability for both 1-min$_{peak}$ and 90 min (Panel B) are shown for total distance (TD), high-speed running distance (HSRD), very high-speed running distance (VHSRD), sprint distance (SPR), acceleration (ACC) and deceleration (DEC).
$^*P < 0.05$ vs TD; $^\#P < 0.05$ vs HSRD; $^§P < 0.05$ vs VHSRD; $^°P < 0.05$ vs sprint; $^\wedge P < 0.05$ vs acceleration.

TABLE 1. The most demanding passage of match play for each metric during official matches for different time duration (1, 2, 3, 4, 5, 10, 15, 90-min). All data are reported as average (SD). 95% confidence intervals of the effect size were shown for the differences between 1-min *vs* all other time durations (horizontal direction).

	1-min	2-min	3-min	4-min	5-min	10-min	15-min	90-min	ES (95% CI)
TD	169.6 (15.4)	149.1 (12.8)	140.3 (11.4)	135.7 (10.7)	132.2 (10.6)	123.8 (10.3)	119.6 (9.8)	104.2 (8.5)	1.66 to 5.20
HSRD	56.2 (13.2)	39.0 (9.7)	32.0 (7.5)	28.4 (6.6)	26.3 (6.5)	20.7 (5.2)	18.5 (4.8)	12.3 (3.3)	1.49 to 4.51
VHSRD	31.2 (9.9)	18.9 (6.5)	14.2 (5.0)	12.0 (4.3)	10.5 (3.9)	7.2 (2.9)	6.0 (2.4)	2.9 (1.4)	1.56 to 3.96
Sprint	19.7 (13.2)	10.9 (7.7)	7.6 (5.6)	5.9 (4.4)	5.0 (3.9)	2.9 (2.4)	2.2 (1.9)	0.7 (0.4)	1.08 to 2.01
ACC	1.8 (0.6)	1.1 (0.4)	0.8 (0.3)	0.7 (0.3)	0.6 (0.3)	0.4 (0.2)	0.3 (0.2)	0.1 (0.0)	0.63 to 3.29
DEC	3.8 (1.3)	2.5 (0.9)	1.9 (0.7)	1.6 (0.6)	1.4 (0.6)	1.0 (0.4)	0.9 (0.4)	0.4 (0.2)	1.56 to 3.61

Abbreviations: TD, maximum relative total distance; HSRD, high-speed running distance; VHSRD, very high-speed running distance; Sprint, sprint distance; ACC, acceleration distance with velocity changes calculated using > 3 $m \cdot s^{-2}$; DEC, deceleration distance with velocity changes calculated using < 3 $m \cdot s^{-2}$.

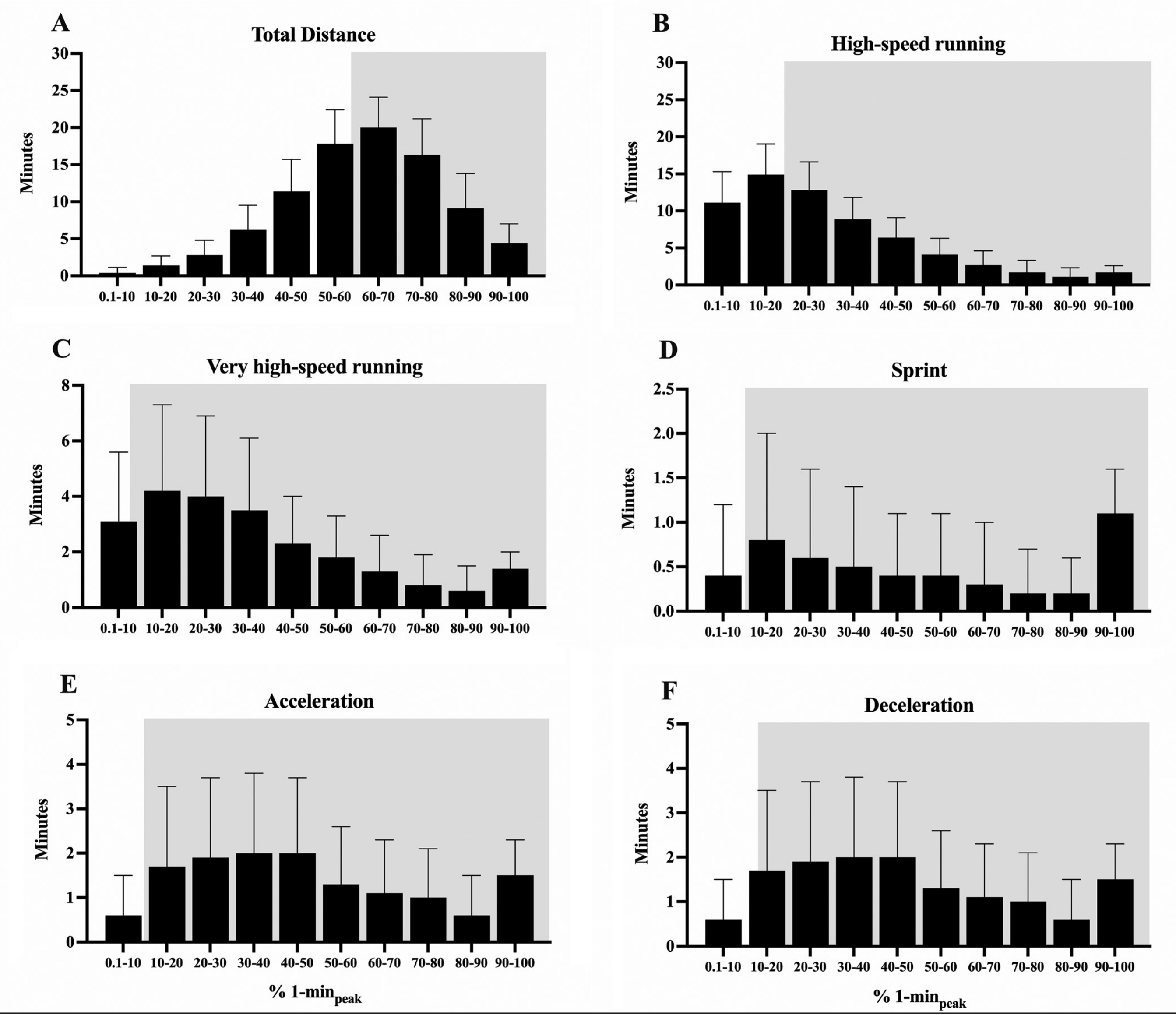

FIG. 2. The time spent at different percentages (from 0–10% to 90–100%) of the peak demands recorded in 1 min (% 1-min_{peak}) is shown for each metric. The grey area highlights the time spent at match activities higher than the average whole-match demands. Total distance: Panel **A**; high-speed running: Panel **B**; very-high speed running: Panel **C**; sprint: Panel **D**; acceleration: Panel **E**; deceleration: Panel **F**.

Figure 3 summarizes the time spent and the total distance covered > 90-min_{avg} for TD, HSRD, VHSRD, sprint, acceleration and deceleration; the percentage of the total distance covered > 90-min_{avg} than 90-min_{avg} was ~66.6(4.0)% for TD, ~84.8(1.9)% for HSRD, ~97.4(0.2)% for VHSRD, ~100(0.0)% for sprint, ~99.1(0.3)% for acceleration and ~98.2(0.5)% for deceleration; the relative distance covered at > 90-min_{avg} was higher ($P < 0.05$) than the relative 90-min_{avg} (ES: 2.22 to 7.58; *very large*) for each metric [TD: 125(9.1) $m \cdot min^{-1}$ vs 104.2(8.5) $m \cdot min^{-1}$; HSRD: 23.7(4.3) $m \cdot min^{-1}$ vs 12.3(3.3) $m \cdot min^{-1}$; VHSRD: 12.9(2.3) $m \cdot min^{-1}$ vs 2.9(1.4) $m \cdot min^{-1}$; sprint: 12.3(2.1) $m \cdot min^{-1}$ vs 0.7(0.4) $m \cdot min^{-1}$; acceleration: 1.0(0.4) $m \cdot min^{-1}$ vs 0.1(0.4) $m \cdot min^{-1}$; deceleration: 1.6(0.3) $m \cdot min^{-1}$ vs 0.4(0.2) $m \cdot min^{-1}$].

DISCUSSION

The current study aimed to describe the 1-min_{peak}, the MDP across different time windows, the distribution of match activities relative to the maximum intensities and the match-to-match variability in 1-min_{peak} and 90-min_{avg} during official matches in top-class women soccer players. For the first time, the 1-min_{peak}, the MDP across different time windows and the distribution of match activities with regards to 1-min_{peak} determined during an official match have been described. Firstly, the locomotor activities calculated at 90-min_{avg} were much lower than 1-min_{peak} for each metric, especially for the high-intensity activities; interestingly, no differences in the match-to-match variability between 90-min_{avg} and 1-min_{peak} were found except for sprint, with a lower variability in 1-min_{peak} than 90-min_{avg} (~61%

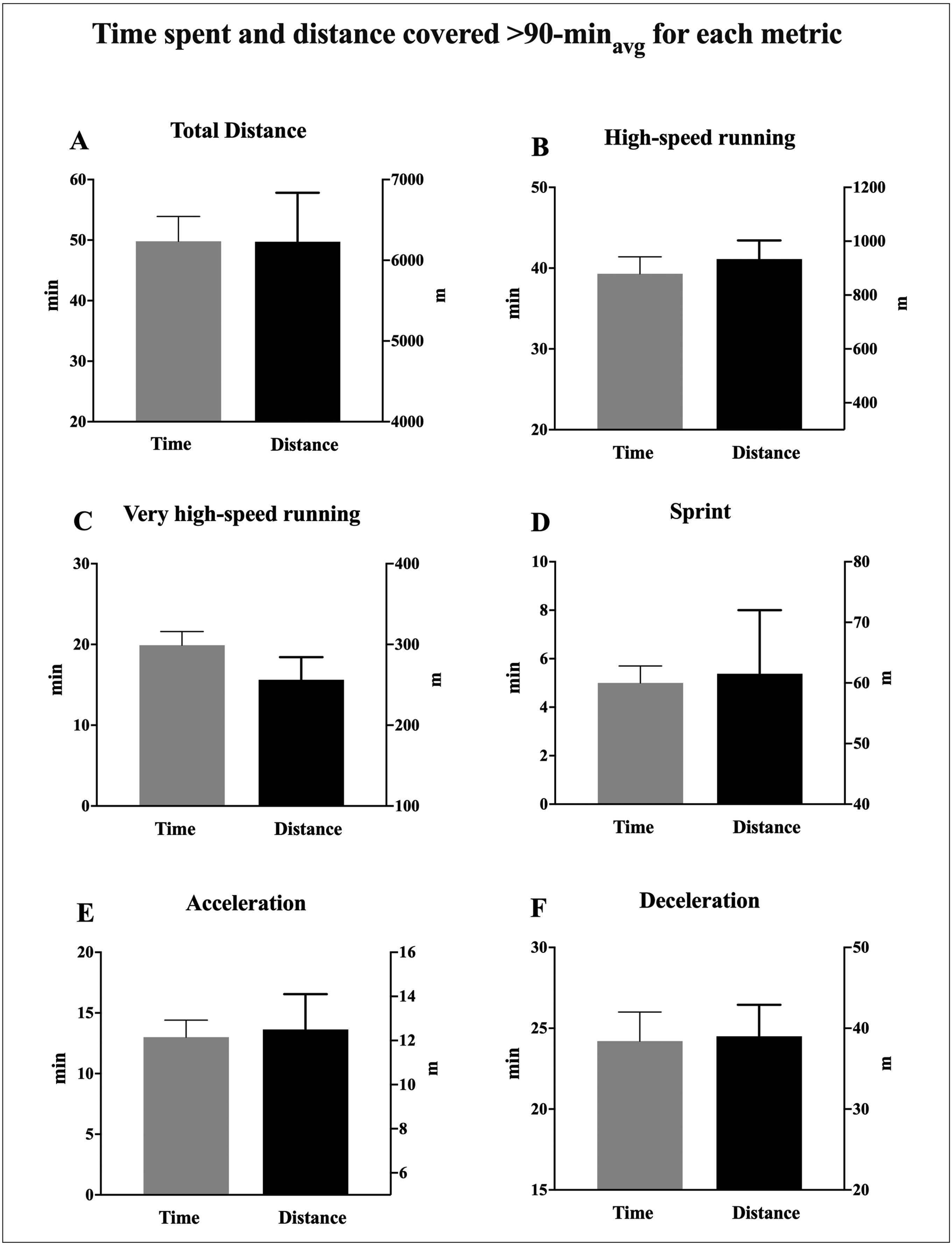

FIG. 3. The time spent (min) and distance covered (m) at match activities higher than the average whole-match demand (90-min$_{avg}$) are shown for each metric. Total distance: Panel **A**; high-speed running: Panel **B**; very-high speed running: Panel **C**; sprint: Panel **D**; acceleration: Panel **E**; deceleration: Panel **F**.

vs 48%, for 90-min$_{avg}$ and 1-min$_{peak}$, respectively). Secondly, most of the locomotor activities occur at an intensity > 90-min$_{avg}$. Thirdly, except for the *small* difference for acceleration, the relative distance > 90-min$_{avg}$ was significantly higher (ES: *large* to *very large*) than the 90-min$_{avg}$ for each metric.

For the first time, the present findings show the official match peak demands during top-class women's soccer. As previously described in men's soccer, also the current study in women's soccer highlights that the locomotor demands for TD, HSRD, VHSRD, acceleration and deceleration were higher during shorter time windows. As such, the 1-min$_{peak}$ locomotor demands are higher than the other longer time periods (e.g. 1-min$_{peak}$ vs 4-, 5-, 10-, 15-min periods), and especially than 90-min$_{avg}$. Similar results were previously described in Italian Serie A [11], French Ligue 1 [4], Spanish La Liga [20], Spanish La Liga 123 [18, 28] and Youth/Adult Premier league [29] male soccer players. Comparisons with previous findings are challenging due to the lack of previous studies about peak demands across different durations in top-class women's soccer. This is the first study that identify the 1-, 2-, 3-, 4-, 5-, 10-, 15-min peak demands for different metrics in top-class women's soccer. Comparing match performance of Italian Serie A women vs previous results in Italian Serie A men [11] soccer players, the current results highlights 1-min$_{peak}$ demands of ~169 vs ~188 m·min^{-1} for TD, ~56 *vs* ~58 m·min^{-1} for HSRD, ~31 vs ~37 m·min^{-1} for VHSRD, ~19 vs ~42 m·min^{-1} for sprint and ~6 vs ~32 m·min^{-1} for acceleration+deceleration in women vs men, respectively. Therefore, women players covered lower TD, similar HSRD, lower VHSRD and a significantly lower sprint and acceleration+deceleration distance than men soccer players of a similar Italian Serie A population. Similarly, the present findings show a lower total distance (i.e. ~169 vs ~190 m·min^{-1}) and a lower high-speed running (i.e. ~51 vs ~59 m·min^{-1}) in Italian Serie A women player than English Championship men players [29]. The differences with regards to men soccer are probably due to a lower neuromuscular ability (i.e. muscular strength, power, etc.) in women, as previously reported [30]. Lower cardiorespiratory [31] and neuromuscular [30] abilities were previously demonstrated in women than men across different sports [30, 31] including elite soccer [30, 31]. Therefore, the lower distance covered at the highest speed and/or acceleration/deceleration thresholds in women than men could be explained by between-gender neuromuscular [30], cardiorespiratory [30, 32] and anthropometric [32] differences. Unfortunately, the lack information about peak locomotor demands in top-class women's soccer challenges the comparisons of peak demands across a similar women population.

For the first time here, the current findings describe the distribution of match activities with regards to 1-min$_{peak}$. The average (90-min) locomotor match demand was about ~60% and ~20% of the 1-min$_{peak}$ for TD and HSR, respectively, while it was ~10% for VHSR, sprint, acceleration and deceleration. As such, when a woman soccer player plays a match, most running activities are covered at intensity higher than 90-min$_{avg}$ official-match demands, especially for high-speed running, sprint and acceleration/deceleration activities. Since the current findings in women's soccer are shown for the first time here, comparisons with previous results in women's soccer are challenging. Comparing the current information with previous findings in male Italian Serie A [21] and male Spanish La Liga 123 [20] soccer players, a similar distribution of match demands for different metrics was found. However, the gap between 1-min$_{peak}$ and 90-min$_{avg}$ is larger in women than men for HSR, VHSR, acceleration and deceleration. For HSR, the 90-min$_{avg}$ was at ~20% or ~30% than 1-min$_{peak}$ in women or men [21], respectively; for VHSR, acceleration and deceleration the 90-min$_{avg}$ was at ~10% or ~20% than 1-min$_{peak}$ in women or men [33], respectively. Therefore, coaches and sport scientists should consider the current results for preparing women players for peak locomotor demands determined during the official matches. Interestingly, the official match demands require an intensity higher than 90-min$_{avg}$ with ~6226 m covered in ~50 min for TD, ~933 m covered in ~39 min for HSR, ~256 m covered in ~20 min for VHSR, ~61 m covered in ~5 min for sprint, ~12.5 m covered in ~13 min for acceleration and ~39 m covered in ~24 min for deceleration. These findings suggest that the official match locomotor demands are often higher than the 90-min$_{avg}$. Therefore, the 90-min$_{avg}$ official match demands should not be considered alone as a reference for training prescriptions because it may underestimate the locomotor demands during official matches. Similar findings have been reported in Italian Serie A [21] and Spanish La Liga [20] male soccer players; similarly, it was suggested that the average match demands did not effectively reflect the locomotor match demands. Other comparisons with previous research findings are challenging because no previous studies investigated the distribution of match activities during official matches in top-class women's players. Coaches and sport scientists should consider the intensity higher > 90-min$_{avg}$ as a possible reference for the whole training intensity across training periodization. In detail, the 90-min$_{avg}$ vs the > 90-min$_{avg}$ official match demands was ~104 vs ~124 m·min^{-1} for TD, ~12 vs ~24 m·min^{-1} for HSR, ~2.9 vs ~12.8 m·min^{-1} for VHSR, ~0.7 vs ~12.3 m·min^{-1} for sprint, ~0.1 vs ~1.0 m·min^{-1} for acceleration and ~0.4 vs ~1.6 m·min^{-1} for deceleration. Therefore, practitioners should consider intensifying the training demands to cope with the official match demands > 90-min$_{avg}$ for preparing women players for match performance demands. Moreover, as reported above, during most conditioning training sessions, the stakeholders could try to replicate the > 90-min$_{avg}$ (i.e., as a reference for the full session demands) and the peak demands across different durations (i.e., as a reference for sport-specific drills and/or running-based exercises) to prepare the women players for the average and peak demands of the competition. These findings further concern the > 90-min$_{avg}$ match-play demands and the peak demands for both performance development [14] and injury prevention [34] purposes.

The current findings come with some limitations: i) this is a team study, so between-squad differences (e.g., formation, style of play, style of coaching and cardiorespiratory or neuromuscular individual player characteristics, etc.) could affect the current results; ii) the locomotor metric utilized in this study was arbitrary and not individualized, affecting the possibility to highlight also the locomotor demands with regards to the maximal individual capacities. As such, it should be acknowledged that the maximal individual capacity in different metrics (e.g., VHSR, sprint, acceleration, deceleration, etc.) can exceed the maximal positional match-play requirements. For example, locomotor load > 90-min$_{avg}$ or 1-min$_{peak}$ for a given player could be lower than her VHSR, sprint, acceleration or deceleration maximal capacity. iv) Despite the current results open to the opportunity to contextualize the maximal match-play locomotor demands in women's soccer, the locomotor load > 90-min$_{avg}$ or 1-min$_{peak}$ did not take into account the cardiorespiratory and metabolic individual capacity [23] and it could lead to lower the training stimuli; coupling locomotor and physiological demands during training routine is suggested for appropriate player's conditioning [6, 11]. Therefore, soccer-specific exercises (e.g., small- or large-side games) [6], position-specific drills [35] and/or individualized running based exercises [36] with the aims to recreate or overload locomotor load from > 90-min$_{avg}$ to 1-min$_{peak}$ should be coupled with soccer-specific, positional-specific or individual running-based exercises near to the maximal individual aerobic [37], anaerobic [38] and neuromuscular [39] capacity for maximizing the performance development in top-class women soccer players. Therefore, despite the current limitations, these findings open several new future perspectives in top-class women's soccer.

The present findings have several practical applications. In practice, coaches and sport scientists could utilize the MDP determined during the official match as a reference for training prescriptions and performance development during daily on-field routine. Although the 90-min$_{avg}$ demands are usually considered as a reference for training prescription [6], the current findings further suggest that the 90-min$_{avg}$ could not be the only reference for prescribing the intensity for the full training demands; an intensity > 90-min$_{avg}$ should be considered for the full training session demands, as previously reported in male's soccer [14, 20]. As an example, at match-day minus 4 or minus 3, coaches and sport scientists could consider replicating the MDP, the 90-min$_{avg}$ and the > 90-min$_{avg}$ of official matches using small-sided games in specific pitch sizes [14] for mimicking and/or overloading the individual official match peak locomotor demands. Additionally, when practitioners aim to prescribe ball drills of different durations, the 90-min$_{avg}$ and/or the > 90-min$_{avg}$ demands may underestimate the MDP of the official matches, possibly unpreparing the women players for the peak demands of the competition [4, 10, 11]. Therefore, coaches and sport scientists could manage the intensity of ball-drills of different durations using the 1-, 2-, 3-, 4-, 5-, 10-, 15-min peak demands as a reference to replicate the MDP of a similar duration determined during the official matches. For example, the manipulation of the relative pitch sizes during small-sided games may help to replicate the official match 90-min$_{avg}$ [6] and/or the peak demands (e.g. 4-min$_{Peak}$) [14] for each metric, especially for HSRD and sprint. Using small-sided games, it has been recently shown that a relative area per player of ~350 m^2 · player should be utilized for replicating the 4-min$_{peak}$ determined during official matches in elite Serie A men soccer players [14]. Conversely, when small-sided games have to be played on small pitches for overloading the technical demands [40], supplemental individual exercises (i.e. running base and/or positional exercises) should be considered to prepare the players for the individual official match peak locomotor demands, especially for high-speed to sprint running. This approach may help to maximize the performance development in top-class women's soccer. Since VHSRD and sprint have been previously proposed as effective tools for injury prevention purposes [34], preparing players for the maximal match-play demands, especially for VHSRD and sprint, may help to optimize the individual exposure to the worst-case scenario during the official matches. This may help to reduce the gap between training and official match demands, helping to maximize the performance development and possibly positively affecting injury prevention in women's soccer [34, 41].

CONCLUSIONS

The official match peak demand and the distribution of match activities with regards to 1-min$_{peak}$ have been described. Firstly, the locomotor activities calculated at 90-min$_{avg}$ were much lower than 1-min$_{peak}$, especially for the high-intensity activities; interestingly, no differences in the match-to-match variability between 90-min and 1-min$_{peak}$ were found. Secondly, most of the locomotor activities occur at an intensity > 90-min$_{avg}$. Thirdly, the relative distance > 90-min$_{avg}$ was *very largely* than the 90-min$_{avg}$ for each metric. Therefore, the current results should be considered as a reference for training prescription with the aim to prepare top-class women soccer players for the maximal locomotor demands during official matches.

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Conflict of interest declaration

The authors declare no conflicts of interests.

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Changes in physical and technical match performance variables in football players promoted from the Spanish Second Division to the First Division

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ABSTRACT: The aim of this study was to compare physical and technical match performance variables in football players who competed in the Spanish second division for one season and were promoted to the top (first) division in the following season. A total of 97 male outfield football players who were promoted from the second to the first division of the Spanish professional football league within the same team were analysed. Data were recorded using the TRACAB (ChyronHego, New York, USA) multicamera computerised optical tracking system during five seasons (2015–2016 to 2019–2020). A one-way ANOVA repeated measures analysis showed that players executed a greater number of high-intensity running (HIR) efforts ($P < 0.001$; ES: 0.258), as well as covering greater HIR distance ($P < 0.010$; ES: 0.106) and total running distance (TD) ($P < 0.010$; ES: 0.080), when they played in the first division compared with the second division. Moreover, players performed a lower number of passes ($P < 0.01$; ES = 0.116), short passes ($P < 0.01$; ES = 0.106), long passes ($P < 0.05$; ES = 0.067), dribbles ($P < 0.001$; ES = 0.146) and shots ($P < 0.01$; ES = 0.074) in the first division compared to the second division. No significant differences were found for any of the defensive variables evaluated. In conclusion, being promoted from the second to the first division of professional football requires players to adapt to greater physical demands and a reduced number of technical actions.

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INTRODUCTION

Professional football players require a great capacity for performing intermittent high-intensity physical efforts interspersed with fast technical and tactical actions [1]. In the last decades, professional football has evolved and now the game demands a higher quantity of high-intensity running (HIR) efforts and greater technical accuracy [2, 3, 5, 6, 7, 8]. This physical and technical evolution may be due to the interaction of multiple factors such as the improvements in the physical preparation of players [8], the new trends in tactical periodization [4], as well as the incorporation of modern technologies to monitor the competition and the training process [9, 10]. All these factors contribute to implementing better control and management of professional players' physical load within each game and throughout the season.

A great number of studies have focused on the analysis of physical and technical performance of top categories of professional football [11]. However, professional football in most national leagues encompasses two or more categories that retain the same structure of competition. In these national leagues, teams may promote/relegate between categories, which exposes some players to play in both levels. Hence, the comparison of game characteristics between the first and second categories of professional football in national leagues deserves investigation to understand the process that the players undergo when they are promoted to a higher category. This would allow a better understanding of how players' demands can change between different competitive levels to allow faster adaptation to the new category [12, 13].

In this regard, the literature that has analysed how the competitive level affects match performance physical and technical variables in professional football is scarce and has provided controversial findings.

For instance, it was concluded [12] that English Premier League players covered less total and HIR distance compared to players playing at lower competitive levels such as the Championship and League One. Also, this study observed superior technical ability in the Premier League compared to the lower-level competitions. In the same way, it was observed [20] that players in the Championship covered more total, high-speed running and sprinting distances than those in the English Premier League.

In contrast with these results, recent reports in the Spanish *LaLiga* found that HIR distances were greater in the Spanish first division compared to the second division [13, 14] and the top-ranking teams in the first division covered significantly greater distances than the other teams in the same division and in the second division [15].

Moreover, the referred study [15] reported that first division teams performed more passes and registered a higher percentage of successful passes than second division ones. When analysing different playing positions, greater high-intensity actions were found for the central defenders (CD), wide midfielders (WM), and attackers in the first division compared to the second division [16].

However, all these investigations were cross-sectional because they analysed different teams competing in each category. From a player development perspective, there is a lack of scientific evidence on the possible changes in game demands that the same player can have when being promoted from the second division to the first division. To the best of our knowledge, only one study [17] has compared the individual physical and technical performance of the same group of players when being promoted from the English second division to the Premier League. In Morgan's study, the distance covered over the season was slightly higher in the first division with no effect on sprint and high-intensity distances, although the limited sample of players used in this investigation may limit the extrapolation of these results to other teams or competitions.

Overall, the different methodological approaches and the contradictory findings impede understanding of how the physical and technical demands of the game change for players who are promoted to a higher category of professional football.

Therefore, the aim of this study was to compare physical and technical match performance variables of football players who were promoted from the Spanish second division to the first division within the same team. Based on previous studies in Spanish football, we hypothesized that players would perform more HIR efforts and cover more HIR distance in the first division compared to the second division, regardless of their playing position.

MATERIALS AND METHODS

Sample

A total of 97 professional outfield football players who played in the second division and were promoted with the same team to the first division of the Spanish professional football league were included in this investigation (Table 1). To achieve this sample of players, data were gathered from five seasons (from 2015–2016 to 2019–2020) with a total of 12 teams promoted to the first division. The only inclusion criterion was the selection of players who played a minimum of four and a maximum of thirty-eight full matches in each division, maintaining his outfield position. Goalkeepers were excluded from the study because of their different match performance demands compared to outfield players. Players were classified into five playing position roles – central defenders (CDs) (n = 26), full backs (FBs) (n = 19), central midfielders (CMs) (n = 32), wide midfielders (WMs) (n = 11) and forwards (FWs) (n = 9) – following the classification of multiple previous studies [6, 7, 18].

Variables and Procedures

The design of the study is intrasubject comparative, where the mean value of the matches that the player played in the second division

Table 1. Description of the players evaluated in each team (N), average number of matches per player and team ranking position at the end of the season in both divisions.

Period	Team	N	2nd Division		1st Division	
			Matches	Ranking Position	Matches	Ranking Position
2015–2017	Team A	4	37.7 ± 0.5	1	25.5 ± 5.4	9
	Team B	6	32.2 ± 9.4	6	26.3 ± 7.6	19
	Team C	9	30.2 ± 9.3	2	24.8 ± 6.8	17
2016–2018	Team D	10	34.1 ± 4.3	1	26.5 ± 7.4	15
	Team E	9	29.2 ± 12.0	2	29.1 ± 9.6	10
	Team F	6	35.1 ± 7.0	3	27.3 ± 9.3	8
2017–2019	Team G	7	30.8 ± 8.4	1	28.2 ± 9.6	20
	Team H	8	32.2 ± 8.6	2	28.9 ± 8.1	19
	Team I	12	32.3 ± 5.4	5	27.2 ± 8.7	16
2018–2020	Team J	7	32.7 ± 9.0	2	24.3 ± 9.6	7
	Team K	9	31.7 ± 7.0	1	26.5 ± 6.9	10
	Team L	10	31.0 ± 7.0	5	29.1 ± 8.9	19

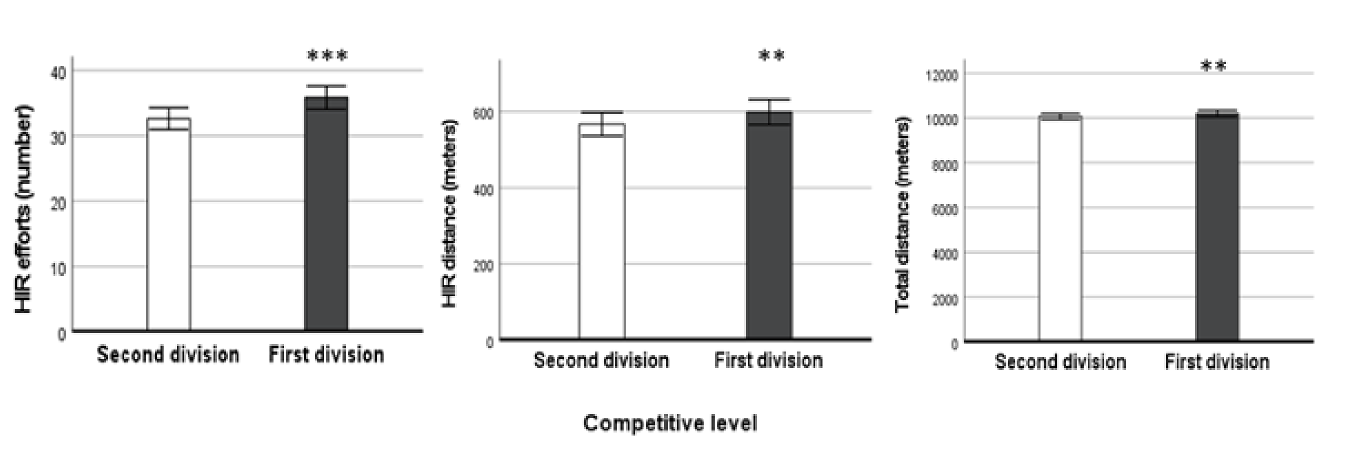

FIG. 1. Number of high-intensity running (HIR) efforts, HIR distance and TD (total distance) covered according to the competitive level in Spanish professional football players. * = *P < 0.05; ** = P < 0.01; *** = P < 0.001.*

was compared with the mean value of the matches that the same player played in the first division in the following season.

Data were collected using the TRACAB (ChyronHego, New York, USA) multicamera computerised optical tracking system, which has a sampling frequency of 25 Hz, and processed using the Mediacoach software (*LaLiga*, Madrid, Spain). This system has been deemed as a valid and reliable tool to analyse football performance activities [19]. In accordance with the ethical guidelines of *LaLiga*, this investigation does not include information that identifies football players.

The variables of the present study were divided into two categories: individual match running performance variables and technical performance variables. For the first group of variables, the number of efforts performed at HIR (number of HIR), the distance covered at HIR (i.e., $> 21\ km \cdot h^{-1}$, in m) and the total distance covered (TD, in m) were obtained for each match. The technical performance variables included total number of passes, passing accuracy (%), passing verticality (%) (proportion of passes with forward direction from the total number of passes), number of short passes (those of less than 30 m), number of long passes (those of more than 30 m), dribbles, shots, aerial duels, interceptions, clearances, and tackles.

Statistical Analysis

All analyses were conducted using statistical software (SPSS Inc., V20, Chicago, IL, USA). Descriptive statistics were implemented through the mean (M) and standard deviation (± SD). Data normality was examined using the Kolmogorov-Smirnov test. One-way repeated-measures ANOVA was used to calculate the differences in match performance variables between the first and second division. Also the playing position was considered an inter-subject factor to examine its interaction with the competitive level. *Post hoc* analysis was performed using the Bonferroni test to examine the differences between the first and second division for each playing position. The magnitudes of the differences for all variables were analysed using partial eta squared (ES) (ηp^2).

RESULTS

Figures 1 and 2 present physical performance variables of players in the first vs second division. Players executed a greater number of HIR efforts (P < .001; ES: 0.258), HIR distance (P < .01; ES: 0.106) and TD (P < .01; ES: 0.080) when they played in the first division compared with the second division (Figure 1). For TD, an interaction effect between the competitive level and the playing position was found (P < .01; ES: 0.147).

In Figure 2 it can be observed that all playing positions, except for the FWs, performed more HIR efforts when competing in the first division than in the second division. As for HIR distance, FBs (641.5 ± 140.4 vs 601.4 ± 130.1; P < 0.05) and WM (759.7 ± 117.0 vs 708.9 ± 100.1; P < 0.05) covered greater distance in the first division than in the second division, whereas no significant differences were found for the rest of playing positions. Concerning TD, no differences were found for all playing positions except for FWs, who covered greater TD in the first division compared to the second division (10320.7 ± 897.8 vs 9803.5 ± 621.7; P < 0.001).

Table 2 shows the match offensive and defensive technical variables of players according to the competitive level, as well as the interaction effect of their playing position. Repeated-measures analysis indicated that players performed fewer passes (P < 0.01; ES = 0.116), short passes (P < 0.01; ES = 0.106), long passes (P < 0.05; ES = 0.067), dribbles (P < 0.001; ES = 0.146) and shots (P < 0.01; ES = 0.074) in the first division compared to the second division. Statistical analysis showed no significant differences for passing accuracy and passing verticality between categories.

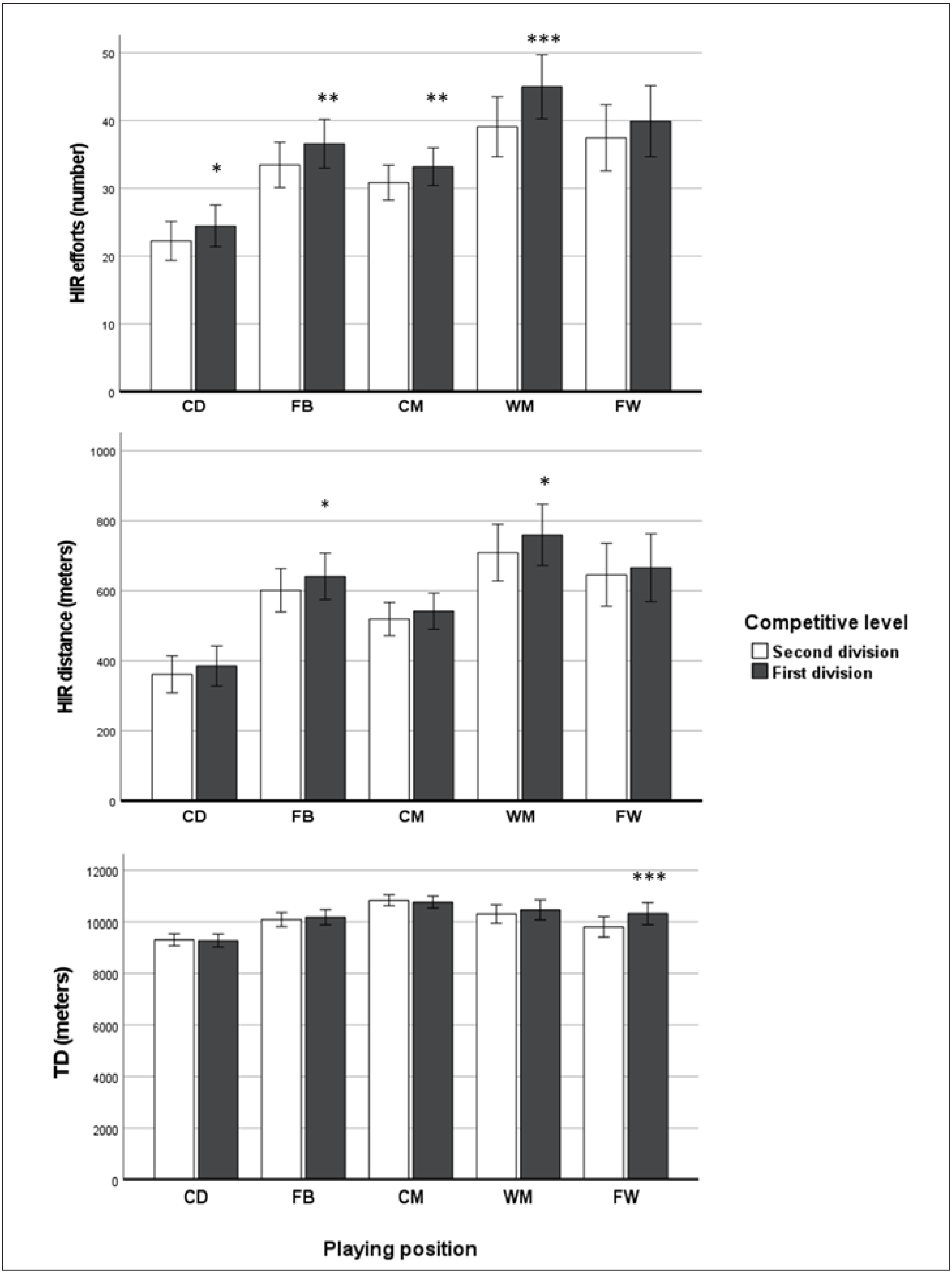

FIG. 2. Number of high-intensity running (HIR) efforts, HIR distance covered and total distance (TD) according to playing position and competitive level in Spanish professional football players.
Note: * = P < 0.05; ** = P < 0.01; *** = P < 0.001.

Table 2. Comparative analysis of offensive and defensive technical variables according to the competitive level and its interaction with playing position (mean ± SD).

Variable (unit)	Competitive level		Division			Division*Position		
	Second Division	First Division	F[1]	P[2]	ES[3]	F[1]	P[2]	ES[3]
Total passes (n)	42.6 ± 9.9	38.7 ± 9.1	12.13	0.001	0.116	1.50	0.209	0.061
Passing accuracy (%)	73.3 ± 6.8	73.8 ± 6.9	0.64	0.425	0.007	0.55	0.695	0.024
Passing verticality (%)	65.8 ± 11.2	65.8 ± 10.1	0.57	0.449	0.006	1.06	0.379	0.044
Short passes (n)	35.3 ± 8.5	32.2 ± 7.9	10.85	0.001	0.106	0.98	0.418	0.041
Long passes (n)	7.3 ± 3.8	6.5 ± 3.4	6.59	0.012	0.067	2.42	0.054	0.095
Dribbles (n)	2.0 ± 1.8	1.7 ± 1.6	15.67	< 0.001	0.146	1.83	0.128	0.074
Shots (n)	1.1 ± 0.9	1.0 ± 0.8	7.38	0.008	0.074	1.98	0.103	0.079
Aerial duels (n)	3.4 ± 2.0	3.2 ± 2.0	0.04	0.839	0.000	3.81	0.006	0.142
Interceptions (n)	4.5 ± 1.4	4.5 ± 1.3	1.04	0.309	0.011	1.61	0.178	0.066
Tackles (n)	0.7 ± 0.4	0.7 ± 0.4	2.01	0.159	0.021	0.33	0.853	0.014
Clearances (n)	2.5 ± 1.7	2.4 ± 1.7	0.19	0.659	0.002	0.39	0.814	0.017

Note: F[1] = F-value P[2] = ANOVA of repeated measures; ES[3] = effect size: partial eta squared

In addition, no changes were found for any of the defensive variables such as aerial duels, interceptions, tackles, and clearances. No significant interaction effects were found in any technical variable, except for aerial duels ($P < 0.01$; ES = 0.142).

Table 3 displays the match offensive and defensive technical variables according to the competitive level categorized by playing positions. In this regard, CBs completed lower numbers of passes, short passes, long passes ($P < 0.01$) and aerial duels ($P < 0.05$) in the first division compared to the second division. With regard to FBs, players performed fewer passes, short passes, long passes and dribbles ($P < 0.05$) in the first division than in the second division. In the position of CMs, players performed fewer passes, short passes, long passes ($P < 0.01$) and aerial duels ($P < 0.05$) in the first division. For WMs, no significant differences were found for any of the technical variables. Finally, FWs performed fewer dribbles and shots ($P < 0.01$) but more aerial duels ($P < 0.01$) and interceptions ($P < 0.05$) in the first division compared to the second division.

DISCUSSION

The aim of this study was to compare the individual match physical and technical performance of football players who were promoted from the Spanish second division to the first division within the same team. The main finding of this study is that football players covered more HIR distance and performed more HIR efforts when playing in the first division compared to the second division. Also, regarding the technical side, players in the first division executed a lower number of offensive technical variables than in the second division, including lower frequency of passing, dribbling and shooting, while no significant differences between divisions were found for the defensive variables.

These results are in line with previous studies in Spanish football, which found that the HIR distance and the number of sprints were significantly higher in first division teams than in second division teams [13, 14]. In this respect, our study is innovative because it followed a longitudinal analysis by analysing changes within the same players, and now we can confirm that is the player who adapt to the demands of the category beyond simple variation between the teams competing in each category. In contrast, our findings are contrary to those observed in previous studies performed in English football, which revealed that players playing in the second division covered more HIR distance [12] and TD [20] than those playing in the first division.

In the same way, our findings differ from those of other researchers [17] who found no differences in sprint performance and HIR distance between the first and second division in English football after promotion. This lack of agreement between studies may be due to differences in the different tactical and physical contexts experienced by the players in English and Spanish leagues [21, 22].

It is important to note that the change in the physical demands of the game from the second to the first division of Spanish football was different depending on the playing position. In this sense, the present study revealed that all playing positions except FWs performed more HIR efforts. Possibly, playing in the top division should expose players to a more demanding tactical scenario with high-skill opponents than in the second division [16]. In this context, the playing tempo and technical accuracy of matches are higher, so that more HIR efforts may be necessary to adapt to the new tactical demands. Particularly, FBs and WMs were the playing positions that registered the greatest increase in HIR distance in the first division.

Table 3. Comparative analysis of offensive and defensive technical variables according to the competitive level and playing positions (mean ± SD).

Variable (unit)	Competitive level			p
	Playing position	Second Division	First Division	
Total passes (n)	CD	41.4 ± 5.3	36.1 ± 4.1	0.001
	FB	48.0 ± 7.1	43.7 ± 5.7	0.014
	CM	46.1 ± 10.1	41.4 ± 10.7	0.001
	WM	39.3 ± 9.0	38.0 ± 8.6	0.565
	FW	26.5 ± 7.4	27.2 ± 9.8	0.781
Passing accuracy (%)	CD	74.6 ± 7.2	75.1 ± 6.6	0.594
	FB	72.8 ± 5.1	72.4 ± 3.9	0.679
	CM	75.7 ± 6.1	76.4 ± 6.5	0.390
	WM	70.6 ± 5.6	70.0 ± 6.8	0.690
	FW	66.1 ± 7.3	68.1 ± 9.2	0.216
Passing verticality (%)	CD	78.4 ± 5.6	76.8 ± 4.6	0.146
	FB	67.7 ± 6.8	68.0 ± 6.2	0.844
	CM	62.3 ± 8.1	62.6 ± 6.9	0.798
	WM	54.0 ± 6.2	55.3 ± 4.0	0.426
	FW	52.0 ± 5.3	54.2 ± 11.5	0.246
Short passes (n)	CD	31.8 ± 6.6	27.6 ± 4.8	0.002
	FB	38.6 ± 6.8	35.2 ± 4.3	0.031
	CM	39.5 ± 8.0	35.9 ± 8.4	0.002
	WM	34.8 ± 7.6	33.3 ± 7.1	0.444
	FW	24.5 ± 6.9	24.8 ± 9.2	0.892
Long passes (n)	CD	9.7 ± 3.0	8.4 ± 3.0	0.001
	FB	9.4 ± 2.2	8.5 ± 2.1	0.021
	CM	6.6 ± 3.7	5.5 ± 3.4	0.002
	WM	4.5 ± 1.8	4.7 ± 1.9	0.693
	FW	2.0 ± 1.5	2.4 ± 2.2	0.515
Dribbles (n)	CD	0.4 ± 0.3	0.4 ± 0.3	0.764
	FB	1.7 ± 1.2	1.3 ± 0.9	0.042
	CM	2.0 ± 1.8	1.7 ± 1.6	0.321
	WM	4.7 ± 1.3	4.2 ± 1.6	0.056
	FW	3.8 ± 2.1	2.9 ± 1.5	0.005
Shots (n)	CD	0.5 ± 0.2	0.4 ± 0.2	0.613
	FB	0.5 ± 0.3	0.6 ± 0.3	0.754
	CM	1.4 ± 0.8	1.2 ± 0.8	0.107
	WM	1.3 ± 0.7	1.2 ± 0.8	0.489
	FW	2.7 ± 1.0	2.2 ± 1.2	0.003
Aerial duels (n)	CD	4.4 ± 1.7	3.8 ± 1.3	0.021
	FB	2.4 ± 1.1	2.5 ± 1.3	0.829
	CM	3.4 ± 2.3	2.9 ± 2.1	0.036
	WM	1.9 ± 1.0	1.9 ± 1.0	0.985
	FW	4.5 ± 2.2	5.7 ± 3.2	0.008
Interceptions (n)	CD	5.1 ± 1.2	5.3 ± 1.1	0.561
	FB	4.9 ± 0.7	4.7 ± 0.8	0.369
	CM	4.6 ± 1.3	4.4 ± 1.3	0.456
	WM	3.7 ± 1.2	3.8 ± 1.1	0.780
	FW	2.0 ± 0.8	2.9 ± 1.4	0.033
Tackles (n)	CD	0.7 ± 0.2	0.6 ± 0.3	0.247
	FB	0.8 ± 0.3	0.8 ± 0.4	0.894
	CM	0.8 ± 0.5	0.7 ± 0.4	0.193
	WM	0.8 ± 0.4	0.7 ± 0.3	0.240
	FW	0.5 ± 0.3	0.5 ± 0.6	0.909
Clearances (n)	CD	4.7 ± 1.1	4.6 ± 1.3	0.517
	FB	3.1 ± 0.7	2.9 ± 0.8	0.232
	CM	1.3 ± 0.8	1.3 ± 0.7	0.758
	WM	1.1 ± 0.8	1.1 ± 0.9	0.963
	FW	0.9 ± 0.5	1.1 ± 0.6	0.564

Multiple studies have observed that FBs and WMs are the playing positions with more HIR distance covered during matches [23, 24, 25], probably due to their wide positioning where players should run long distances both to attack and defend. In the case of FBs, it seems very important to perform HIR runs when performing recovery runs, covering space, supporting their teammates in attack, as well as when overlapping [26]. For WMs, it is more frequent to perform HIR runs by carrying the ball and by supporting the offensive play than the rest of the playing positions [26]. Thus, our findings highlight the even greater importance of covering HIR distance in FBs and WM after promotion to the first division. From a practical standpoint, the strength and conditioning staff of teams promoted to a higher division should focus on enhancing the running capacity of all the players, but especially at high intensity and for players in wide positions.

Concerning TD, although significant differences between divisions were found when all playing positions were analysed conjointly, only FWs covered significantly more distance in the first division versus the second division. This result indicates that FWs are required to perform an extra effort in the first division, probably related to the higher playing tempo of the new category, as well as the possible necessity of having more involvement and participation in the defensive phase in comparison with the second division.

Regarding technical variables, our findings indicated that players, especially CBs, FBs and CM, performed fewer passes, short passes and long passes when playing in the first division, although no differences were found in terms of passing accuracy and playing verticality. Furthermore, FBs, WMs and FWs performed a lower quantity of dribbles, and FWs registered fewer shots in the first division compared to the second division. It is interesting to observe how the significant changes are specific to the playing positions, showing the relevance of different technical demands according to the tactical role assumed per each player, as previous studies have pointed out in professional football [27]. These results contrast with several studies that revealed that players at a higher competitive level/category performed a greater quantity of technical actions than players competing at lower levels such as second division [12, 16]. In this sense, it is crucial to highlight that those previous studies compared categories independently, but our study compared the performance of the same players when competing in both categories. Interestingly, our findings suggest that the individual performance of players could be influenced by the different team status and ranking position in each division. In the second division, the sampled teams and players achieved promotion, revealing that they were the most successful teams in the league, which probably entailed high values of offensive technical indicators. When being promoted to the first division, professional football players had to adapt to a more demanding context with lower level of offensive success, which may explain the lower offensive values registered in comparison with the second division.

As for defensive variables, no general differences between divisions were found for the variables analysed. Nevertheless, the FWs were the players who experienced the biggest change in this aspect, so that they registered slightly higher values of interceptions and aerial duels in the first division than in the second division. These changes may be due to higher defensive demands when playing in the first division, which also entailed greater efforts in terms of TD covered. Otherwise, the rest of playing positions maintained a stable defensive performance in both competitive levels.

This study has limitations that require acknowledgment. First, all the variables evaluated in this research are based on match statistics, which limits the capacity to capture the complex dynamic of football tactics based on the interactions and synergies between players and teams [28]. Additionally, the study was performed with data from the Spanish football league of professional male players, and the results should not be extrapolated to other leagues, other categories or women's football.

However, the large sample of players and the methodology implemented based on a repeated measures analysis reinforce the consistency of the findings, which have important practical applications.

Practical Applications

This study has strong practical applications to professional football and for those teams being promoted to a higher category. Firstly, it shows how players from the Spanish second category being promoted to the first division have to face a more challenging game, especially in terms of total distance and HIR. Interestingly, the magnitude of the physical demands of the game depends on the playing position, and it may be higher in players with wider field positions. Therefore, the outcomes of this study could be useful for coaches and fitness coaches to design training strategies that allow optimal preparation of players when they achieve promotion, especially to make them aware of the greater demands in the higher league. Secondly, the offensive technical values were found to be lower in the first division than in the second division, having a strong relationship with the specific playing positions. This finding suggests that players must become adapted to the new technical demands in the new category, reducing their offensive involvement with the ball while maintaining their capacity to defend.

CONCLUSIONS

In conclusion, male professional football players covered more HIR distance and performed more HIR efforts when playing in the first division of Spanish football, compared to the second division. In addition, players in the first division registered a lower number of offensive technical variables than in the second division, including lower frequency of total passes, short passes, long passes, dribbles, and shots, while no general significant differences between divisions were found in the defensive variables.

Conflict of interest declaration

The authors reported no conflict of interest.

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Supplementary materials

Table S1. Comparative analysis of physical performance variables according to the competitive level and its interaction with playing position (mean ± standard deviation).

Variable (unit)	Competitive level		Division			Division*Position		
	Second Division	First Division	F[1]	P[2]	ES[3]	F[1]	P[2]	ES[3]
HIR efforts (n)	30.6±9.1	33.4±10	31.9	<0.001	0.258	1.24	0.298	0.051
HIR distance (m)	526.3±176.1	555.6±188.3	10.8	0.001	0.106	0.36	0.832	0.016
TD (m)	10122.5±840.2	10176.6±867.1	8.05	0.006	0.080	3.95	0.005	0.147

Note: [1]F = F-value [2]P = ANOVA of repeated measures; [3]ES = effect size: partial eta squared

Table S2. Comparative analysis of physical performance variables according to the competitive level and playing positions (mean ± standard deviation).

Variable (unit)	Competitive level			p
	Playing position	Second Division	First Division	
HIR efforts (n)	CD	22.2±1.4	24.4±1.5	0.026
	FB	33.4±1.6	36.6±1.7	0.007
	CM	30.8±1.2	33.2±1.3	0.009
	WM	39.1±2.2	44.9±2.3	<0.001
	FW	37.4±2.4	39.9±2.6	0.147
HIR distance (m)	CD	361.4±26.4	385.2±28.4	0.151
	FB	601.4±30.8	641.4±33.2	0.040
	CM	519.4±23.8	541.9±25.6	0.130
	WM	708.9±40.5	759.7±43.7	0.047
	FW	646.0±44.8	666.0±48.3	0.475
TD (m)	CD	9302.4±116.9	9271.8±127.0	0.709
	FB	10089.2±136.8	10183.3±148.6	0.328
	CM	10835.2±105.4	10767.2±114.5	0.359
	WM	10306.5±179.8	10467.5±195.3	0.203
	FW	9803.5±198.7	10320.7±9891.8	<0.001

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Hamstring muscle injury is preceded by a short period of higher running demands in professional football players

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ABSTRACT: The aim of this study was to examine match running patterns before a hamstring muscle injury occurs during a match in male professional football players. A total of 281 male professional football players belonging to 7 teams from *LaLiga* were prospectively monitored over three seasons. Among these, 36 players suffered a non-contact hamstring muscle injury during an official match. The injuries were recorded by the medical staff, including the minute when the injury occurred. Running distances at different speed thresholds for 5 min and 15 min before the injury were compared to mean values of the previous 5 matches for the same time points. There were a total of 44 non-contact hamstring muscle injuries, which represents a hamstring muscle injury incidence of 3.34 injuries/1000 h of match exposure. The average time loss for these injuries was 33 ± 28 days (range 7 to 117 days). In the 15 min prior to the injury, players ran a similar distance as in control matches (p from 0.22 to 0.08). However, players ran a greater distance in the 5-min period before the injury than in control matches at 21.0–23.9 km/h ($p < 0.001$) and at ≥ 24 km/h ($p < 0.001$). The odds ratio for a hamstring muscle injury was 7.147 for those players who ran > 30.0 m at ≥ 21 km/h in a 5-min period ($p < 0.001$). Hamstring muscle injuries during competition were preceded by 5 min of higher running demands at > 21 km/h, compared with control matches. This suggests that a short period of unusual running increases the risk of hamstring muscle injury in professional football players.

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INTRODUCTION

Hamstring strain injury is one of the major worries in professional football [soccer] due to the high incidence and severity of this type of injury [1]. A recent study including the analysis of 2636 hamstring injuries for 21 years indicated that this type of injury represented 19% of all reported injuries [2]. Additionally, the incidence of hamstring injury has increased over time as it represented only 12% of all reported injuries in the 2001–2002 season and reached 24% of all injuries in the 2021–2022 season [2]. On average, a hamstring strain injury represents a burden of 13 days of absence although some players may need several weeks to return to play [3]. The hamstring injury incidence was 10 times higher during match play than training and around 18% of all reported hamstring injuries were recurrences with over two-thirds occurring within 2 months of the prior injury [2]. All these data indicate that hamstring injury produces a high burden for football teams with negative performance and economic implications. From a clinical viewpoint, the identification of meaningful risk factors is essential to produce effective prevention models [4]. However, the aetiology of hamstring muscle injury is complex and multifactorial and the factors that increase the likelihood of this type of injury are still under debate [4, 5].

Systematic reviews and meta-analyses conducted in football and other field-based team sports have identified several non-modifiable risk factors for hamstring muscle injuries [6–8]. Athlete's age and the existence of a previous hamstring injury within the same season are the strongest risk factors for hamstring injury [6–8], although a previous anterior cruciate ligament injury and previous calf strain injury have also been identified as contributing factors [8]. Among the modifiable factors that may increase the likelihood of hamstring muscle injury are accumulated fatigue [9] or strength imbalances [6, 7, 10, 11], although their exact contribution to the development of the injury requires more investigation. In those players with a previous hamstring injury, there is a modification of lower limb kinematics including reductions of hip flexion and rotation [12] and a reduction of sprint performance [13] that may predispose these players to reinjury or to difficulties in returning to play. Despite the significant scientific effort made in recent years to identify the risk factors associated with hamstring injury and the implementation of prevention programmes in professional teams [14], this type of injury is still highly prevalent in professional football [3, 15]. Ekstrand et al. [2] proposed that the increase of intensity that elite men's football has experimented with in the last years, with a larger volume of high-intensity actions and a congested competitive calendar, is a potential explanation for the high hamstring injury incidence. Hence, there is still much to understand about the causes of hamstring muscle injury, particularly about the influence of sprinting biomechanics and the effect of running exposure before the injury occurs during a match [16, 17].

As happens with all types of muscle injury in football [18, 19], the injury rates of hamstring injury are greater during matches compared with training [2, 20], likely because players are involved in higher physical demands such as larger running volumes, especially at high velocity. Recent data describing the injury-inciting events of acute hamstring injuries in professional male football players suggested that sprinting and high-intensity running are the common actions just before a hamstring injury [2, 21]. Additionally, hamstring injuries are more common in the last 15 min of each half [2, 22]. These data suggest that the combination of accumulated fatigue during a match and the need to produce a high-intensity running action to follow the play may be a trigger for hamstring injury. In this regard, two recent investigations indicate that the sprinting covered over a 1-min period [23] or a 5-min period [22] before a muscle injury occurs during a match is superior than in control matches without injury. Interestingly, when the period of running analysed is extended to 15 min before the injury, there is no difference regarding control matches. These investigations suggest that a 1-to-5 min period of higher-than-habitual intense running increases the odds of muscle injury in professional football players. However, there is no information to determine whether a period of high-intensity running above the normal is also an inciting event of acute hamstring injury. The aim of this study was to examine match running patterns before a hamstring muscle injury occurs during a match in male professional football players.

MATERIALS AND METHODS

Participants

A total of 281 male professional football players of 7 teams competing in the top division of the Spanish football league (*LaLiga*) were prospectively monitored over three seasons (2016–2017, 2017–2018 and 2018–2019). This was a convenience sample as we obtained data from the medical staff of professional football teams that had collaborated with our research team in previous investigations. From this sample, only 36 players suffered a hamstring muscle injury, and they were selected for the current investigation (age: 26.5 ± 4.2 years; body mass: 72.4 ± 5.4 kg; height: 179.2 ± 5.8 cm). In the final sample, there were 8 external midfielders, 8 external defenders, 10 forwards, 3 central midfielders and 7 central defenders. All players performed ~ 8–12 hours of football training and 1–2 competitive matches per week. Before the start of this investigation, an institutional Ethics Review Committee (code: DPC.VMP.01.18) approved the procedures included used in this study, following the latest version of the Declaration of Helsinki. In addition, *LaLiga* has authorized the use of data on players' running performance during official matches and the study does not contain information to identify players, as per *LaLiga's* ethical guidelines for research.

Injury data collection

In each team, non-contact hamstring muscle injuries were diagnosed and recorded by the medical staff using the classification system developed by the International Olympic Committee Consensus Group [24]. To be included in the study, the hamstring injury should be characterized by representing a player's physical complaint during an official competitive match, which prevented the player from participating in the following competition or training session [25]. Only hamstring injuries that produced an absence of at least seven days were considered for this investigation to avoid the influence of minor complaints [21]. All injuries were confirmed by magnetic resonance imaging (MRI). The injury report included the minute when the injury occurred during the match (certified by video analysis), injury severity (number of days from the date of injury to the date of returning to full participation), and the existence of recurrence (an injury of the same type and at the same site). An injury of the same type and at the same site occurring previously during the same season was catalogued as recurrent injury. All injuries were recorded in an electronic document which was ended once the player returned to play. Ended injury reports were forwarded to the research group once a month during the duration of the study and the researchers included injury data in an *ad hoc* database.

Data collection of running patterns during match play

Match performance data were collected using a validated multicamera tracking system called Mediacoach [26, 27]. Mediacoach consists of 8 stable synchronized and calibrated cameras positioned at the top of the stadium with a sampling frequency of 25 Hz. Mediacoach also contains associated software to analyse running demands and match events for each player. Running data of the players who sustained a hamstring muscle injury during the match were analysed for 15 minutes and 5 minutes before the injury event, according to the injury report. The moment of injury was confirmed by video analysis. To be valid, the player had to be a starter player in the match where the injury occurred. Running data before the injury were compared with normative data of the same player in the previous 5 matches, mimicking the duration of the periods and the minutes analysed (i.e., control situation). To be valid, the 5 "control" matches had to be carried out within the 30 days before the injury and the player had to be a starter player, to mimic the conditions of the "injury" match. The following physical performance variables were selected for analysis: the total distance covered (m), the distance at 18.0–20.9 km/h (intense running), the distance at 21.0–23.9 km/h (sprinting at low intensity) and the distance at ≥ 24.0 km/h (sprinting at high intensity), following a previous classification of running speed thresholds in professional football [28]. Running distance covered at ≥ 21.0 km/h was also calculated to identify the sprint distance. Additionally, information about match venue (home or away match) and match result (win, draw, or loss) was obtained in all matches where a hamstring muscle injury occurred.

Statistical analysis

The normality of the data was verified using the Shapiro-Wilk test. All variables had a normal distribution (p > 0.050). Data are presented as frequencies for qualitative variables and as mean ± SD for quantitative variables. Differences in the distribution of injuries depending on the match day, match time and severity were identified with χ^2 tests and standardized residuals. A two-way ANOVA (running speed × injury; 3 × 2) was used to compare running distances at different velocities in the match with injury with respect to control matches. The sphericity assumption was checked with Mauchly's test. ANOVA effect sizes were calculated with partial eta squared (ηp^2) and interpreted as follows: small, 0.02; medium, 0.13; large, 0.26. In the case of running velocity, injury, or interaction between these two factors, pairwise comparisons between data of the match with injury and control matches were made with Bonferroni *post hoc* tests. Paired-samples t-tests were used to compare total distance and distance at ≥ 21 km/h in a match with hamstring muscle injury vs control matches. These analyses were performed separately for 5- and 15-min periods. The level of statistical significance for the differences was set at $p < 0.050$. Cohen's *d* and its 95% confidence intervals (CI) were calculated as effect size (ES) for those variables with a statistically significant difference and interpreted as < 0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; 1.2–2.0, large; 2.0–4.0, very large and; > 4.0, extremely large. The odds ratio (OR) and 95% CI were calculated for running distance at ≥ 21 km/h for the 5 min before the injury. All analyses were performed using the SPSS software (version 27.0; IBM, Armonk, NY, USA).

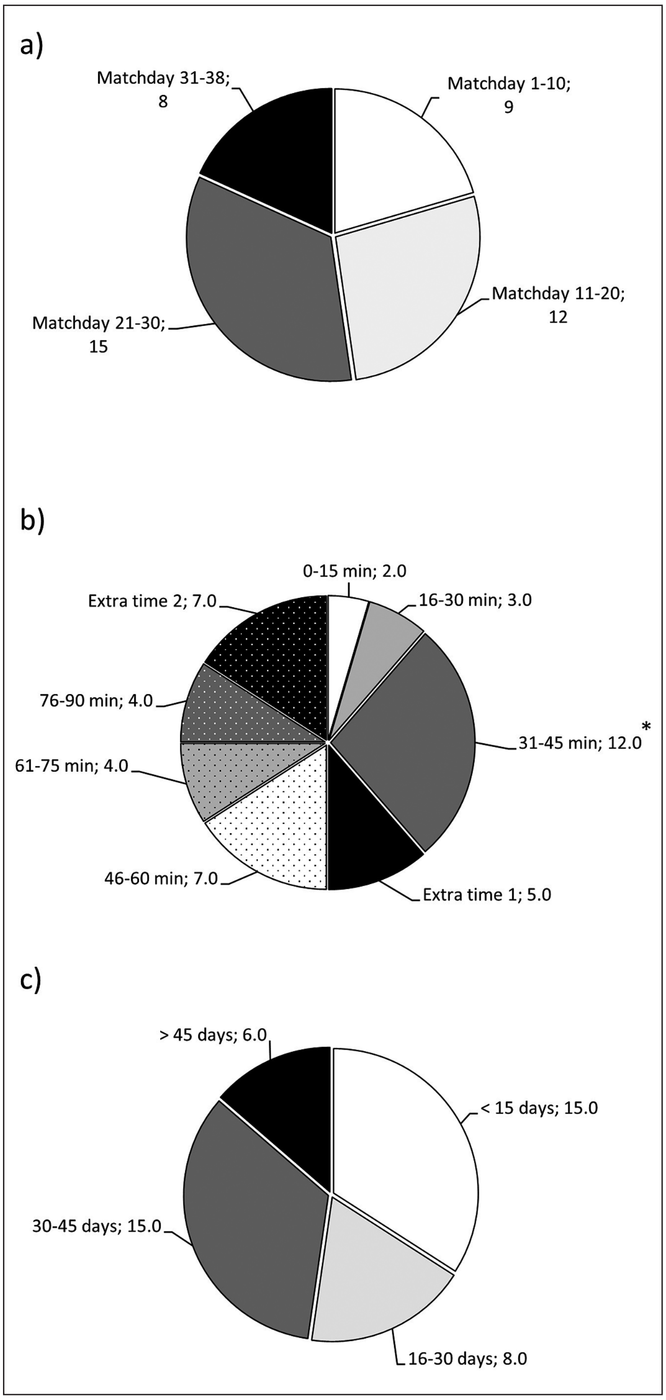

FIG. 1. Proportion of non-contact hamstring muscle injuries that occurred during professional football competition according to match day (a), minute (b) and (c) severity.
Data in the pie charts are proportions and the number of injuries within each category is included in the label of the category (*) Different from the expected value at $p < 0.05$.

RESULTS

A total of 44 non-contact hamstring muscle injuries occurred during official matches for the three seasons under investigation. This represented an overall hamstring muscle injury incidence of 3.34 injuries per 1000 h of match exposure (range = 0.0–17.5 hamstring injuries per 1000 h of match exposure). Thirty players had only one hamstring muscle injury, four players had two muscle injuries and two players had three muscle injuries during the study period. From the total, 18.2% of the hamstring injuries recorded were catalogued as recurrent injury. The injuries were equally distributed across all the season ($p = 0.304$, Figure 1a) but there was a higher number of injuries in the last 15 min of the first half when compared to other 15-min sections of the matches ($p < 0.05$, Figure 1b). The average time loss for these injuries was 33 ± 28 days (range 7 to 117 days) with 15%

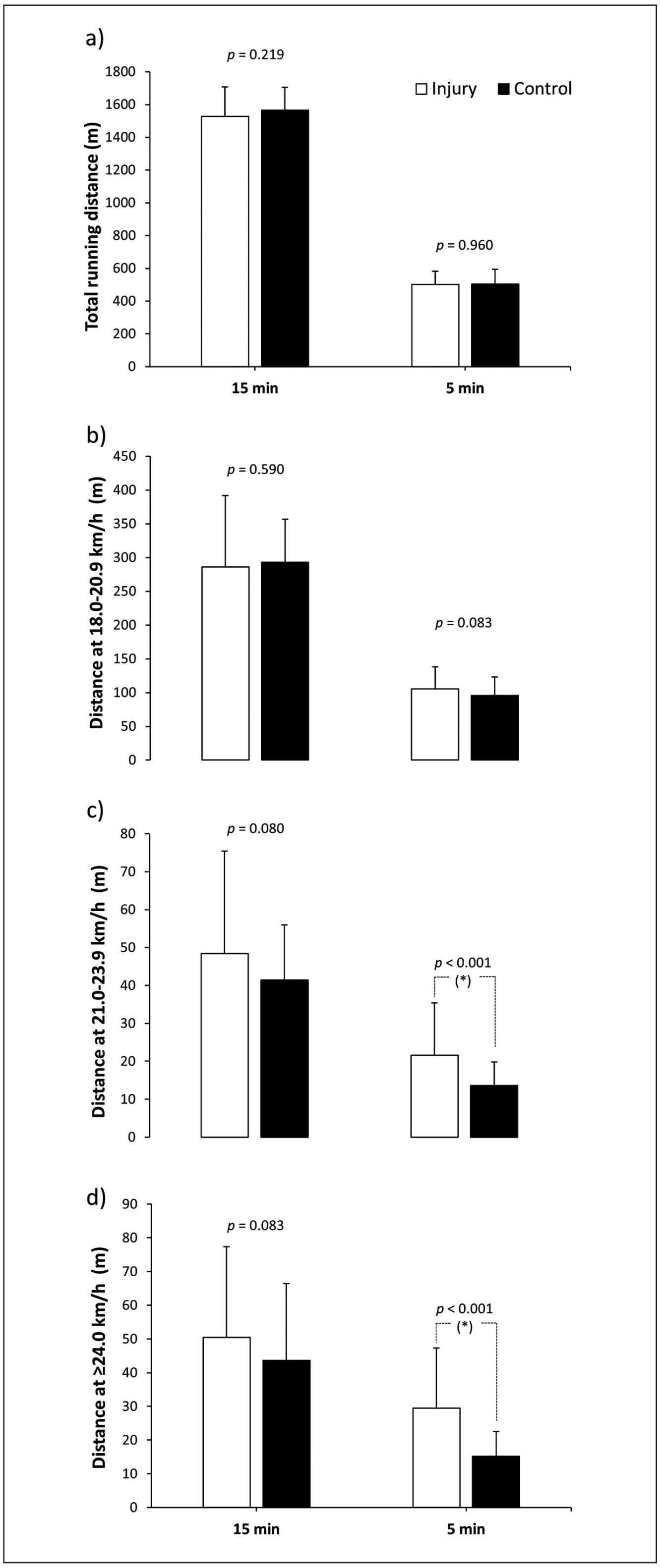

FIG. 2. Total running distance (a), running distance at 18.0–20.9 km/h (b), at 21.0–23.9 km/h (c), and ≥ 24 km/h (c) in the 15 and 5 min prior to suffering a non-contact hamstring muscle injury compared to the same match period of control matches.
"Injury" refers to running distances at different velocities in the match with injury. "Control" refers to running distances at different velocities in the previous 5 matches for the same time points. (*) Statistically significant difference between control and injury condition at $p < 0.05$.

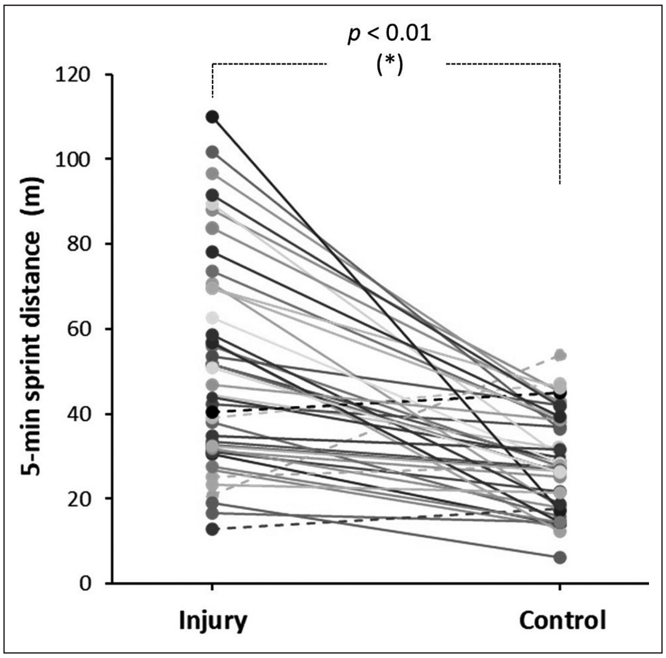

FIG. 3. Running distance at ≥ 21 km/h 5 min prior to suffering a non-contact hamstring muscle injury compared to the same match period of control matches.
Each line represents individual values for 5 min before the injury and the same period of control matches. Continuous lines depict participants with higher values on the day of injury than in the control matches and the dashed lines depict participants with lower values on the day of injury than in the control matches. (*) Statistically significant difference between control and injury condition at $p < 0.05$.

of injuries needing more than 45 days of recovery (Figure 1c). There was an equal distribution of injuries during matches played at home (54.5%) and away (45.4%; $p = 0.394$). The result of the match at the moment of injury was win/draw/lose = 50.0/20.5/29.5%) for the team of the injured player, which was similar to the control matches ($p = 0.168$).

Figure 2 contains data on total running distance and distance at different speed thresholds for 15-min and 5-min periods before the injury occurred compared to the same periods of time in the control matches without injury. In the 15-min period prior to the injury, total running distance was similar to control matches ($p = 0.219$). Regarding the analysis of running distance at different speed thresholds, there was a main effect of the running speed on the running distance covered ($F = 496.10$, $p < 0.001$, $\eta p^2 = 0.920$), but there was no main effect of injury ($F = 0.16$, $p = 0.692$, $\eta p^2 = 0.004$) or running speed × injury interaction ($F = 1.57$, $p = 0.570$, $\eta p^2 = 0.024$). The *post hoc* analysis indicated that players ran a similar distance 15 min before the injury compared with the control matches (p from 0.590 to 0.083). In the 5-min period prior to the injury, total running distance was similar to control matches ($p = 0.960$). However, there were main effects of the running speed

($F = 460.47$, $p < 0.001$, $\eta p^2 = 0.915$) and of the injury ($F = 22.67$, $p < 0.001$, $\eta p^2 = 0.345$) on the running speed covered at different speed thresholds, with no running speed × injury interaction ($F = 0.80$, $p = 0.451$, $\eta p^2 = 0.018$). The *post hoc* analysis indicated that players ran a greater distance in the 5-min period before the injury compared with the control matches at 21.0–23.9 km/h ($p < 0.001$; ES = 0.57 [0.23, 0.89]) and at ≥ 24 km/h ($p < 0.001$; ES = 0.78 [0.43, 1.12]), with no difference at 18.0–20.9 km/h ($p = 0.083$).

Figure 3 contains individual data for the running distance at ≥ 21 km/h in the 5 min before suffering a non-contact hamstring muscle injury compared to the same match period of control matches. Overall, the running distance at ≥ 21 km/h was greater on the day of the injury than in the control matches (51.1 ± 24.7 vs 28.8 ± 11.5 m; $p < 0.001$; ES = 1.09 [0.70, 1.47]). Of the 44 injuries, 39 (88.6%) of them were preceded by a 5-min period of greater running distance at ≥ 21 km/h. The OR for a hamstring muscle injury was 7.147 (95% CI = 2.689 to 18.992) for those players who ran > 30.0 m at ≥ 21 km/h in a 5-min period ($p < 0.001$).

DISCUSSION

The aim of this study was to examine match running patterns before a hamstring muscle injury occurs during a match in male professional football players. This investigation was designed to determine whether a period of more intense than usual running is an inciting event for acute hamstring injuries in professional football. The main result of the study was that players showed an increase of the distance covered running at high intensity (21–24 km/h; +76.1 ± 110.0%) and at sprint velocity (> 24 km/h; +114.0 ± 152.3%) in the 5 minutes before the injury occurred when compared to the same periods of five control matches (Figure 2). This scenario of unusual high-intensity running was present in most injury events as 39 out of 44 hamstring muscle injuries were preceded by a 5-min period of high-intensity running (i.e., distance covered at ≥ 21 km/h) of higher intensity than the high-intensity running performed in the control matches (Figure 3). Interestingly, the total distance and the distance covered at 18.0–20.9 km/h in the 5 minutes before the injury were similar to the control matches. Collectively, this information suggests that a short period of higher-than-usual sprint-like distance may trigger the onset of a hamstring muscle injury. Specifically, sprinting more than 30 m for a period of 5 min may increase the likelihood of hamstring injury by several-fold.

Muscle injury is a complex phenomenon determined by the non-linear interaction of several factors, but fatigue and high external workloads are within the most common inciting factors for this type of injury [29]. Similar findings when analysing all types of muscle injuries have been previously reported in professional football players competing in the Qatar Stars League [23] and *LaLiga* [22]. Specifically, Gregson et al. [23] investigated running distances at different speed thresholds 1 min and 5 min prior to a muscle injury in comparison to normative running data and they found that an increase in sprinting distance of 11 m, covered over a 1-min period, increased the odds of muscle injury. Moreno-Perez et al. [22] carried out a similar investigation but they analysed running distances 15 min and 5 min prior to the muscle injury. These authors found that the running distance covered at all intensities was similar for the 15 min before the muscle injury as in control matches, but the distance covered at sprinting was greater for the 5 min before the injury event. The current investigation complements these outcomes as it indicates that an unusually long sprinting distance covered during a short period may trigger the onset of hamstring muscle injury. It has been recently reported by video analysis that rapid movements with high eccentric demands of the posterior thigh are likely the main hamstring injury mechanism [21]. These movements include linear acceleration, high-intensity running, closed chain movements such as braking or stopping and open chain movements such as kicking. These inciting events are more likely associated with a hamstring strain when they are preceded by a short period of high-intensity running, as this and previous investigations have reported [22, 23]. Overall, all these studies contribute to understanding how hamstring injuries occur in professional football and support the need to create custom prevention programmes for hamstring muscle injury that include short periods of high-intensity running, mimicking the demands of the game and the performance of rapid movements with high eccentric demands of the posterior thigh in a controlled state of fatigue.

In line with previous research [2, 30], the current findings confirm that the number of hamstring injuries increases at the end of the first half of the match (Figure 1). Interestingly, the proportion of injuries in extra time 1 and extra time 2 was similar to the other 15-min periods despite extra times being on average ~1.6 min and ~4.2 min for the matches with injury. This indirectly suggests a high rate of injury during extra times, particularly in the second half. A possible explanation for the observed results may involve the interactions between acute fatigue and hamstring muscle activation and function [9, 31]. It is well known that a competitive football match leads to acute fatigue and a reduction of performance that normally occurs at the end of the first half, and with more severity at the end of the match [32, 33]. The fatigue developed during a football match is probably linked to the depletion of muscle glycogen concentrations [34] and entails a decline in physical performance [35, 36], altered coordination of muscle activation patterns [9] and changes in lower limb kinematics [37]. Additionally, muscle fatigue may alter the neuromuscular coordination and cause an excessive tensile load on adjacent tissues, decreased hip flexion, increased knee extension and anterior pelvic tilt [37]. Recent data indicate that there is a reduced capacity of the hamstrings to decelerate the lower leg during sprint running with fatigue [31]. Taken together, all this information explains why hamstring muscle injury is more likely to occur at the end of each half [2], as players are more fatigued and running kinematics is modified. Hence, fatigue and all the above-mentioned fatigue-induced changes in performance, running kinematics and neuromuscular coordination can be considered as potential contributors to hamstring injury, at least during competitive matches. However, further investigation is required to determine to what degree fatigue is a mechanism of hamstring injury in professional football. In this regard, the independent and combined analysis of the effects of acute fatigue (transient and developed during the match) and the chronic residual fatigue, developed over the season as result of the competitive calendar and the training workload [38], on hamstring injury incidence should be developed in future investigations.

Several potential limitations may be recognized in the present study. Firstly, as the current study has been performed on a sample of male professional football players, the findings may not be generalizable to other professional team sport athletes or female football players. Further, the present study did not quantify the training load carried out during the training week before the matches where the injury occurred. Probably, the occurrence of the hamstring muscle injury was also associated with a higher training workload and higher self-perceived fatigue in those players who suffered the injury, as these two factors have been found in the week prior to a muscle injury in professional football players [22]. Additionally, the cumulative training workload for several weeks can also increase the risk of muscle injury [39]. Therefore, future studies could benefit from investigating the internal and external loads in the days and weeks before the hamstring injury to examine the contribution of these factors to hamstring muscle injury aetiology. The current study only included the analysis of running 5 and 15 min before the injury occurred. However, it is possible that the effect of prior fatigue accumulated throughout the match also contributed to the mechanism of hamstring injury. Future investigations should include the analysis of running patterns for longer periods before the injury occurs during a match. Only hamstring muscle injuries during competitive matches in male professionals were investigated while hamstring strains during training may have a different mechanism of onset. Last, 8 out of the 44 hamstring injuries analysed in this investigation were classified as recurrent injury, which represents 18.2% of the total number of injuries, a value similar to previous data [2, 3]. However, this low number of recurrent injuries impeded performance of a sub-analysis of running patterns before injury vs recurrent injuries with proper statistical power.

CONCLUSIONS

Male professional football players who suffered a non-contact hamstring muscle injury during a competitive match ran a greater distance at ≥ 21 km/h in the 5 minutes before the injury, at least when compared to their habitual ≥ 21 km/h running distance at the same match time in control matches without injury. Additionally, a high proportion of injuries occurred in the last 15 min of each half, suggesting a potential role of high-intensity running and accumulated fatigue in the development of hamstring muscle injuries. These results could be used to create specific training programmes and recovery strategies which can help to prepare players for periods of higher-than-habitual running demands during competitive matches, ultimately decreasing the incidence of hamstring muscle injuries in professional football.

In summary, this study reveals that hamstring muscle injuries during competition were preceded in most cases by 5 min of higher running demands at > 21 km/h, compared with the five prior matches. This outcome suggests that a short period of unusual running at high speed increases the risk of hamstring muscle injury in professional football players.

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Conflict of interest

The authors declare that they have no conflict of interest derived from the outcomes of this study.

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The combined effects of growth and maturity status on injury risk in an elite football academy

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ABSTRACT: This study aimed to explore the interaction between growth rate on specific injury incidence and burden on pre-, circa- and post-peak height velocity (PHV) periods. Injury and stature data collected during the 2000–2020 seasons in an elite football academy were retrospectively analysed. Only players with height measurements from childhood until the attainment of adult height were included in the study (N = 84). Growth data were smoothed using a cubic spline to calculate daily growth rate and height. Growth rate was categorised into three groups: fast (> 7.2 cm/year), moderate (3.5–7.2 cm/year) and slow (< 3.5 cm/year). Percentage of observed adult height was used to classify players as pre-PHV (< 88%), circa-PHV (88–95%) or post-PHV (> 95%). Overall and specific injury incidence and burden and rate ratios for comparisons between growth rate groups were calculated on pre-, circa- and post-PHV periods, separately. Overall injury incidence and burden were greater in pre-PHV players with quicker growth rates compared to players growing moderately and slowly. All in all, players with more rapid growth-rates were at higher risk for growth-related injuries in all pre-, circa- and post-PHV periods. Post-PHV, the incidence and burden of joint/ligament injuries were 2.4 and 2.6-times greater in players growing slowly compared to players growing moderately. Practitioners should monitor growth rate and maturity status and consider their interaction to facilitate the design of targeted injury risk reduction strategies.

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INTRODUCTION

Injuries can result in long absences from training and matches in academy football players, reducing the opportunity for players to develop their fitness and skills [1]. Consequently, injuries negatively impact players' academy progression [2]. Injuries occurring during childhood and adolescence can also result in long-term consequences, making players more susceptible to future injuries and long-term health risks (e.g., osteoarthritis) [3]. Thus, injury risk reduction strategies in youth footballers are vital to ensure the development of healthy youth players and ensure the long-term health of the professional football players.

During adolescence, players experience a marked and rapid period of somatic growth [4], leading to evident changes in limb length, limb mass, and moments of inertia [4]. As a consequence of these changes, temporary delays or regressions in sensorimotor mechanisms and motor control may be observed during this period [5], adversely impacting injury risk. Accordingly, the International Olympic Committee [6] and league governmental bodies (e.g., English Premier League) [7] have highlighted the importance of assessing and monitoring inter-individual variations in growth and maturity.

Growth rate is used to describe changes of a physical dimension (e.g., standing height) over a given time [4]. During the adolescence there is an increase in the rate of growth, with highest point known as peak height velocity (PHV). PHV is observed around the age of 13–14 years in boys, reaching maximal growth rates of 5.6–12.4 cm/year [4]. To date, a limited number of studies in youth football academies have investigated the influence of adolescent growth rates upon injury [8–11]. Kemper et al. [8] and Rommers et al. [9] observed that injured male adolescent players had a higher rate of growth compared to non-injured players. Similarly, Johnson et al. [11] reported that players with a rate of growth rate > 7.2 cm/year were more likely to be injured than players growing less than 7.2 cm/year. Not only that, but they also showed that there was a linear increase in injury risk associated with growth rate [11]. Concerning the risk for specific types of injuries, Wik et al. [12] found that overall growth rate was associated with a greater risk of bone and growth plate injures in adolescent athletics.

Biological maturation is a separate and more complex concept. The level of biological maturation at a given point, defined as maturity status, indicates where along the process towards a mature state a given tissue or organ system (somatic, skeletal, or sexual) is at the time of measurement [4]. The percentage of adult height at the time of observation is an indicator of somatic maturity that is increasingly used in youth athletes and allows to easily classify players as pre- (< 88%), circa- (88–95%), or post-PHV (> 95%) [13]. Available research has suggested that injury incidence and burden is higher in circa-PHV compared to pre-PHV period [14], whilst a recent study has found that the occurrence of specific injuries varies according to the percentage of adult height [15]. Growth-related injuries were more frequent in percentages around PHV (91.2%) while muscle and joint/ligament injuries were more common in post-PHV [15]. Interestingly, growth-related injuries occurred from distal to proximal body regions, following the pattern of growth and maturation [15]. As a result, growth-related injuries occurring on distal segments (e.g., Sever´s and Osgood-Schlatter´s disease) peaked in pre- and circa-PHV periods while proximal injuries (e.g., spondylolysis) peaked in post-PHV [15].

To date, only one study has analysed the interaction between growth-rate and maturity status upon injury risk. Johnson et al. [11] showed that there is an increase in estimated injury likelihood at a high growth rate circa-PHV. However, they found an increase in estimated injury burden likelihood at a lower growth rate and a higher percentage of predicted adult stature (post-PHV). Despite the novel results found by Johnson et al. [11], this study has potential limiting factors. First, the data were recorded over a single season period, making it impossible to follow individuals during a sufficient interval of time to model individual growth curves and account for the non-linear characteristic of growth [16]. Further, the Khamis-Roche equation was used to estimate adult height. If measured accurately, this equation is reported to predict adult height to within 2.2 and 5.3 cm for the 50th and 90th percentile, respectively; therefore, the use of Khamis-Roche equation might have led some players to be misclassified as pre-, circa- or post-PHV due to errors associated with the prediction [13]. Most importantly, this research did not study the interaction between growth-rate and injury risk of specific injuries in pre-, circa- and post-PHV periods. Considering that growth-rates [4] and injury patterns [15, 17] differ according to maturity status, studying the impact of growth-rate on specific injury risk in each period seems vital.

The present study builds upon the abovementioned limitations by using height and injury data recorded in an elite football academy over two decades. This permits a more accurate estimation of growth rate and percentage of the observed adult height of players and affords the opportunity to explore potential interactions between growth rate (cm/year) and risk for specific types of injuries (incidence and burden) in pre-, circa- and post-PHV periods, separately.

MATERIALS AND METHODS

Study design and participants

This retrospective analysis studied height and injury data recorded longitudinally for 20 consecutive seasons (2000–2020) in Athletic Club's elite soccer academy whose professional male team plays in Spanish LaLiga. The academy has a team in each of the age-based levels or categories. In men, this includes U11, U12, U13, U14, U15, U16, U17, and U19 teams, in addition to 3rd and 2nd teams comprising 17–23-year-old players competing in the Spanish Fourth and Third Divisions, respectively. Among the 1123 players who were followed, only players who were ≤ U12 when they entered the academy and continued until they attained adult height were included in the study (n = 84) attempting to equally represent pre-, circa- and post-PHV periods.

The study was conducted in accordance with the National Health Council resolution (466/2012) and was approved by the Ethics Committee of the University of The Basque Country (UPV/EHU) (CEISH/340/2015). Written informed consent to use regularly collected data for research purposes was obtained from the players.

TABLE 1. Stature, growth velocity, % of observed adult height, injury counts, exposure, incidence rates, mean severity, and injury burden according to maturity status.

Maturity status	Stature (cm)[a]	Growth velocity (cm/year)[a]	% of observed adult height[a]	Injury count (n)	Exposure (hours)	Injury incidence (per 1000 hours)[b]	Mean time loss (days)[b]	Injury burden (per 1000 hours)[b]
Pre-PHV	149.7 ± 6.0	5.8 ± 2.5	83.5 ± 2.6	147	51544	2.85 (2.43–3.35)	15.4 (12.6–18.2)	43.9 (37.3–51.6)
Circa-PHV	165.9 ± 6.3	7.7 ± 2.7	92.4 ± 2.4	234	40417	5.79 (5.09–6.58)	23.5 (19.7–27.3)	136.0 (119.6–154.6)
Post-PHV	176.8 ± 5.2	2.0 ± 1.9	98.4 ± 1.1	401	70353	5.70 (5.17–6.29)	26.5 (21.8–31–2)	151.1 (137.0–166.6)

[a] Anthropometrical variables are shown as mean ± SD.

[b] Incidence, severity, and injury burden are expressed with 95% confidence intervals

Height measurement, growth-rate estimation, and maturity status assessment

Standing stature was measured by trained doctors at least twice annually using a portable stadiometer (Añó Savol, Spain). Participants stood barefoot with feet together and their head in the Frankfort plane. They were required to take a deep breath and hold their head still while measuring. Two of the four doctors worked in the academy during the entire study period, thereby reducing chance of bias. The intra-rater typical error of measurement for standing stature of these two doctors was 0.23 cm while the inter-rater error was 0.29 cm.

Growth rate was calculated as the change in stature over the change in time (cm/year). Growth data were smoothed using a Cubic spline. The spline would fit a curve across the whole time period using the multiple measurement points and subsequently, a growth rate and height per day could be estimated from this curve [18]. The calculation of the spline allowed an estimate of growth rate for each training/match day, which allowed the growth and maturation data to match with daily observations of daily training/match exposure.

Growth rate was categorised into three groups: fast (> 7.2 cm/year), moderate (7.2–3.5 cm/year) and slow (< 3.5 cm/year), based on previous literature [8, 11] and to achieve an approximately equal number of observations per group.

The percentage of observed adult height was used as a maturity status indicator [4]. A player was considered to have attained final height once growth-velocity was < 1 cm/year for one year [4]. The observed adult height allowed to calculate percentage of adult height using estimated height. Players were classified as: pre-PHV (< 88%), circa-PHV (88–95%) or post-PHV (> 95%) [11, 13].

Injury definitions, exposure, and recording procedures

Time-loss injuries were recorded in the club's online database by academy's doctors when a player was unable to take part in full football training or match due to a physical complaint [19]. Absence days were calculated as the number of days elapsed between the initial injury date and the player's return to full availability for training and matches [19].

From the 2007–2008 season onward, injuries were described following the International Federation of Association Football (FIFA) Consensus [19]. For each injury, the date of injury, injury type, session type, contact type and specific mechanism were reported. In the previous seasons, specific injury diagnosis and absence days of time-loss injuries were recorded. This allowed to categorise type of injuries (e.g., muscle injury) recorded before the publication of the FIFA Consensus. As the Consensus by Fuller et al. [19] did not explicitly consider growth-related injuries, the injury surveillance system was customised by adding a category for "growth-related injuries", which were defined as "unique injuries not seen in adults but common in skeletally immature athletes (e.g., growth plate fractures, apophysitis, apophyseal avulsion fractures, and greenstick fractures)" [20]. Growth-related injuries were classified according to physical examination (e.g., pain at insertional points on palpation, passive movements and stretches, and active movements including resistance testing) and imaging diagnosis (ultrasound and/or magnetic resonance imaging). Two of the four doctors worked in the academy since the start of the study, thereby reducing the chance of bias, differences in injury interpretation, and changes in observation methods between doctors.

Daily exposure in matches and training sessions in available non-injured players was estimated based on the number and duration of matches and trainings, squad size and the number of players on the pitch in each category [21]. Players had 3 (U11–U12) or 4 (U13–Reserves) 90-minutes training sessions per week and played a match every weekend. Match length was 70 minutes for U11–U14, 80 minutes for U15–U16 and 90 minutes for older age-groups. The number of players on the pitch was 11 for all categories except for U11–U12, in which 7 players played in each team.

Data analysis

Injury incidence (number of time-loss injuries/1000 hours) and injury burden (number of days lost/1000 hours) were calculated with 95% CI assuming a Poisson distribution [22]. Generalized linear mixed-effects models (GLMM) were used to compare incidence and burden between growth-rate groups (fast *vs*. moderate *vs*. slow) in each maturity status period (pre-, circa- or post-PHV) using a Poisson distribution and log-link function. The predictor variables were modelled as categorical fixed effects and player ID was included as a random effect to account for repeated observations. Statistical significance was accepted at $p < 0.05$ for incidences, while significant differences for injury burden were considered when the 95% confidence intervals did not overlap [23]. Bonferroni adjustments were performed to control the Type I error rate when making multiple comparisons. All analyses were performed using R version 4.1.2 (R Core Team 2021, R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Player demographics, growth, and maturity data according to maturity status are presented in Table 1. There were 782 injuries and 162,314 hours of total exposure. The mean (SD) exposure for each player was 1932.3 (±439.9) hours. The mean (SD) values for the percentage of observed adult stature and growth rate were 92.38 (±6.64) % and 5.57 (±3.35) cm/year, respectively. The overall injury incidence rate was 4.82 injuries per 1,000 hours (95% CI 4.49–5.17), the mean time-loss of injuries was 23 days (95% CI 21–26) and injury burden was 113 days absent per 1,000 hours (95% CI 105–121). Injury incidence, time-loss, and burden in each maturity status period are shown in Table 1.

Overall injury incidence was 1.65- and 2.38-times greater in pre-PHV players with fast growth rates (4.1 injuries/1000 h, 95% CI: 2.8–5.2/1000 h) compared to players growing moderately (2.6 injuries/1000 h, 95% CI: 1.9–3.0/1000 h) and slowly (1.8 injuries/1000 h, 95% CI: 0.8–3.1/1000 h), respectively. Similarly, overall injury burden in pre-PHV players growing fast (86 days lost/1000 h,

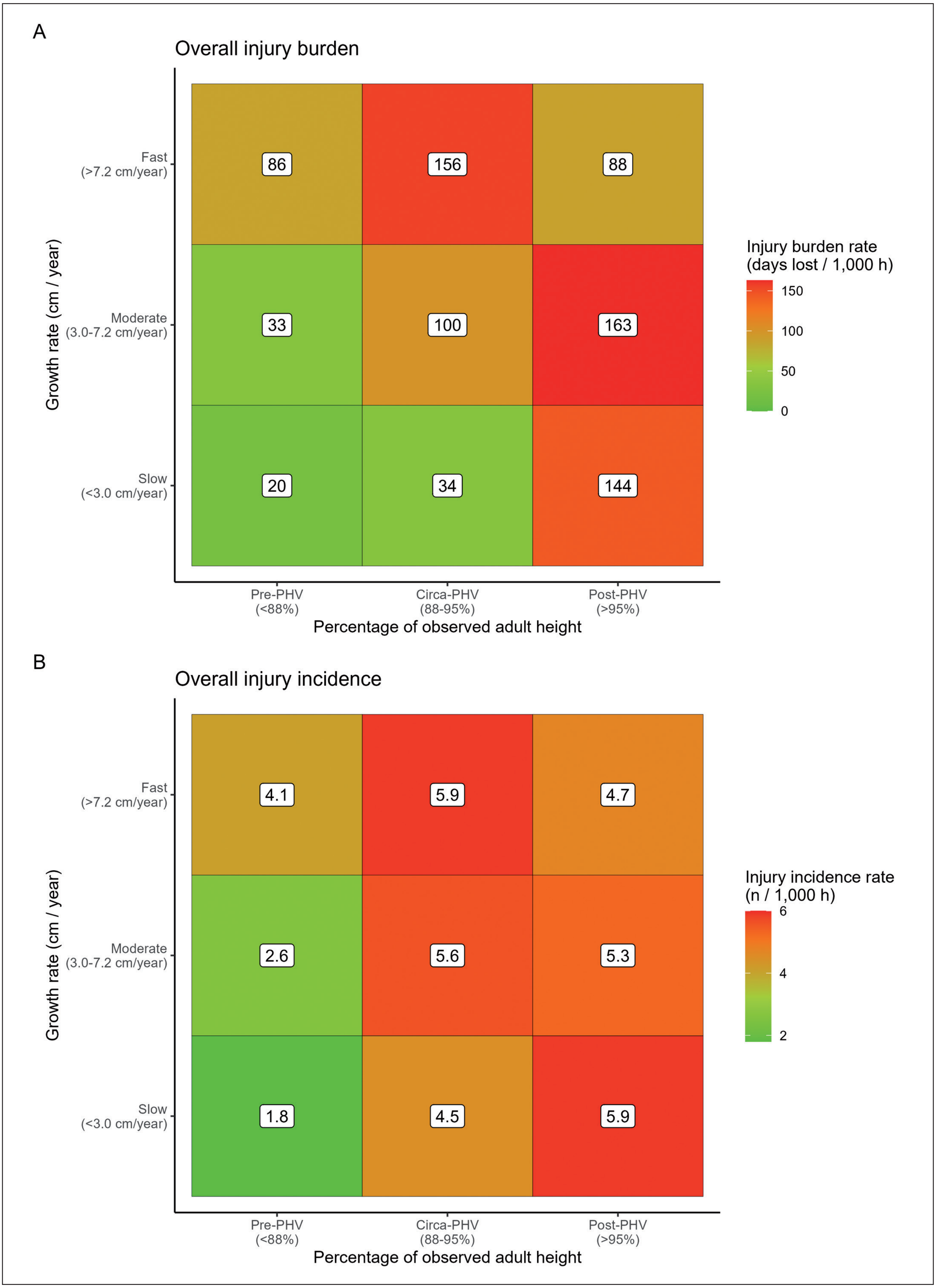

FIG. 1: Overall injury burden (A) and incidence (B) according to growth rate and percentage of observed adult height.

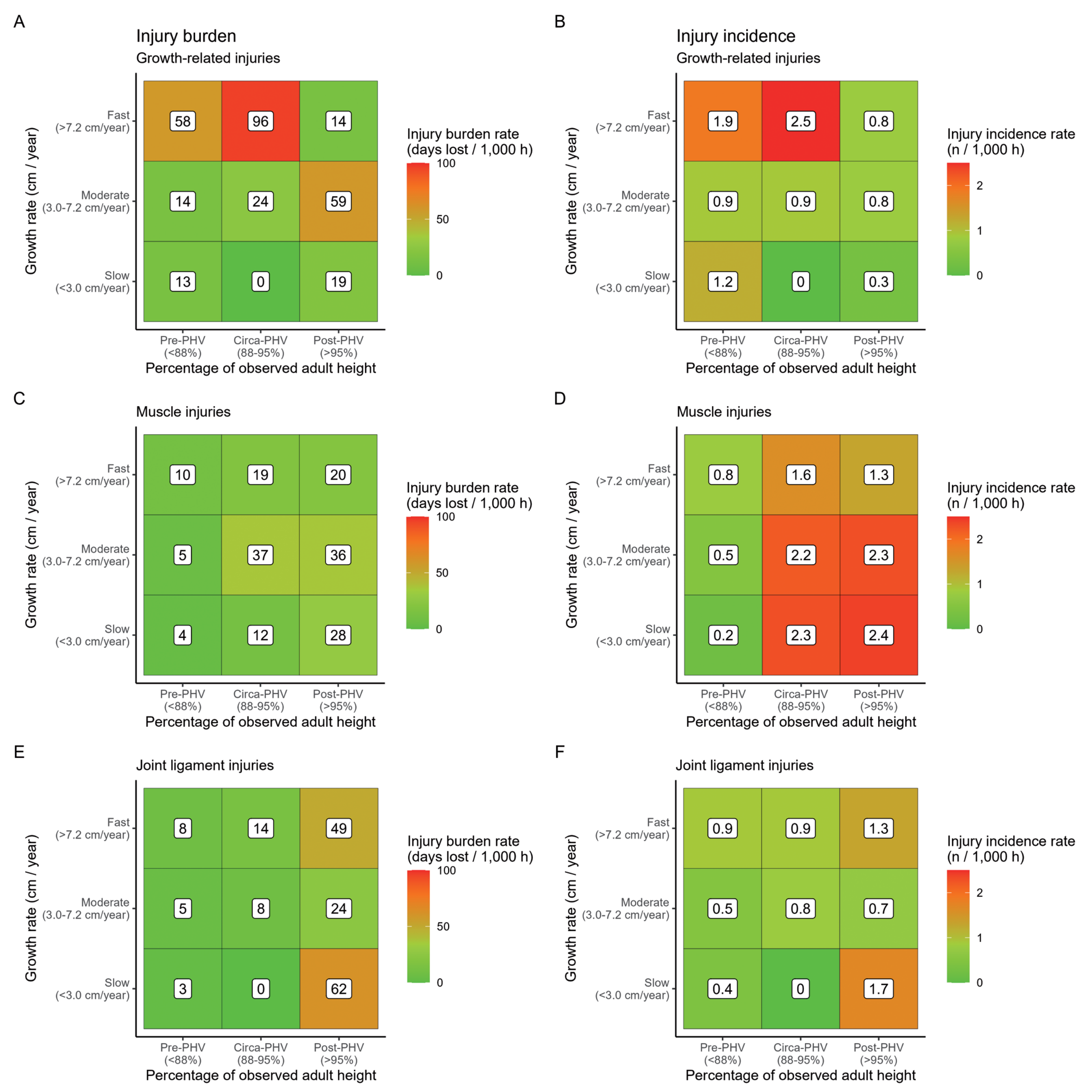

FIG. 2: Injury burden and incidence of growth-related (A, B), muscle (C, D) and joint/ligament injuries (E, F) according to growth rate and percentage of observed adult height.

95% CI: 59–125/1000 h) was 2.9- and 4.4-times higher compared to pre-PHV players with moderate (33 days lost/1000 h, 95% CI: 25–44/1000 h) and slow (20 days lost /1000 h, 95% CI: 8–46/1000 h) growth rates (Figure 1).

Concerning growth-related injuries, in the pre-PHV period, incidence and burden were 2.5- and 5.4-times higher in players with fast growth rates (1.9 injuries/1000 h, 95% CI: 1.2–2.8/1000 h and 58 days lost/1000 h, 95% CI: 34–101/1000 h) compared to players growing moderately (0.9 injuries/1000 h, 95% CI: 0.5–1.1/1000 h and 14 days lost/1000 h, 95% CI: 9–23/1000 h). In the same line, circa-PHV players growing fast showed 2.8- and 3.4-times greater injury incidence and burden (2.5 injuries/1000 h, 95% CI: 1.7–3.2/1000 h and 96 days lost/1000 h, 95% CI: 68–136/1000 h) compared to players growing moderately (0.9 injuries/1000 h, 95% CI: 0.4–1.6/1000 h and 24 days lost/1000 h, 95% CI: 10–57/1000 h) (Figure 2). In post-PHV, growth-related injury incidence was 2.4-times higher in players growing fast (0.8 injuries/1000 h, 95% CI: 0.2–3.4/1000 h) compared to players

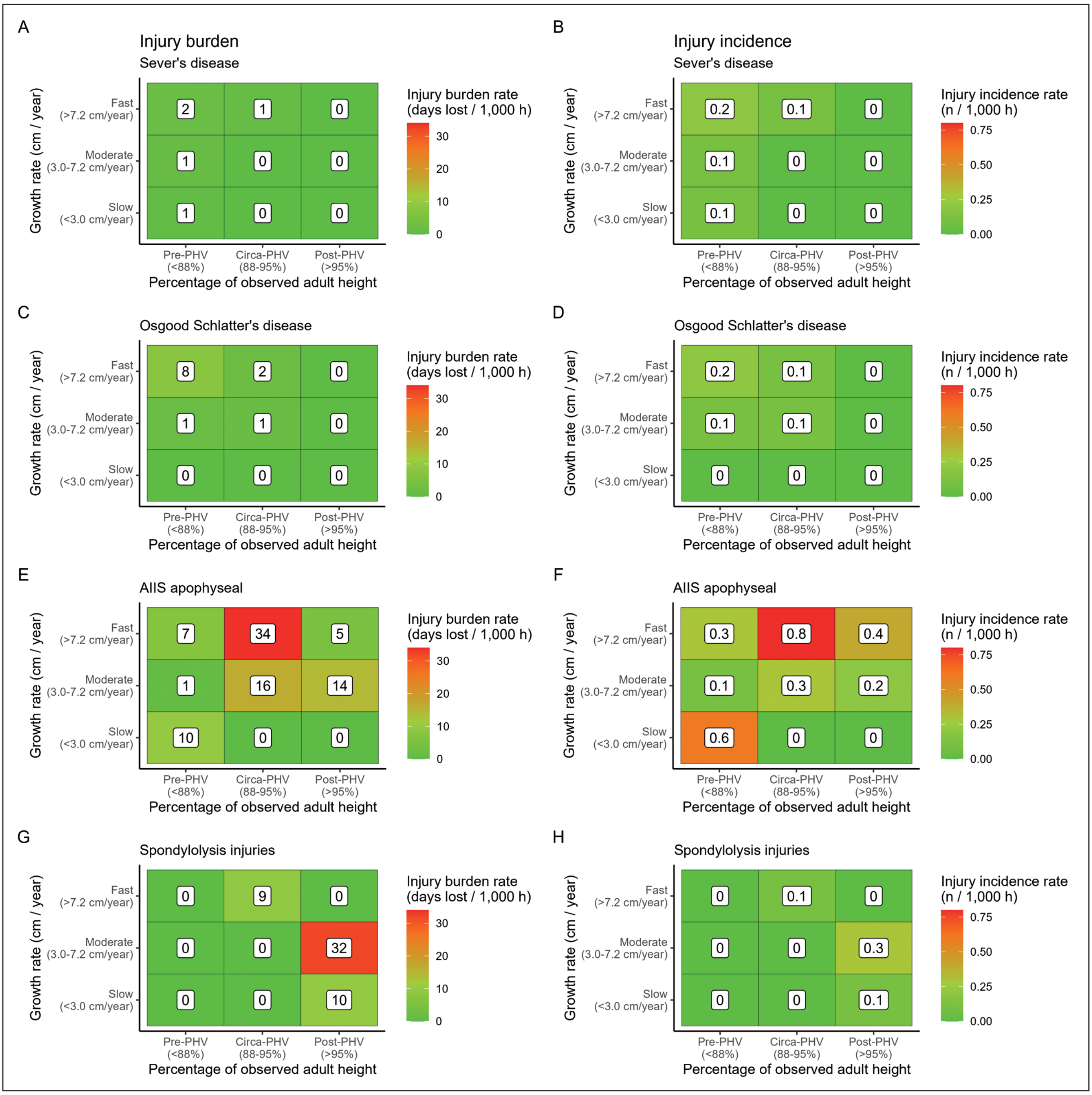

FIG. 3: Injury burden and incidence of specific growth-related injuries according to growth rate and percentage of observed adult height.

growing slowly (0.3 injuries/1000 h, 95% CI: 0.2–0.5/1000 h) (Figure 2). Concerning injury risk for specific growth-related injuries, pre-PHV players growing fast showed a 4.4-times higher Osgood-Schlatter´s disease incidence (0.2 injuries/1000 h, 95% CI: 0.1–1.2/1000 h) compared to players growing moderately (0.1 injuries/1000 h, 95% CI: 0.1–0.3/1000 h) (Figure 3). Moreover, post-PHV players growing fast had a higher incidence of anterior inferior iliac apophyseal injuries (0.4 injuries/1000 h, 95% CI: 0.1–3.9/1000 h) compared to players growing slowly (0.2 injuries/1000 h, 95% CI: 0.1–0.2/1000 h) (RR: 257.9) (Figure 3).

Significant differences for incidence and burden of muscle injuries were not found between any of the growth rates groups in pre-, circa- and post-PHV periods. Nevertheless, the incidence and burden of joint/ligament injuries were 2.4 and 2.6-times greater in post-PHV players growing slowly (1.7 injuries/1000 h, 95% CI: 1.3–2.1/1000 h and 62 days lost/1000 h, 95% CI: 47–81/1000 h) compared to those growing moderately (0.7 injuries/1000 h, 95% CI: 0.4–1.1/1000 h and 24 days lost/1000 h, 95% CI: 12–45/1000 h) (Figure 2).

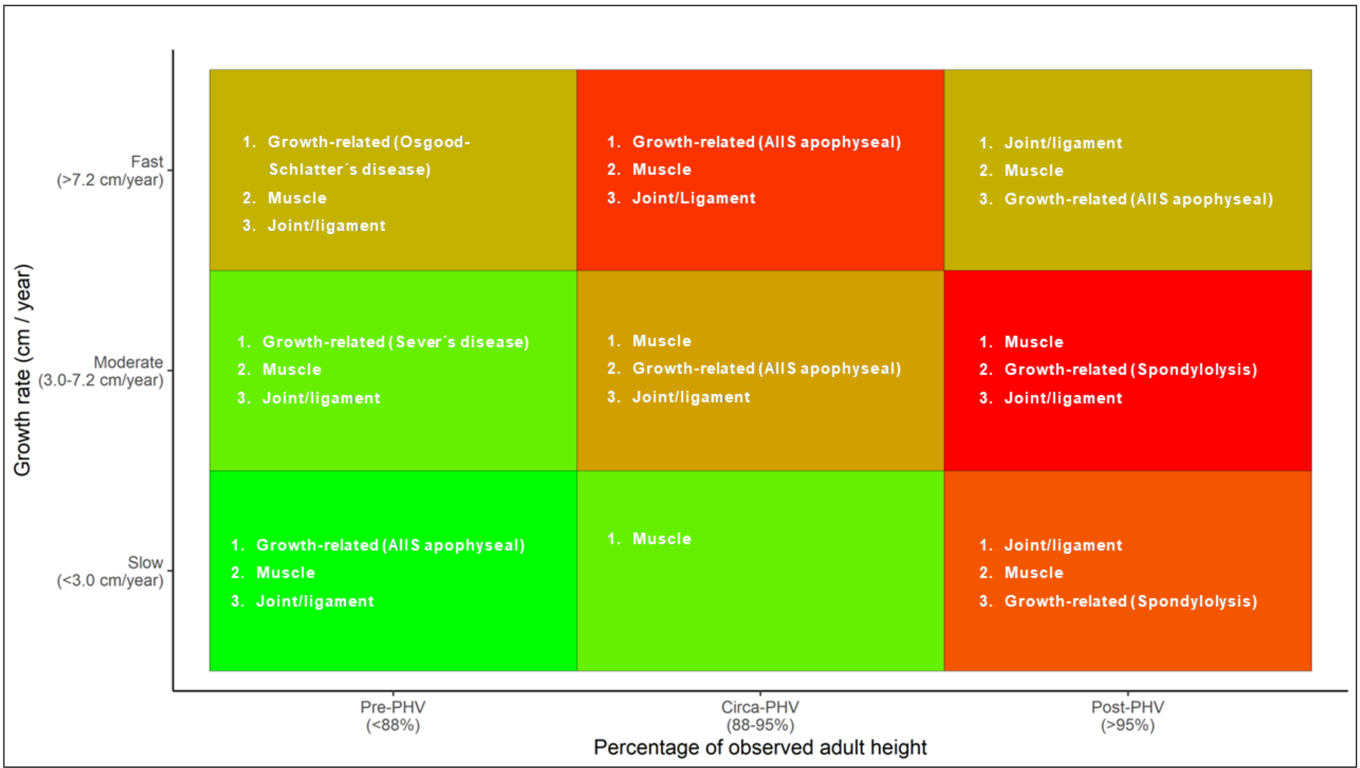

FIG. 4: Ranking for most burdensome type of injuries according to growth rate and maturity status.

DISCUSSION

This is the first research studying the main and interactive effects of growth rate and maturity status on risk for specific types of injuries in academy football. We improved upon the limitations of previous research by using longitudinal height data from childhood to adulthood to estimate daily growth rate and percentage of observed adult height to study how growth rate influences overall and specific incidence and burden in pre-, circa- and post-PHV periods. All in all, our results demonstrated that players with higher growth-rates were at higher risk for growth-related injuries independently to the somatic maturation status. Besides, slow growth rate post-PHV players had a higher incidence and burden of joint/ligament injuries.

The major finding of this study is that growth-rate affects overall injury risk in pre-PHV period, which highlights the importance of regular growth monitoring from an early age. Multiple injury mechanisms may explain increased injury risk in pre-PHV players with fast growth rates. Rapid growth might lead to larger changes to limb length, limb mass, and moments of inertia [24], alterations in motor control [5], which may adversely impact injury risk. Rapid longitudinal skeletal growth is also associated with a temporary decrease in bone mineral density and weakness of the epiphyseal growth plates [25], and may facilitate the appearance growth-related conditions [26]. Considering that the growth-related injuries have the highest incidence [15] and burden [17] in pre-PHV period, increased growth-related injury risk in players growing fast might have contributed to increased overall injury risk. Another reason that could explain the higher risk in pre-PHV players growing fast, might be that pre-PHV players with faster growth-rates could be earlier maturers [4]. Players maturing earlier usually have faster growth rates [4] and might be physically superior to their peers [27]. Thus, they may develop a more physical way of playing football [28] exposing them to a higher injury risk in pre-PHV [17]. Future research should consider maturity timing when studying the interaction of growth-rate, maturity, and injury risk.

The results of the current investigation showed a higher incidence and burden of growth-related injuries in players with fast growth rates compared to those growing moderately in pre- and circa-PHV, and a higher incidence in players with moderate growth rates compared to those growing slowly in post-PHV. The small number of playing growing slowly (< 3.5 cm/year) in pre- and circa-PHV might have led to not finding significant differences in those groups. In the same line, the lack of players growing fast in post-PHV period may explain why significant differences compared to this group were not found; however, players growing quick had the highest incidence of growth-related injuries in this period. The combination of altered sensorimotor mechanisms and motor control [5] and vulnerability of apophyses [25] might result in increased injury growth-related injury incidence and burden in players growing fast [26], which is in line with previous research by Wik et al. [12]. Besides, it was not surprising to find that faster growth rates lead to higher risk for growth-related injuries in all pre-, circa- and post-PHV periods, as previous research has already shown that these injuries can occur all along the maturation process [15, 17]. Interestingly, our results showed that growth-rate affected risk for specific types of growth-related injuries differently according to maturity status, which is in accordance with the distal to proximal pattern of growth-related injuries found in previous research [15, 17].

No significant results between incidence and burden of muscle injuries were found between growth rate groups (fast *vs*. moderate *vs*. slow) in pre-, circa- and post-PHV. These results are in line with previous research by Wik et al. [12], who only found an association between growth and risk of bone and growth-plate injuries. More research is needed to better understand if neuromuscular alterations that appear around PHV [29] are related to the higher muscle and joint/ligament injury risk in circa- and post-PHV periods [15, 17].

Concerning injury risk for joint/ligament injuries, players growing slowly had a higher incidence and burden compared to those with fast/moderate growth rates in post-PHV. Our results are in accordance with recent results found by Monasterio et al. [17], who found a higher injury burden for joint/ligament injuries in adult players (growth rate < 1 cm/year), compared to post-PHV players who may have been growing at higher rates. Considering that post-PHV players growing slow may be more mature (and older) than players growing fast and moderately, our results might be explained by the accumulation of multiple seasons of training and competition throughout their careers [30], with previous injury increasing the risk of subsequent injury [31].

Practical application

In light of the results above, we recommend academy practitioners to measure players height every 3–4 months [32] to model individual growth curves and estimate growth velocities. In order to monitor maturity status (percentage of predicted adult height), an x-ray of the hand-wrist complex is considered the best method to use [4]. However, exposure to low-level radiation, the need for specialised equipment and trained technicians makes it impractical in academies. Thus, other non-invasive and cost-efficient alternatives such as the Khamis-Roche method (somatic maturity) [33] or SonicBone BAUSPORT system (skeletal maturity via ultrasound) [34] could be used to estimate percentage of adult height.

Once estimated each player´s growth rate and maturity status (pre-, circa-, post-PHV), Figure 4 could be used in a practical setting to identify players at higher risk (red colour). This figure will be helpful to facilitate the interpretation of our results to key decision-makers in football academies (players, coaches, and directors), who may be unfamiliar with scientific figures and data analysis. As a result, it may improve communication with key decision-makers and increase their engagement in injury management strategies. Practitioners may choose the adjust training content and training and competition load during periods of heightened injury risk (i.e., adolescent growth spurt) to mitigate injury risk. Jan Willem Teunnisen, a former movement scientist at Ajax Football Club describes an innovative bio-banding (i.e., maturity matching) strategy whereby the player's entering the adolescent growth spurt were prescribed a training programme that emphasised core strength, balance, coordination, the re-training of fundamental and sport-specific motor skills, and the maintenance mobility, in addition to a reduction in training and competition load [35]. The purpose of this programme was to reduce injury risk and aid transition through this phase of development.

The growth/maturity heat maps also highlight the most burdensome injuries [36] in each quadrant and may guide practitioners to design targeted injury risk reduction strategies. As shown in previous research [15, 17], reducing the impact of growth-related injuries seems vital in pre- and circa-PHV periods. Further, this research highlights the need for special attention to those players growing at velocities > 7.2 cm/year. Strategies such as controlling week-to-week changes in load [11, 37], changing training content [35] or monitoring symptoms of musculoskeletal complaints to detect early growth-related conditions [38] may be of the utmost importance in those players. Due to the distal to proximal patterns of growth-related injuries, special awareness to symptoms in the ankle/ knee should be taken in pre-PHV period, while focussing on complaints on the hip/pelvis and lower back is essential in circa- and post-PHV, respectively. On the other hand, reducing the impact of spondylolysis, muscle and joint/ligament injuries seems vital in post-PHV. For instance, controlling training load [37] or neuromuscular training programmes [39] might be beneficial to reduce injury risk during this period.

Methodological considerations

The principal strength of this study is its longitudinal design over two decades, which allowed to model growth rates and estimate daily growth rate and percentage of observed adult height. This research has improved on previous data that recorded growth during short periods [8–12], not allowing to account for the non-linear characteristic of growth [16]. Besides, this study used percentage of observed adult height as a maturity status indicator, while previous studies calculated percentage of predicted adult height [11, 14]. Most importantly, this is the first study investigating the interaction between growth rate and injury risk (incidence and burden) for specific types of injuries according to maturity status (pre-, circa- and post-PHV).

However, the limitations of the current investigation should also be noted. Firstly, we did not account for individual exposure. Thus, as suggested by the latest international Olympic Committee consensus statement [21], exposure was estimated based on the number and duration of matches and training sessions, squad size and the number of players on the pitch in each category. Besides, our findings apply to a single elite soccer academy, and only players who attained adult height were included in the study. Considering that injuries have a negative impact on academy progression [2], players who sustained severe injuries may have been missed. Moreover, injury data was analysed retrospectively and classification by the FIFA Consensus was not considered since the start of the study. Further, there were no protocols to check intra- and inter-tester reliability of all the doctors that recorded injuries during the whole study period.

Further, many factors such as equipment used to measure height or diagnose players' injuries, preventive strategies and training content might have changed over the study period and were not controlled for in analyses. Another limitation is that our sample size was not large enough to detect association with all specific injuries [40], and the limited number of specific injuries resulted in wide confidence intervals for the injury incidence and burden of many injuries. Thus, we only studied the most frequent injuries in our dataset. Future studies should build on this work by conducting multi-team collaborative studies with a sufficiently powered sample size.

CONCLUSIONS

Our results demonstrated that players with higher growth-rates were at higher risk for growth-related injuries in all pre-, circa- and post-PHV periods. A higher incidence and burden for joint/ligament injuries in players with slow growth rate post-PHV compared to players with moderate growth rate was found. Thus, practitioners in football academies should consider the combined effects of growth rate and maturity status when designing targeted injury risk reduction strategies.

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Conflict of interest declaration

The authors report there are no competing interests to declare.

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Maximum strength and power as determinants of on-ice sprint performance in elite U16 to adult ice hockey players

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ABSTRACT: In ice hockey, speed strength is one of the major physical key performance indicators, which is significantly influenced by maximum strength. The objective of this study was to evaluate the age-dependent relationship of off-ice maximum strength and vertical jump performance with on-ice linear sprint performance, considering age and performance level. Ninety-one male youth and adult professional ice hockey players (age: 19.3 ± 5.49 years) were recruited and divided into four age groups: under 16, 18, 21 years old and professional elite players (Pro) (i.e., > 21 years). They were tested in maximal isometric strength, squat jump (loaded and unloaded), countermovement jump and on-ice sprint performance (15 m and 30 m linear sprint; 15 m flying linear sprint). Statistical analysis revealed that on-ice sprint performance correlated with isometric strength performance (r = |0.34|-|0.63|) and with off-ice jump performance (r = |0.61|-|0.77|) without an influence of age group or performance level. However, performance differed between age groups and performance level, the largest differences being found between the youngest age group (U16) and the Pro group (g = 0.966–3.281). The present study shows that maximum strength influences on-ice sprint performances in ice hockey players, as well as performance differences between age groups and professional players. Strength and jumping performance should therefore be included in regular performance testing in ice hockey. Since performance differences are observed for almost all strength and speed-strength performances of the youth teams to the Pros, training of these variables is strongly recommended to improve in the transition phase from junior to elite level.

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INTRODUCTION

Maximum and repetitive sprint performance seem to be of high importance in ice hockey [1]. During each minute on ice, a player skates approximately 119 m at high intensity and 31 m at maximum intensity [2]. The total distance covered during a game is about 4600 m, of which 2042 m is at high intensity in roughly 15 min [2]. Therefore, higher sprint performance in 10–30 m sprint seems to be correlated with higher playing level [3, 4], leading to benefits in winning the puck [2, 5].

Therefore, speed strength is a performance determinant which seems to be strongly influenced by maximum strength [6, 7]. Literature investigating the influence of speed strength on on-ice performance is scarce; however, off-ice, studies including elite and recreational team sports athletes other than ice hockey show strong correlations (r = 0.67–0.78) between maximum strength (1 repetition maximum back squat [1RM]) and vertical jumps (countermovement [CMJ] and squat jump [SJ]) as well as linear sprint performance independent of age groups [8–10]. Furthermore, the isometric mid-thigh pull is an often-used strength test in (sport-) performance tests, showing moderate to high correlations with jumping (r = |0.51–0.73|) [11–14] and sprinting performance (r = |0.53–0.69|) [15, 16]. Studies including male and female college hockey players showed contrasting results ranging from r = |0.21| to |0.74| examining the relationship between different maximum strength performances and on-ice linear sprint (6–44.8 m)) [17–19]. This heterogeneity in correlations could be due to large differences in study design and partially small sample sizes (high sampling error). Additionally, some studies show correlations of r = |0.09|-|0.85| for off-ice performances (different jumps [loaded and unloaded/vertical and horizontal]) with on-ice linear sprint (6–55 m) performances in different performance levels (youth, sub-elite and professional) [5, 17–21].

Similar to other team sports [22–24], in ice hockey [3, 4, 25–27], speed strength is considered to be an important factor differing between age groups or between elite and sub-elite. Players of a Polish professional team were divided into two groups according to their playing level. The group with the best players showed significantly better performances in the 30 m off-ice sprint and in the 6 × 9 m change of direction test compared to the weaker group [25]. Therefore, the authors suggested that speed parameters can be used for the selection of top hockey players [25]. Accordingly, Vigh-Larsen et al. [3] observed significantly better CMJ performance, change-of-direction ability, and linear sprint performance over 0–33 m in professional ice hockey players from the 1st Danish league compared to 2nd league players. Also Bracko & George [26] reported significantly higher performance results in professional compared with amateur female ice hockey players (15 m "on-ice" sprint). The fitness profiles of 204 professional female ice hockey players from 13 countries were compared [28] considering their age (junior < 18 years old or senior group > 18). Compared to the junior group, the senior players performed significantly better in vertical jump, 4-jump, and standing long jump [28]. Hoff et al. [27] analysed the performance of elite (age: 24.2 ± 4.7 years) and junior elite players (age: 17.6 ± 0.9 years), finding significantly better performances in the 1RM back squat, bench press, 10 m sprint, CMJ and SJ with 50 kg in older players.

Although there is already some evidence on the relationship between maximal strength performance and off-ice speed strength performance as well as differences between age and performance groups, there is a need for a further study to get deeper insights for the determining variables for on-ice performance. Therefore, this study was conducted to investigate the influence of maximum strength (absolute and relative maximal isometric strength) using the isometric trap bar pull (ITBP) on vertical jump performance, CMJ, CMJ with an extra 40% of bodyweight (BW), SJ height and "on-ice" linear sprint performance (15 m, 30 m and flying 15 m) in youth elite and professional ice hockey players of the two highest Swiss leagues. Furthermore, differences in performance across age groups, ranging from under 16-year-olds to professional players, were analysed.

MATERIALS AND METHODS

In order to answer the research question, a cross-sectional study was conducted. To investigate the relationship between performance "off-ice" and performance "on-ice" 91 highly trained male youth and professional ice hockey players were tested off ice in ITBP CMJ, SJ, CMJ 40% BW and maximum speed on-ice (15 m, 30 m, flying 15 m). The tests were performed after two days of rest in the second week of the pre-season. Tests were carried out on 2 test days within a 1-week period. On test day 1 the off-ice tests were performed, followed by the on-ice tests on test day 2 (see Figure 1). A familiarization period was not necessary because all tests are performed at regular intervals (jumps = weekly; strength = monthly, sprint = semi-annually) and were therefore known to the players.

Subjects

Ninety-one male youth and adult ice hockey players (height: 178 ± 6 cm; weight: 75.9 ± 10.8 kg; age: 19.3 ± 5.5 years) competing at the national and international level from a professional ice hockey club in Switzerland were recruited and divided into four (age)

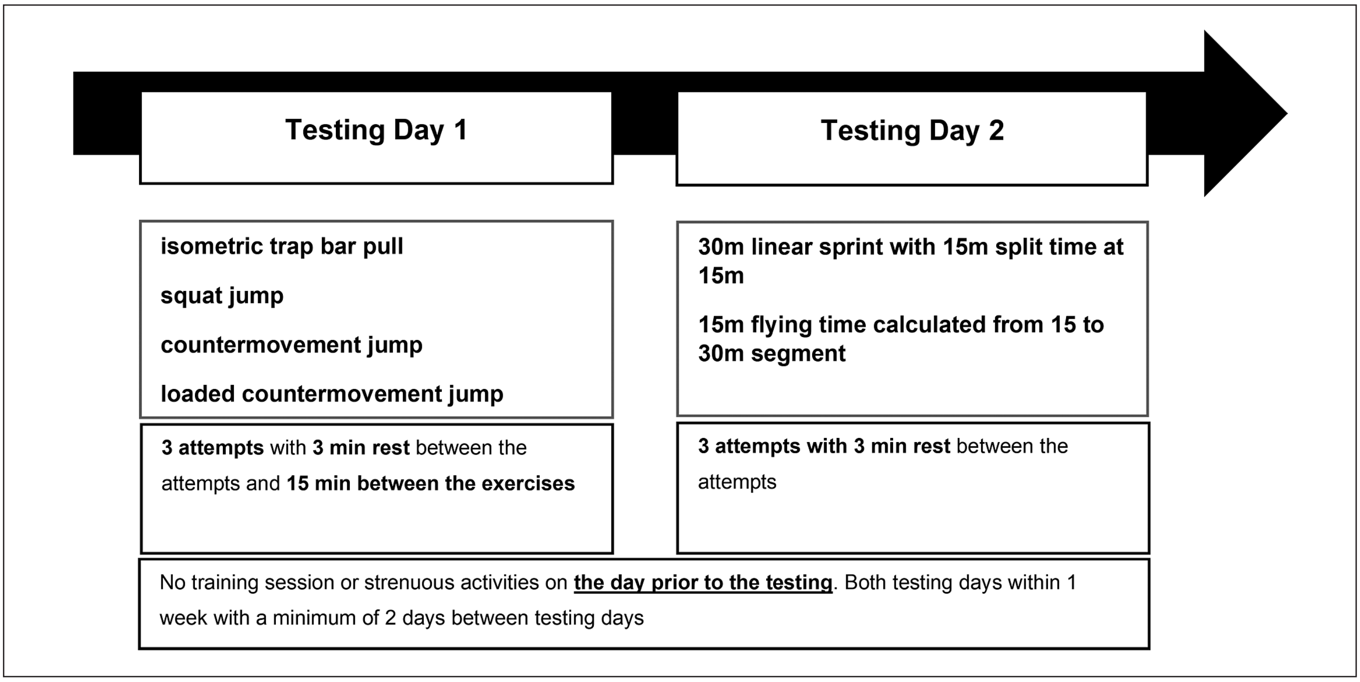

FIG. 1. Test procedure.

groups: U16 (n: 20; height: 175.8 ± 8.1 cm; weight: 66.9 ± 9.4 kg; age: 14.8 ± 0.4 years), U18 (n: 28; height: 177.9 ± 5.9 cm; weight: 71.7 ± 7.9 kg; age: 16.4 ± 0.5 years); U21 (n: 22; height: 178.6 ± 5.2 cm; weight: 80.2 ± 9.2 kg; age: 18.8 ± 1.0 years); Pro (n: 21; height: 180.1 ± 5.3 cm; weight: 85.7 ± 6.8 kg; age: 28.4 ± 3.9 years). The players of the Pro subgroup play in the highest and the U21 in the second highest national league. Five players of the subgroup Pro are A national team players. For the U18 and U16, players were recruited who play in the highest junior leagues in their respective age groups. Of these, 14 players also play for the junior national teams. Training volume is stated with 14 hours per week (h/w) during the off season in both professional teams (Pro and U21) and 10 hours per week (h/w) in all youth teams. In the preseason and in-season, the training volume varies between 6 and 10 hours/week and an additional 1 to 3 games per week in all subjects. The subjects did not participate in fatiguing training sessions for a minimum of 2 days prior to testing. None of the subjects reported any injuries at the time of testing. Each subject and their parents (for underaged participants) were informed about the aims of the study and the experimental risks involved with the research and provided written informed consent. Furthermore, this study was performed in accordance with the Helsinki Declaration and was approved by the Universities Ethics Committee (DHGS-EK-2021-002).

FIG. 2. Isometric trap bar pull.

Procedure and Measurements

Off-ice Tests

All strength and power tests were performed on a split force plate (Hawkin Dynamic Wireless Dual Force Platform V.3.0., Main, USA). All participants completed a standardized 20 min warm-up protocol before the off-ice tests. The protocol included glute bridges, various mini band exercises to activate the hip muscles, 10 repetitions each of BW split squats, BW squats, SJ, and CMJ. After the standardized warm-up, the maximum strength was first determined with the ITBP (Figures 1 and 2). Here, 3 trials were performed with a rest period of 3 min between attempts. After another breaks of 15 min, the SJ and CMJ were tested, each with three attempts. Maximum concentric power can be generated using a range of external loads between 30% and 60% of maximum strength [21, 29]. Therefore, also 3 attempts for CMJ 40% BW were performed after another break of 15 min.

The ITBP was performed with a hip-width start position and with minimal outward rotation of the feet allowed. The athlete held the trap bar under fixed pins attached to the rack. In this position, the knee angle was determined by a mobile app (Coach's Eye, TechSmith Corporation) and protractor. If a knee angle of 90 degrees was measured, the athlete was allowed to start the first attempt after a brief pause. Once the test started, the athlete was instructed to increase the pull to a maximum against the pins over 5 seconds (s). If the athlete could not keep their back straight, the attempt was considered invalid. The highest value in N and N per kg of BW (N/kg) was used for the data evaluation. This protocol was very similar to the one used by another study in the field of ice hockey, where maximum isometric strength was assessed [30]. The intersession reliability is assumed with ICC = 0.99 [30].

The jump height was calculated with take-off velocity^2 / (9.81*2) and from flight time ($gt^2/8$; with g being the gravitational acceleration (9.81 $m \cdot s^{-2}$) and t = flight time in seconds) via software (Hawkin Dynamic, Main, USA). For the SJ the athlete placed the left foot on the left plate and the right foot on the right plate. The jump was only scored if the body travelled directly upwards. If a downward movement to the ground was executed before take-off the jump was scored as invalid. Likewise, a jump was considered invalid if the athlete removed their hands from their hips during the jump. The same criteria applied to the CMJ; however, a countermovement should be induced. Interclass reliability for similar test setups is assumed with ICC = 0.87–0.98 [31, 32]. In the CMJ with extra 40% BW, the athlete with the loaded trap bar also placed themself on the plate. In general, the exact same conditions were chosen as for the classic CMJ. Additionally, the trap bar was gripped centrally, with a neutral grip, and a neutral spine position was assumed. The weight could be adjusted to within 500 g of the calculated value. Interclass reliability following other studies with similar protocol is assumed with an ICC = 0.92 [33].

On-ice Tests

On the ice 5 min (submaximal skating) warm up was performed including two 30 m acceleration runs and an all-out 10 m sprint. Considering match demands and most reported test distances in the literature a 30 m linear sprint was measured [34]. For the timing of the 30 m sprint (with a section of 15 m as a measure for the acceleration [34]), light gates (Smartspeed, Vald Performance, Newstead, Australia) were used. The starting point was set 0.5 m in front of the light gates to avoid an early release that could occur inadvertently by a hand or stick movement or by bending the upper body forward at the start. The height of the light gate was set to 90 cm. The athletes started with complete ice hockey equipment including the stick without an external signal. After two attempts with a rest period of three minutes in between, the best 15 m and 30 m times were used for further analysis. For the determination of the flying 15 m (15 to 30 m segment time; this variable is based on match demands, because various sprint performances are generated from a submaximal speed), the sprint with the best 30 m final time was taken. The best attempt of each test is listed on the data sheet in the appendix. For on-ice sprints, the interclass reliability has been reported to be ICC = 0.86 in previous research [35].

Statistical analysis

The data were analysed using SPSS 28.0 (IBM). The significance level was set to < 0.05 for all statistical tests. In descriptive statistics, ensemble mean, standard deviation (SD) and 95% confidence intervals (95% CI) were calculated. The Shapiro-Wilk test was used to test the data's distribution for normality.

The relationships between the SJ, CMJ, CMJ 40%, relative and absolute strength and the on-ice sprint tests were evaluated using the one-tailed bivariate Pearson correlation coefficient for the entire sample and differentiated for the respective age groups (U16, U18, U21, Pro). The explained variance (r^2) was calculated by squaring r. Additionally, 95% CI for correlation coefficients were reported. To determine significant differences in the correlation coefficients between subgroups (U16 vs. U18; U16 vs. U21; U16 vs. Pro; U18 vs U21; U18 vs. Pro; U21 vs Pro), the data were z-transformed according to the Fisher method. The difference of the two transformed values after standardization was tested for significance:

$$Z = \frac{z'_1 - z'_2}{\sqrt{\frac{1}{n_1-3} + \frac{1}{n_2-3}}}$$

Further, the Benjamin-Hochberg method was applied to control the false discovery rate. Also the Benjamin-Hochberg method was used to correct for potential alpha errors [36].

Between-age-group differences were investigated using a one-way ANOVA with Bonferroni corrected post hoc tests. In addition, the effect size was determined with Hedges' g. Post-hoc power (1-ß) was calculated via G*Power 3.1.9.6 (University Düsseldorf, Düsseldorf, Germany).

RESULTS

The Shapiro-Wilk test result showed that all parameters were normally distributed.

The mean performance and SD for all the different tests, as well as the 95% CI, are shown in (Table 1). ICC coefficients were found for all tests (0.93–1.0).

Pairwise comparison of coefficients from independent samples showed that there were no significant differences ($p < 0.05$) between the age groups in 88 out of 90 cases. Only the correlation coefficients for the variables maximum strength and flying 15 m, between the age groups U16 and U18 ($p = 0.02$), as well as U16 and Pro ($p = 0.02$), showed significant differences. After applying the Benjamin-Hochberg method, these values also showed no

TABLE 1. Descriptive statistics and intraclass correlation coefficients of performance variables for total group

Tests	Mean ± SD	95% CIs	ICC
CMJ (cm)	38.64 ± 4.87	37.62–39.65	0.99
SJ (cm)	35.86 ± 5.13	29.04–30.40	0.99
CMJ 40% BW (cm)	27.08 ± 3.84	26.28–27.88	0.99
ITBP (N/kg)	29.718 ± 3.258	29.04–30.40	1.00
ITBP (N)	2269.5 ± 467.8	2172.0–2366.9	1.00
Sprint 15 m (sec)	2.57 ± 0.87	2.55–2.59	0.93
Sprint 30 m (sec)	4.37 ± 0.15	4.34–4.44	0.95
Flying 15 m (sec)	1.80 ± 0.08	1.78–1.81	0.95

SD = standard deviation; ICC = intraclass correlation coefficient; CMJ = counter movement jump; SJ = squat jump, CMJ 40% BW = counter movement jump 40% bodyweight; ITBP = isometric trap bar pull.

TABLE 2. Correlation coefficients and 95% confidence intervals for the off- and on-ice tests

Tests	Sprint 15 m	Sprint 30 m	Flying 15 m
CMJ	-0.63 (-0.76 – -0.50)	-0.77 (-0.86 – -0.69)	-0.77 (-0.86 – -0.69)
SJ	-0.60 (-0.73 – -0.47)	-0.73 (-0.83 – -0.63)	-0.72 (-0.82 – -0.62)
CMJ 40% BW	-0.61 (-0.74 – -0.48)	-0.75 (-0.84 – -0.66)	-0.75 (-0.84 – -0.66)
ITBP (W/kg)	-0.41 (-0.58 – -0.24)	-0.57 (-0.71 – -0.43)	-0.63 (-0.76 – -0.50)
ITBP (W)	-0.34 (-0.53 – -0.16)	-0.53 (-0.68 – -0.38)	-0.63 (-0.76 – -0.50)

CMJ = counter movement jump; SJ = squat jump, CMJ 40% BW = counter movement jump 40% bodyweight; ITBP = isometric trap bar pull; * < 0.05.

TABLE 3. Descriptive statistics of performance variables for age groups and professional players

Tests	Mean ± SD			
	U16 (n = 20)	U18 (n = 28)	U21 (n = 22)	Pro (n = 21)
CMJ (cm)	35.00 ± 3.54	36.82 ± 3.41	40.32 ± 5.00	42.76 ± 3.77
SJ (cm)	32.85 ± 3.73	33.75 ± 3.95	37.14 ± 5.64	40.19 ± 3.72
CMJ 40% BW (cm)	23.80 ± 2.98	26.00 ± 2.69	28.23 ± 3.52	30.43 ± 3.06
ITBP (N/kg)	26.54 ± 2.45	29.18 ± 2.54	31.20 ± 3.36	31.91 ± 1.88
ITBP (N)	1775.0 ± 300.2	2092.0 ± 271.6	2499.5 ± 368.1	2736.1 ± 286.2
Sprint 15 m (sec)	2.62 ± 0.09	2.58 ± 0.07	2.53 ± 0.09	2.54 ± 0.08
Sprint 30 m (sec)	4.50 ± 0.14	4.40 ± 0.11	4.30 ± 0.13	4.27 ± 0.11
Flying 15 m (sec)	1.87 ± 0.06	1.82 ± 0.06	1.77 ± 0.06	1.74 ± 0.05

n = sample size; SD = standard deviation; CMJ = counter movement jump; SJ = squat jump, CMJ 40% BW = counter movement jump 40% bodyweight; ITBP = isometric trap bar pull, U16 = under 16 years old; U18 = under 18 years old; U20 = under 20 years old; Pro = professional players.

TABLE 4. Effect sizes of differences between youth age groups and professional players

		CMJ	SJ	CMJ 40%BW	ITBP (W/kg)	ITBP (W)	Sprint 15 m	Sprint 30 m	Flying 15 m
U16/U18	g	0.525	0.233	0.781	1.056*	1.117*	0.502	0.755	0.947*
U16/U21	g	1.218*	0.888*	1.353*	1.570*	2.146*	1.003*	1.460*	1.735*
U16/Pro	g	2.122*	1.969*	2.193*	2.464*	3.281*	0.966*	1.752*	2.593*
U18/U21	g	0.837*	0.711*	0.726	0.690	1.464*	0.656	0.898*	0.831*
U18/Pro	g	1.665*	1.671*	1.552*	1.195*	2.316*	0.585	1.188*	1.525*
U21/Pro	g	0.551	0.635	0.666	0.261	0.715	0.106	0.191	0.576

g = effect size hedges; CMJ = counter movement jump; SJ = squat jump, CMJ 40% BW = counter movement jump 40% bodyweight; ITBP = isometric trap bar pull, * = significant different ($p < 0.05$); U16 = under 16 years old; U18 = under 18 years old; U20 = under 20 years old; Pro = professional players.

significant differences between the age groups. Therefore, the correlations for the total group were calculated in Table 2. Squaring correlation coeficients showed 36-59% explained variance (r^2) for on-ice sprint and jump performance and 12-40% for strength and on-ice sprint performance. The Benjamin-Hochberg method was also used to adjust alpha error. Significant differences for all parameters were found for each group and in all combinations. Post hoc power was calculated with 96% (lowest effect size) to 100% (highest effect size) assuming an alpha level of 0.05 for correlation analysis.

Table 3 shows performance variables for age groups and professional players. ANOVA revealed that the groups (U16, U18, U21, Pro) differed ($p < 0.001$) from each other in all test results

(CMJ [$F_{3,87}$ = 16.5, p < 0.001, η^2 = 0.363], SJ [$F_{3,87}$ = 13.0, p < 0.001, η^2 = 0.311], CMJ40&BW [$F_{3,87}$ = 18.3, p < 0.001, η^2 = 0.387], ITBP [$F_{3,87}$ = 40.8, p < 0.001, η^2 = 0.584], 15 m sprint [$F_{3,87}$ = 5.6, p = 0.002, η^2 = 0.161], 30 m sprint [$F_{3,87}$ = 14.7, p < 0.001, η^2 = 0.336], flying 15 m [$F_{3,87}$ = 23.0, p < 0.001, η^2 = 0.443]). Results of the post-hoc test (Bonferroni) are presented in Table 4. Post hoc power was calculated with 94% (lowest effect size) to 100% (highest effect size) assuming an alpha level of 0.05 for ANOVA analysis.

DISCUSSION

The objective of this study was to evaluate the age-dependent relationship between maximum strength and vertical power, with on-ice linear sprint performance, in elite youth and professional ice hockey players. Statistical analysis revealed that on-ice sprint performance correlates moderately to highly with isometric strength performance (r = |0.34|-|0.63|) and highly with off-ice jump performance (r = |0.61|-|0.77|). These correlations did not differ between age groups or performance levels. In contrast, however, it is noteworthy that most of the assessed performance parameters (i.e., on-ice, off-ice) differed between age groups and performance level with the largest observed differences between the youngest age group (U16) and the Pro group (g = 0.966–3.281), indicating a better performance in the older athletes.

The correlation coefficients for strength and "on-ice" performances in this study (r = |0.34–0.63|) are found to be approximately in the middle of the range of correlations stated in previous literature (r = |0.21|-|0.75|) [17–19]. The broader range of correlation coefficients in the mentioned studies may be due to a higher sampling error in these studies caused by the smaller sample sizes of *n* = 16–40. Consequently, a higher dispersion around the true coefficient can be expected in these studies, and it seems stringent to locate (roughly in the middle of the range of coefficients documented in the literature) the coefficients measured in this study, which should scatter less around the true coefficient [8].

Furthermore, the explained variance (12–40%) shows that, in addition to the influence of maximum strength, other variables (e.g., technique) can be expected to influence performance. Interestingly, the correlation coefficients of the strength performances are higher in the flying 15 m and 30 m sprint compared to the 15 m sprint. This may be explained by the high velocity specificity of muscular performance [37], as longer ground contact times (longer period of time available for the development of forces) with increasing skating speed [38–40]. Since unfamiliarity of athletes with isometric testing conditions can be assumed, it can be hypothesized that strength level using isometric testing might be underestimated [41–43]. Since the majority of the athletes perform strength and sport-specific training predominantly under dynamic conditions, the difference in contraction specificity might negatively impact correlation coefficients [44]. Not surprisingly, jumping performances have higher correlation coefficients with on-ice performances than strength performances [17, 18, 20]. However, jumping performance is also strongly dependent on strength performance [6, 8]. Nevertheless, the data obtained in this study strengthen Schmidtbleicher's theory [45] that maximum strength, as a basic strength ability, positively influences the performance of high-speed strength. For this reason, the correlations also remain stable between the youth athletes and professionals and do not show any significant in-between differences.

The observed performance differences in favour of elite and older populations are basically consistent with findings in the literature for ice hockey [3, 4, 25–28] and other team sports [23, 46–48]. The higher performances in the elite and older subjects could possibly be attributed to the higher level of experience and training age. Playing ice hockey (and, therefore, sprinting and changing direction) may be an effective training stimulus for improving on-ice and off-ice performances. Therefore, the extent (years) to which the athletes have performed sport-specific training and additional strength and plyometric training could explain the higher performance level with increasing age. Nevertheless, athlete allocation also might influence the results, as speed-strength performance determines performance in ice hockey; as performance level (and consequently age) increases, elite sport selects primarily high-performance athletes. This study revealed that speed strength seems to be one main difference between elite and junior ice hockey players at a high performance level. The results therefore identify important factors for juniors to improve in the transition phase from junior to elite level.

This study had some limitations. Based on the study design, by investigating ice hockey teams with a fixed number of members, a sample size based on an a-priori sample size estimation was avoided. Still, based on the post-hoc G*Power analysis, the sample size of this study turned out to be sufficient for both statistical analyses (correlation and ANOVA) with power values between 94% and 100%). Another limitation of the study was that the investigated sample consisted of multiple field positions with potential differences in performance levels, which might have affected the investigated correlations. However, no goalkeeper was included in the sample as they are considered to receive training with alternative focus compared to the field players that were included in the study sample. Moreover, the inclusion of all field players from all positions might have increased the range of athletic performance levels and, thus, the generalizability of our study results. Differences in performances and influences on correlation were calculated/controlled based on calendrical age. It should be noted that the biological age was not recorded, which might have led to a bias in the above calculations (especially for the age group U16). Despite these limitations, the results of this study are valuable, providing important information about jump, maximum strength and linear sprint performance in the sport of ice hockey.

CONCLUSIONS

The present study shows age-dependent and league-dependent performance differences in professional ice hockey players.

Additionally, the study revealed the influence of maximum strength performed off-ice on on-ice performances. Strength and jumping performance should therefore be part of regular performance testing in ice hockey. Since performance differences in strength and speed-strength performances between youth teams and the Pros were evident, training of these variables is strongly recommended to improve in the transition phase from junior to elite level.

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Conflicts of interest

The authors declare no conflict of interest.

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A comparison of the physical demands generated by playing different opponents in basketball friendly matches

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ABSTRACT: This study aimed to compare the physical demands of playing opponents of different skill levels in basketball. Eighteen men's college basketball players wore accelerometers to measure the relative accumulated acceleration load (AAL), estimated equivalent distance, and frequencies of sprint, jump, and exertion events during games against professional teams (Pro), teams at the same competition level (Collegiate), and teams comprising intra-team members in practice games (Scrimmage). Internal responses were calculated using the relative rating of perceived exertion (sRPE). A repeated measures analysis of variance, Bonferroni post-hoc tests, and standardized Cohen's effect sizes were calculated to compare the physical demands and internal responses across matches played against different levels of opponents. The results showed that in the game against the Pro, AAL (arbitrary units), sprint events (cases per min), and exertion events (cases per min) were significantly ($p < .05$) higher than those in games against the Collegiate and Scrimmage teams. As the competitive level of the opponents increased, the relative external load of the participants also increased. Conversely, internal responses measured using sRPE were lower after games against the Pro than those against the Collegiate. Internal and external loads may vary from each other depending on contextual factors.

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INTRODUCTION

Training load is defined as the amount of stress on an individual from a single or multiple training sessions over time [1]. Understanding the influence of training load outcomes on sports performance and injury prevention is vital in sports medicine; it is also important for strength and conditioning coaches and sports scientists [1]. Therefore, implementing techniques to monitor athletes' responses to training stimuli is pertinent to team sports coaches and conditioning professionals [2]. Training load can be organized as "external load," the work completed by an athlete [3], and internal load, the psycho-physiological responses of the athlete to the exercise demand [4]. The term "external load" refers to any external stimulus applied to athletes that is measured independently of their internal characteristics [5]. The external load will result in physiological and psychological responses in each "individual characteristic," following interaction with, and variation in several other biological and environmental factors [6]. This individual response is referred to as the "internal load" [1]. In other words, the training outcome is the consequence of the internal load determined by individual characteristics, such as genetic factors and previous training experience, and the quality, quantity, and organization of the external load [6]. In recent years, accelerometers have gained interest as a practical approach for measuring the external load in team sports [1].

Basketball is an intermittent sport that, due to court dimensions, number of players, and rules (for example, ball possession time [24 s]), requires the players to perform repeated high-intensity movements, such as rapid changes in direction and cutting actions, changes in speed over short distances, contacts (e.g., post-ups, screens, and box outs), or run-to-jump actions occurring between different locomotor demands (e.g., standing, walking, running, and sprinting) [7]. High-intensity movements measured using accelerometers during a basketball game have been found to involve eccentric and quasi-isometric contractions, such as deceleration, landing, and physical contact [8]. Deceleration movement volumes and intensities define the extent of tissue damage [9] and subsequent injury risk [10]. Therefore, accelerometers can quantify multifaceted and complex movements and are a useful approach for monitoring the external load of basketball players [2, 11, 12]. Furthermore, differences in training load by playing position [13], game time [14], and sex [15] are also evident. Thus, understanding the physical demands of game play is a prerequisite for optimal training [3, 8].

In the clinical field of team sports such as basketball, perceived exertion is the main factor limiting human performance [16] and the most used training load monitoring tool in sports [17]. A typical example is the session rating of perceived exertion (sRPE) method, which is calculated by multiplying the rating of perceived exertion (RPE) by the duration of exercise [18]. Validity and reliability of the sRPE method in several sports and physical activities with men and women of different age categories (children, adolescents, and adults) among various expertise levels have been confirmed [17]. This method could be used as a "stand-alone" method for training load monitoring purposes [17].

An integrated approach to training load is also important, and internal and external training loads should be used in combination to provide greater insight into training stress [19, 20]. For example, athletes repeating the same session on different days may maintain the same power output for the same duration (i.e., same external load), but experience quite different internal loads (heart rate, blood lactate, and RPE) depending on their state of fatigue, emotional disturbances, recent training history, and illness [19]. A previous study on soccer has shown that match-related contextual variables, such as game outcome, game location, and score line, influence external and internal workload [20]. Game load varies by competition level in basketball [21, 22], although it is not clear how physical demands differ when the same individual plays against opponents of different competition levels. When playing against an opponent with superior performance, it is expected that there will be an external load that is not experienced in practice games within the own team or in a game against a team of the same performance level. However, no studies have thus far examined and compared these physical demands by changing the opponent for the same individual.

This study aimed to compare the physical demands of playing different opponents in basketball. Specifically, we hypothesized that the higher the competition level of opponents is, the higher are the physical demands and internal load.

MATERIALS AND METHODS

Participants

Eighteen men's college basketball players (age, 19.7 ± 1.1 years [range: 18–21 years]; stature, 186.4 ± 7.6 cm; body mass, 83.9 ± 10.7 kg) were recruited for this study. The participants belonged to a division 1 top-level college league in Japan, and six of them were members of the U19 or U22 Japanese national teams. The exclusion criteria were based on a screening evaluation by a physical therapist: if a participant had a history of serious musculoskeletal injury, any musculoskeletal injury within the past 3 months, or any disorder that interfered with sensory input, musculoskeletal function, or motor function, they were excluded from participating in this study. After receiving a detailed explanation of the study benefits and risks, each participant provided written informed consent for participation. This study was approved by our university (approval number 21013) and conducted in accordance with the Declaration of Helsinki.

Procedures

Prior to each game, inertial measurement unit (IMU) sensors (Kinexon Mobile Tag, KINEXON Precision Technologies, Munich, Germany) were positioned in a holster stitched into the shorts of each participant's team uniform near the right posterior superior iliac spine. The holsters were constructed in collaboration with the sensor manufacturers and team equipment managers to ensure that unnecessary movement was negligible, and positioning was consistent throughout the games [23]. The closer the accelerometer is to the centre of mass, the greater is the accuracy in quantifying the physical work [24]. This placement is less susceptible to noise in the vertical vector motion resulting from upper body movements such as shoulder blade sway, arm swing, trunk flexion, and the vector magnitudes representing overall dynamic body acceleration [24]. A previous study examining the validity of this system reported the average total typical error of estimates to be 2.5% (± 1.5%) when five adult male team sport amateur athletes performed a variety of movements comprising walking, jogging, and sprinting for different distances, as well as changes of direction and jumping [25].

In this study, opposing teams were divided into three groups according to their competition level: the "Pro" were from the domestic professional league (B-league), which has a higher competition level than that of the league from which the study participants were drawn; the "Collegiate" were university teams of the same conference as the study participants' team; and the "Scrimmage" consisted of players from the same team who play friendly matches as the study participants. Games against professionals and college students were friendly matches. Fifteen games (Pro: 5, Collegiate: 5, and Scrimmage: 5) were measured in this study, with a total of 174 data (Pro: 63, Collegiate: 57, and Scrimmage: 54). Match results were 0-5 against professionals, 3-2 against colleges, and 4-1 in Scrimmages. Data from competitions were only included if players participated in 10 minutes of live playing time [26]. Sessions were recorded throughout each game-day and were initiated and ceased at the same time for each athlete. Individual phase recordings were time stamped and segmented into warm-up, 1st quarter, 2nd quarter, 3rd quarter, and 4th quarter phases. Recording of each quarter began when the game clock started counting down and ended when the game clock reached zero. However, in this study, the analysed dataset included only the external load data obtained during the active competition minutes (i.e., during each quarter).

Outcome measures

Across all games, microsensor data were recorded at 100 Hz via IMU devices and downloaded after each game to a personal computer for analysis using proprietary software. All system installations and calibrations were performed by the same technician before the start of the season. All matches included in this study were held at the home court of the participants. External measures included relative (min^{-1}) accumulated acceleration load (AAL; arbitrary units), estimated equivalent distance (EED; m), and frequency of sprint, jump, and exertion events. AAL is a proprietary measure calculated as the accumulated rate of change in acceleration across three vectors (x, y, and z) based on the following formula:

$$AAL = \sqrt{[(Ac1_n - Ac1_{n-1})^2 + (Ac2_n - Ac2_{n-1})^2 + (Ac3_n - Ac3_{n-1})^2 / 100]}$$

where Ac1, Ac2, and Ac3 are the orthogonal components measured from the triaxial accelerometer and 0.01 is the scaling factor [11, 12, 20, 27]. According to previous studies, AAL has been observed to have moderate to high test-retest reliability (ICC, .94–.97; CV 3.6–9.4%) [24] and this metric has been widely used in basketball [12, 28]. EED is the sum of the estimated distances an athlete runs on a horizontal plane. The distances are derived from the velocity samples predicted from the acceleration load data recorded by the IMU [27]. The raw frequency of 100 Hz measured by the IMU was used to smooth the data to 10 Hz using a Kalman filter to identify each event. "Sprints" were identified using a threshold of 18.72 km/h and a minimum duration of 1.0 s as dictated by the proprietary software. "Jumps" were identified at a minimum dwell time of 0.4 s. "Exertions" were also identified if they maintained a minimum 4.5 G for 1.0 s as dictated by the proprietary software.

Internal measures were evaluated using the relative (min^{-1}) sRPE values. sRPE was used as a perceptual indicator of the internal load based on the following formula [18]:

$$sRPE = RPE \times Duration$$

where RPE = Borg's category-ratio scale (1–10) and Duration = time in minutes.

Statistical analysis

A priori power analysis (α = .05 [two-tailed], β = .80, f = .25) indicated that a minimum of 159 samples was necessary (G*Power, Version 3.1.9.6, University of Duffle Dorf, Duffle Dorf, Germany). This minimum was met in the current analysis, with 162 samples included in the analysis (Pro = 56, Collegiate = 53, Scrimmage = 53). A repeated measures analysis of variance (ANOVA) was used to assess the external and internal loads across games played against different opponents (Pro, Collegiate, and Scrimmage). Bonferroni post-hoc tests were used to determine the source of significant differences, where applicable. The effect sizes for all pairwise comparisons were determined using Cohen's d with 95% confidence intervals. Cohen's d was interpreted as: trivial = 0–0.19, small = 0.2–0.59, moderate = 0.6–1.19, large = 1.2–1.99, very large = 2.0–3.99, and nearly perfect ≥ 4.0 [29]. The significance level for all tests was set at $p < .05$. All statistical analyses were conducted using IBM SPSS Statistics version 26 (IBM Corp., Armonk, NY, USA) software.

RESULTS

The number of samples included in the analysis was 164 (Pro: 56, Collegiate: 53, and Scrimmage: 53). The number of games monitored per player was 9.11 ± 3.98 (Pro: 3.22 ± 1.90, Collegiate: 2.89 ± 1.82, and Scrimmage: 3.00 ± 1.15). The external and internal outcome measures for performance against the Pro, Collegiate, and Scrimmage are presented in Table 1. The effect sizes (d) for all pairwise comparisons between conditions are listed in Table 2. A repeated measures ANOVA revealed significant differences between

TABLE 1. External and internal measures (mean ± SD) during a game against a professional team (vs. Pro), same competition level team (vs. Collegiate), and during an intra-team practice game (Scrimmage) in men's college basketball players (N = 18)

Outcome Measure	Condition		
	vs. Pro (B-league)	vs. Collegiate	Scrimmage
Observations (N)	56	53	53
Duration (minutes)	28.2 ± 11.1	30.5 ± 11.8	17.3 ± 4.7*^
External measures			
AAL (AU per min)	12.5 ± 1.3	11.8 ± 1.5*	10.4 ± 1.1*^
EED (m per min)	94.7 ± 9.2	91.2 ± 9.9	83.1 ± 8.5*^
Sprints (cases per min)	1.64 ± 0.36	1.44 ± 0.31*	1.27 ± 0.26*^
Jumps (cases per min)	0.68 ± 0.28	0.67 ± 0.26	0.53 ± 0.20
Exertions (cases per min)	4.93 ± 0.60	4.51 ± 0.57*	3.88 ± 0.53*^
Internal measures			
sRPE (AU)	142.7 ± 71.8	177.7 ± 81.7*	98.6 ± 44.5*^
RPE (AU)	4.98 ± 1.29	5.72 ± 1.07*	5.50 ± 1.53^

AAL = accumulated acceleration load; EED = estimated equivalent distance; sRPE = session rating of perceived exertion; RPE = rating of perceived exertion; AU = arbitrary units; *Significantly ($p < .05$) different from Professional level. ^ Significantly ($p < .05$) different from College level.

TABLE 2. Effect size (Cohen's d with 95% confidence intervals) for pairwise comparisons between matches against the Pro, Collegiate, and Scrimmages for external and internal measures in men's college basketball players (N = 18).

Outcome Measure	Pro vs. Collegiate				Pro vs. Scrimmage				Collegiate vs. Scrimmage			
	Cohen's *d*		descriptor	*p* value	Cohen's *d*		descriptor	*p* value	Cohen's *d*		descriptor	*p* value
Duration (minutes)	0.20	(-0.18, 0.58)	*small*	0.311	-1.28	(-1.69, -0.87)	*large*	< 0.001†	-1.47	(-1.90, -1.04)	*large*	< 0.001†
External measures												
AAL (AU per min)	-0.50	(-0.88, -0.12)	*small*	0.002†	-1.74	(-2.19, -1.31)	*large*	< 0.001†	-1.06	(-1.47, -0.66)	*moderate*	< 0.001†
EED (m per min)	-0.37	(-0.74, 0.01)	*small*	0.054	-1.31	(-1.72, -0.90)	*large*	< 0.001†	-0.88	(-1.28, -0.48)	*moderate*	< 0.001†
Sprints (cases per min)	-0.60	(-0.98, -0.21)	*small*	0.001†	-1.18	(-1.59, -0.77)	*moderate*	< 0.001†	-0.59	(-0.98, -0.21)	*small*	< 0.001†
Jumps (cases per min)	-0.04	(-0.42, 0.33)	*trivial*	1.000	-0.75	(-1.14, -0.36)	*moderate*	0.142	-0.60	(-0.99, -0.21)	*moderate*	0.243
Exertions (cases per min)	-0.72	(-1.11, -0.33)	*moderate*	0.021†	-1.85	(-2.30, -1.41)	*large*	< 0.001†	-1.14	(-1.56, -0.73)	*moderate*	< 0.001†
Internal measures												
sRPE (AU)	0.46	(0.07, 0.84)	*small*	0.005†	-0.74	(-1.13, -0.35)	*moderate*	< 0.001†	-1.20	(-1.62, -0.79)	*laege*	< 0.001†
RPE (AU)	0.58	(0.20, 0.96)	*small*	0.003†	0.35	(-0.03, 0.73)	*small*	1.000	-0.15	(-0.53, 0.23)	*trivial*	0.032†

AAL = accumulated acceleration load; EED = estimated equivalent distance; sRPE = session rating of perceived exertion; RPE = rating of perceived exertion; AU = arbitrary units. †Significant ($p < .05$) difference.

the groups for AAL, $F_{(2, 142)} = 65.01$, $p < .001$; EED, $F_{(2, 142)} = 43.63$, $p < .001$; sprints, $F_{(2, 142)} = 31.57$, $p < .001$; and exertions, $F_{(2, 120)} = 39.42$, $p < .001$). Post-hoc testing showed that playing against the Pro produced significantly higher AALs than playing against the Collegiate and Scrimmage (d = -0.50, small, $p = .002$; d = -1.74, large, $p < .001$). EED was significantly higher in games against the Pro (d = -1.31, large, $p < .001$) and Collegiate (d = -0.88, moderate, $p < .001$) compared with that in games against the Scrimmage. The number of sprint events was significantly higher in games against the Pro than in games against the Collegiate (d = -0.60, small, $p < .001$) and Scrimmage (d = -1.18, moderate, $p < .001$). Significantly more exertion events occurred during games against the Pro compared with those during games against the Collegiate (d = -0.72, moderate, $p = .021$) and Scrimmage (d = -1.85, large, $p < .001$).

A repeated measures ANOVA revealed significant differences between groups for sRPE, $F_{(2, 141)} = 15.74$, $p < .001$ and RPE, $F_{(2, 141)} = 5.23$, $p = .006$. Post-hoc testing showed that after games against the Pro, significantly lower sRPE and RPE values were reported than after games against the Collegiate (d = 0.46, small, $p = .005$; d = 0.58, small, $p = .003$), whereas games against the Pro produced a significantly higher sRPE than the games against the Scrimmage (d = -0.74, moderate, $p < .001$).

DISCUSSION

This study is the first to identify the differences in physical match demand due to the influence of the opponents in basketball. We found that, in general, as the competition level of the opponents increased, the relative external demands of the participants also increased. Contrarily, the internal response measured by sRPE for the study participants was lower after games against the Pro than after games against the Collegiate.

Game sports are unique events that involve dynamic interactions between players. As a result, the observed behaviour of an athlete or team is influenced by the situation or opponent [30]. In this study, no difference in EED was observed in participants during games against the Pro and Collegiate. Previous studies have reported that elite basketball athletes cover, on average, less distance than sub-elite and youth players [31]. In addition, high-level basketball players have explosive capacities such as sprinting and jumping [32], and this difference in neuromuscular capacity was considered to be reflected in the AAL. AAL is a cumulative measure of impact load in the triaxial direction, and this study revealed that participants had a higher impact load during matches against the Pro compared to during those against the Collegiate and Scrimmage. The differences in AAL measured in professional and collegiate matches may reflect differences other than running, i.e., differences in explosive high-intensity movements.

Petway et al. [31] reported that top-level basketball players spend more time performing high-intensity movements than do sub-elite players. The results of this study showed that the number of sprints and exertions of high-intensity movements increased with the competition level of the opponents. A previous study has shown that the external and internal game workloads vary depending on the contextual factors [20]. For example, losses may be more physically demanding than wins during basketball gameplay [20]. In this study, the participants lost all the matches against the Pro. Losing teams encounter an increased work rate due to a faster game pace when attempting to maximize the opportunities to score points and reduce the score-line [20]. Therefore, the higher AAL values measured during games against the Pro in this study indicate an increase in high-intensity movements performed, especially sprints and exertions.

On the other hand, in the games against the Pro, RPE values were significantly lower, and therefore, sRPE values were also lower, even though there was no difference in playing time. The low RPE value, despite the high level of competition of the opponents, may have been due to psychological factors. According to previous studies that measured sRPE during competition, perceptual measures might be influenced by psychological factors such as stress and anxiety associated with competition [33]. In turn, this might influence how the players perceive exertion, regardless of the physiological stress they are undergoing. Previous studies have shown that sRPE is higher in balanced games (with an end-margin of ≤ 8 points) than in unbalanced games (with an end-margin > 8 points) [20]. In this study, the Collegiate teams were from the same conference as the participants, and although it was a friendly match, there were many close games. As a result, the high psychological stress may have resulted in higher RPE. On the other hand, in the matches against the Pro, although the external load was recorded as high, there were fewer close games, and as a result, there was probably less psychological stress. In addition, in the matches against the Pro, the internal load was lower because the players felt positive towards the challenges according to their introspection reports. According to a previous study, subjective measures may also be more sensitive and consistent than objective measures [34]. Therefore, it is important to use an integrated approach to training loads, with a combination of internal and external training loads, which provides greater insight into training stress.

The results of games played against the Scrimmage showed that each of the variables of external load measured by the accelerometers was lower than that recorded for games against the Pro and Collegiate. This means that the external load was lower during training than during competitive matches, a finding that agrees with those of previous studies [35, 36]. To adequately prepare athletes for games, it is important to match the load (quantity and intensity) of the games through training at specific times during the preparation and competition phases. Furthermore, training should include preparation for worst-case scenarios in a match [37]. The external load intensities of basketball training drills substantially vary depending on the load indicator chosen, the training content, and task and individual constraints [38]. This study's findings regarding the external demands that arise from playing against the Pro and Collegiate could help to guide scrimmage- and game-based drills. For example, the coaching staff can serve as a reference for the load criteria for game-based drills that assume games against higher-ranked opponents cannot be played frequently.

This study has several limitations. First, several elite leagues do not allow technology to be worn during competitions [31]. As a result, the games against the Pro and Collegiate in this study were unofficial. Our findings are relevant to friendly matches and cannot be generalized to official matches. Second, considering the application of the results of this study to training, there may be differences in playing position, which were not considered in this study. In future studies, the number of participants should be increased to clarify the position characteristics. Third, there is a lack of clarification and consensus across different tracking systems and manufacturers on how signals are filtered, calculations performed, or the suitable thresholds for basketball [7]. In this study, the same participants were fitted with the same accelerometers, allowing comparisons between performances against different opponents to be made. Future research is needed to synchronize acceleration data with videos of various event stamps, such as sprints, jumps, and exertion, to identify actual movements.

Practical Application

Our findings provide important practical insights for basketball coaching staff, sports scientists, and players that can be used in various ways. First, AAL might be an optimal approach for quantifying basketball-specific high-intensity movements that cannot be measured by EED. It is inferred that the differences in AAL by competition level reflect differences in movements other than running, that is, explosive high-intensity movements. Second, an integrated approach to training load is important, which provides greater insight into training stress. In the present study, internal response (sRPE) was low despite the higher external workload in the games against the Pro. Thus, external and internal game loads should be monitored with the understanding that they may vary with each other depending on the contextual factors.

CONCLUSIONS

This study examined the differences in physical game demands due to the influence of opponents in basketball. The results showed that as the competitive level of the opponents increased, the relative external load of the participants also increased. AAL is a useful indicator of the external load that reflects the competition level of opponents. In contrast, internal responses as measured by sRPE were lower after games against the Pro than after games with the Collegiate. In summary, it is important to use a combination of internal and external loads and monitor them with the understanding that they may vary with each other depending on the contextual factors. This allows for a better understanding of the stresses of training.

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Conflict of interest declaration

The authors declare no conflict of interest.

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'Setting the Benchmark' Part 1: The Contextualised Physical Demands of Positional Roles in the FIFA World Cup Qatar 2022

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ABSTRACT: This study aimed to contextualise and benchmark the positional role demands during the FIFA World Cup Qatar 2022. With FIFA's official approval, all sixty-four games were analysed during the competition (n=722) using a multi-camera computerised tracking system. During a typical FIFA World Cup Qatar 2022 match, defensive and central midfielders covered 8-19% more total distance than other positional roles (P<0.01; Effect Size [ES]: 0.8-2.5). The distances covered at higher intensities (≥20 and ≥25 $km \cdot h^{-1}$) were 16–92% and 36–138% higher for wide midfielders and wide forwards compared to central defenders, defensive and central midfielders as well as centre forwards (*P*<0.01; ES: 0.7–2.2 and ES: 0.6–1.4). Defensive and central midfielders covered a greater proportion of their distance at higher intensities (≥20 and ≥25 $km \cdot h^{-1}$) out-of-possession (71–83%; *P*<0.01; ES: 1.4–3.0), whilst attacking midfielders, wide and centre forwards more in-possession (55–68%; *P*<0.01; ES: 1.6–3.3). Nine out of the top ten sprint speeds attained at the tournament were from wide positional roles (35.3–35.7 $km \cdot h^{-1}$). All positional roles demonstrated a second half reduction in total distance covered compared to the first half (*P*<0.01; ES: 0.8–1.3). A decline between halves for the distances covered at higher intensities (≥20 and ≥25 $km \cdot h^{-1}$) were more evident in attacking midfielders, wide defenders and midfielders than for other positional roles (*P*<0.01; ES: 0.3–0.7). Defensive midfielders and centre forwards were found to have the highest coefficient of variation (CV: 30.9–35.9% and 67.7–67.8%) for the distances covered at higher intensities (≥20 and ≥25 $km \cdot h^{-1}$) compared to other positional roles. The current findings provide valuable contextual information about the contemporary positional demands of international football. This could be useful in the development and prescription of specific training regimes for national teams.

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INTRODUCTION

Match analysis research can be effectively used to benchmark the demands of match-play, whilst also providing a conceptual framework for the development of specific performance tests and training regimes [1]. Authors have documented the match demands of the leading domestic leagues around the world [2–4], in addition to some European competitions [5]. However, there is limited information on the match demands from contemporary international football tournaments such as the FIFA World Cup. Studies conducted to date have typically used freely available data that had limited metric and positional granularity and were performed on the outdated FIFA World Cup Brazil 2014 [6]. Therefore, a study that was officially approved by FIFA and thus included all metrics and player observations from the FIFA World Cup Qatar 2022 could provide a more accurate depiction of the current demands of international match-play. Since there is extensive variability in the match demands both between and within players according to match and positional role [7–8], it is imperative to benchmark such recent competitions.

A consistent finding in the football science literature is that the match demands of players are highly dependent upon their unique positional role in the team [3, 9]. Most studies use broad categories to define outfield roles such as defenders, midfielders and forwards or even distinct sub-categories within them (e.g., midfielders can be split into central and wide midfielders). Recent findings demonstrated that the match demands of specialised outfield roles in the English Premier League resulted in highly distinguishable movement characteristics compared to more broad categories [10]. Although no research to date has partitioned international players into highly specialised outfield positions in tournaments such as the FIFA World Cup Qatar 2022. This would be highly relevant to the football community especially given the up-to-date nature of this data and its comprehensive positional breakdown. To enable trends across specialised positional roles to be translated more effectively to scientists and practitioners, the author has attempted to layer context throughout the analysis to add a narrative to the numbers [11]. This contextualisation is unlike any published article in this field, as it will highlight with the permission of FIFA distinct individualised examples of positional profiles at the upper and lower extremes to add more context to the trends.

Some researchers have suggested that distances covered at the higher intensities in matches are valid measures of physical performance in football [12], and are a distinguishing characteristic between different standards of players [13–14]. Thus, high-intensity metrics seem important to consider as they have evolved significantly over the last decade [2, 3, 15], and are involved in game-changing moments such as goalscoring opportunities [16]. Research has consistently found that high-intensity metrics were reduced in the second versus the first half of games [1]. However, limited information has been published on half-by-half deficits in recent international tournaments. This is particularly relevant as recent rule changes regarding added time have resulted in much longer game durations in the FIFA World Cup Qatar 2022. Thus, a detailed examination of high-intensity metrics across halves would provide valuable information regarding the distribution of positional work rates in a modified game format (e.g., FIFA accounting for all stoppages). Therefore, this study aimed to contextualise and benchmark the positional role demands during the FIFA World Cup Qatar 2022.

MATERIALS AND METHODS

Sample

With FIFA's official approval, all 64 games during the FIFA World Cup Qatar 2022 were collected and analysed. Analyses involved the examination of the match physical performances of individual players in various positional roles in the team. The data provider assigned eight different outfield roles to enable positional differences to be determined. Games were filtered so only players who completed the entire match were evaluated. Moreover, filters ensured that all match data were collected over the duration of a normal match or regular time plus added time, but no extra-time data were included. This allowed profiling of 722 player observations in various positional roles (219 central defenders [CD], 174 wide defenders [WD], 68 defensive midfielders [DM], 100 central midfielders [CM], 21 attacking midfielders [AM], 49 wide midfielders [WM], 48 wide forwards [WF], and 43 centre forwards [CF]). As this data are freely available [17], no ethical approval was required.

Match Analysis System

All FIFA World Cup Qatar 2022 games were analysed using a multi-camera computerised tracking system (TRACAB, Chyron Hego). All player movements were captured by high-definition cameras operating at 25 Hz. This systems validity has been quantified to verify the capture process and subsequent accuracy of the data [18]. After system calibration and various stringent quality control processes, the data captured were analysed using match analysis software. This produced a data set on each player's activity pattern during a match using specified speed zones.

Speed Zones

Players' activities were coded into the following:

- Zone 1 (0.0–6.9 km · h^{-1}),
- Zone 2 (≥7.0–14.9 km · h^{-1}),
- Zone 3 (≥15.0–19.9 km · h^{-1}),
- Zone 4 (≥20–24.9 km · h^{-1}),
- Zone 5 (≥25.0 km · h^{-1}).

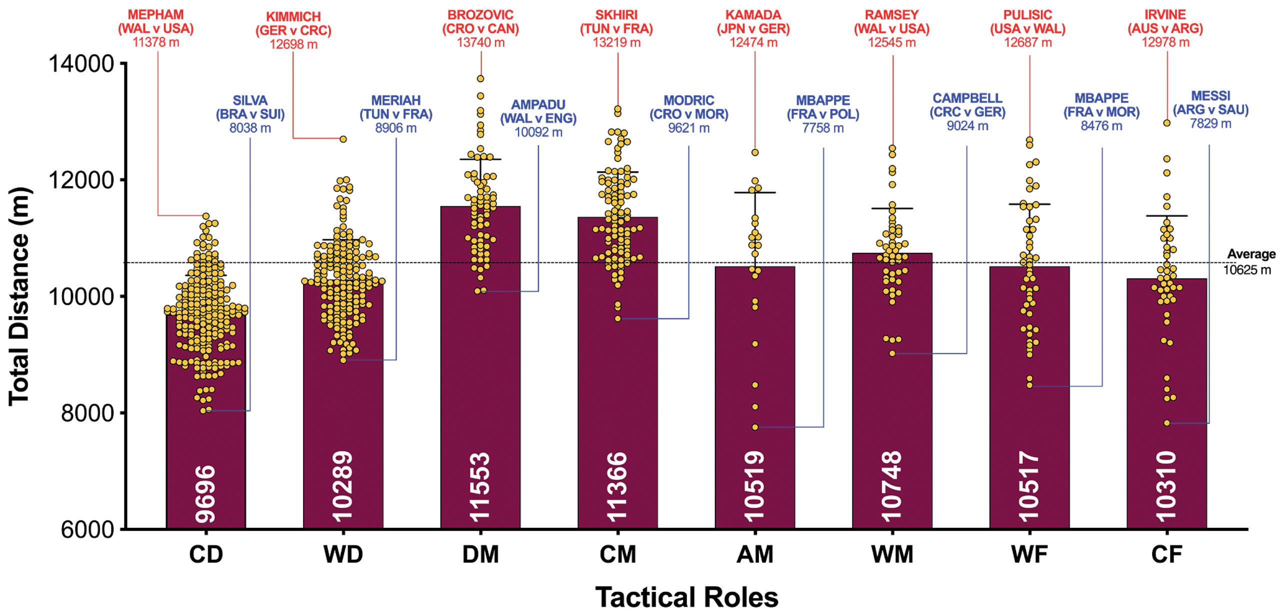

Fig. 1A. Total Distance and variation for each positional role in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). CD = central defender, WD = wide defender, DM = defensive midfielder, CM = central midfielder, AM = attacking midfielder, WM = wide midfielder, WF = wide forward, CF = centre forward. Red = max, Blue = min.

Total distance represented the sum of the distances covered above. High-intensity activity consisted of the aggregation of Zones 4 and 5 (≥20.0 km · h^{-1}), whilst sprinting exclusively included Zone 5 activity (≥25.0 km · h^{-1}). Similar classifications have been employed in elite football for over a decade [13]. Moreover, these speed demarcations were also employed at the 2018 FIFA World Cup Russia [19]. Maximum sprint speeds were also quantified across all positional roles.

Statistical Analyses

All statistical analyses were conducted using SPSS (SPSS Inc., Chicago, USA). Descriptive statistics were calculated on each variable and z-scores were used to verify normality. Differences across positional roles and halves were determined using factorial analysis of variance (ANOVA). In the event of a significant difference, the appropriate post-hoc tests were used to identify any localised effects. Statistical significance was set at $P < 0.05$. The coefficient of variation (CV) was calculated to determine the data spread across each metric. Effect sizes (ES) were computed to determine the meaningfulness of any differences and corrected for bias using Hedges formula. The ES magnitudes were classed as trivial (< 0.2), small (> 0.2–0.6), moderate (> 0.6–1.2) and large (> 1.2). Pearson's coefficients were used for correlation analyses and the magnitudes of the associations were regarded as trivial ($r \leq 0.1$), small ($r > 0.1$–0.3), moderate ($r > 0.3$–0.5), large ($r > 0.5$–0.7), very large ($r > 0.7$–0.9), and nearly perfect ($r > 0.9$). Values are presented as means and standard deviations unless otherwise stated.

RESULTS

Benchmarking & Variation

The data presented in Figures 1A-D benchmarked each positional role from a physical perspective. Figure 1A highlights that CM and DM covered 8–19% more total distance than other positional roles ($P < 0.01$; ES: 0.8–2.5). Figure 1A also demonstrates that attacking positional roles such as AM, WF and CF have the highest coefficient of variation in the total distance covered (CV: 10.2–12.0%) compared to more defensive positional roles such as CD, WD, DM and CM (CV: 6.7–6.9%). Figures 1B and 1C illustrate the distances covered at higher intensities (≥20 and ≥25 km · h^{-1}, respectively) were 16–92% and 36–138% higher in wide positional roles such as WM and WF compared to central positional roles such as CD, DM, CM and CF ($P < 0.01$; ES: 0.7–2.2 and 0.6–1.4). Figures 1B and 1C illustrates that DM and CF have the highest coefficient of variation (CV: 30.9–35.9% and 67.7–67.8%) for the distances covered at higher intensities (≥20 and ≥25 km · h^{-1}, respectively) compared to WM, AM and WF (CV: 23.1–26.2% and 43.2–50.7%). Top sprint speeds were faster during games for WD, AM, WM, WF and CF (32.1–32.3 km · h^{-1}), compared to CD, DM and CM (30.2–30.8 km · h^{-1}; $P < 0.01$; ES: 0.8–1.1). Figure 1D demonstrates that the top ten sprint speeds attained at the tournament were primarily from wide positions with WF (40%), WD (30%) and WM (20%), accounting for 90% of these efforts. The coefficient of variation of these top ten sprint efforts varied across wide roles (WF = 3.5–6.0%, WD = 2.8–5.8%, WM = 1.0–2.4%).

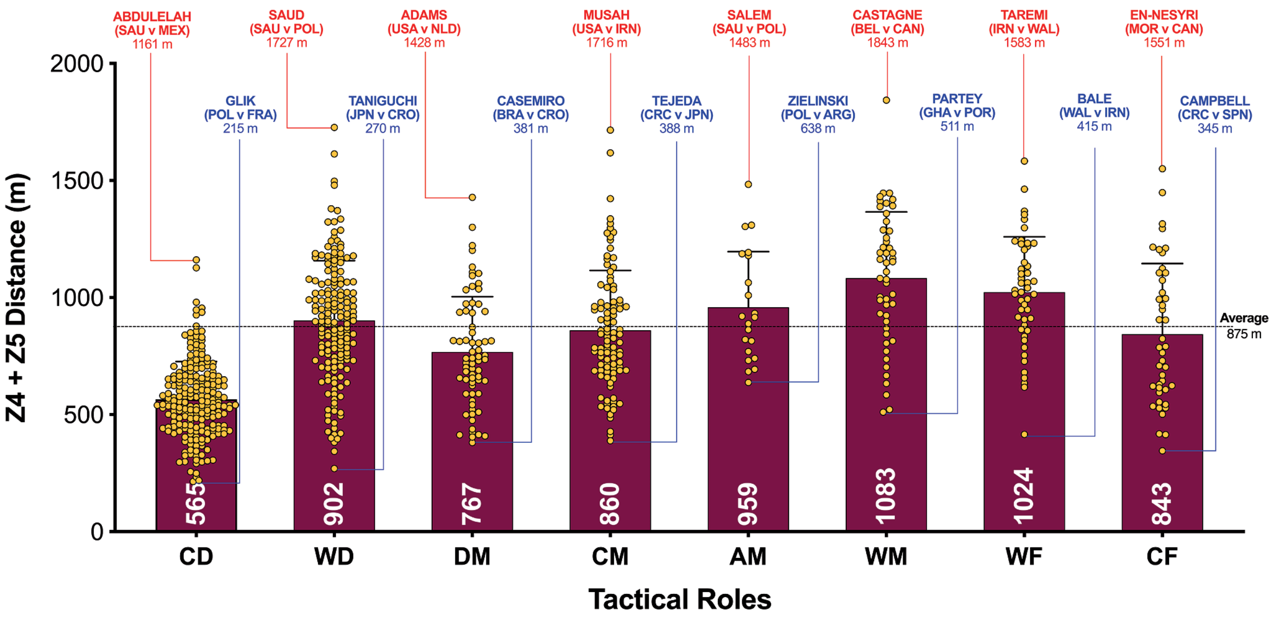

Fig. 1B. High Intensity Distance (≥20 km · h^{-1}; Zone 4 and 5; Z4+Z5) and variation for each positional role in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). CD = central defender, WD = wide defender, DM = defensive midfielder, CM = central midfielder, AM = attacking midfielder, WM = wide midfielder, WF = wide forward, CF = centre forward. Red = max, Blue = min.

Quadrant Plots

The data presented in Figures 2A-C correlates two distinct dimensions of physical performance using quadrant plots to compare the specialist defensive, midfield and attacking positional roles against one another. Figure 2A demonstrates a moderate association between a CD total and high-intensity game distances (r = 0.46; P < 0.01) and this positional role primarily occupied the lower-left quadrant (lower-left [LLQ] = 86%, lower-right [LRQ] = 10%, upper-left [ULQ] = 3% and upper-right quadrant [URQ] = 1%). A large association was observed between a WD total and high-intensity game distances (r = 0.51; P < 0.01), with most residing in the lower- or upper-left quadrants (LLQ = 40%, LRQ = 9%, ULQ = 30% and URQ = 21%). Large correlation coefficients were also found between a DM total and high-intensity game distances (r = 0.51; P < 0.01). DM were primarily split between the upper- and lower-right quadrants (LLQ = 9%, LRQ = 60%, ULQ = 0% and URQ = 31%).

Figure 2B visualises the specialist midfield positional roles, with CM and WM both demonstrating moderate associations between the total and high-intensity game distances (r = 0.31 and 0.45; P < 0.01). Whilst CM mainly occupied the upper- and lower-right quadrants (LLQ = 17%, LRQ = 43%, ULQ = 0% and URQ = 40%), WM were primarily located in the upper-right quadrant (LLQ = 15%, LRQ = 10%, ULQ = 20% and URQ = 55%). However, a small

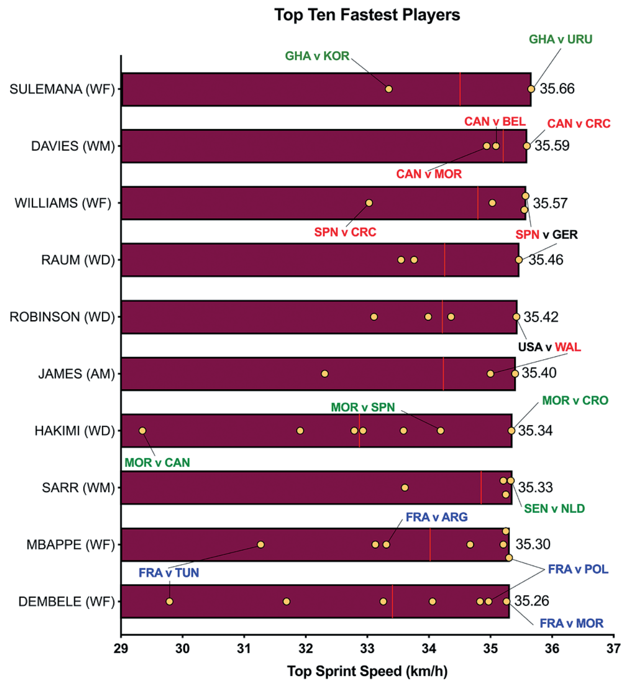

Fig. 1D. Ten Top Speeds and match-to-match variation in the Qatar FIFA World Cup 2022 (yellow dots signify each game and red line is the average). Data are not normalized for 90+ min and each players positional role is indicated in parentheses. WD = wide defender, AM = attacking midfielder, WM = wide midfielder, WF = wide forward. Text colour aligns with each position's national colours.

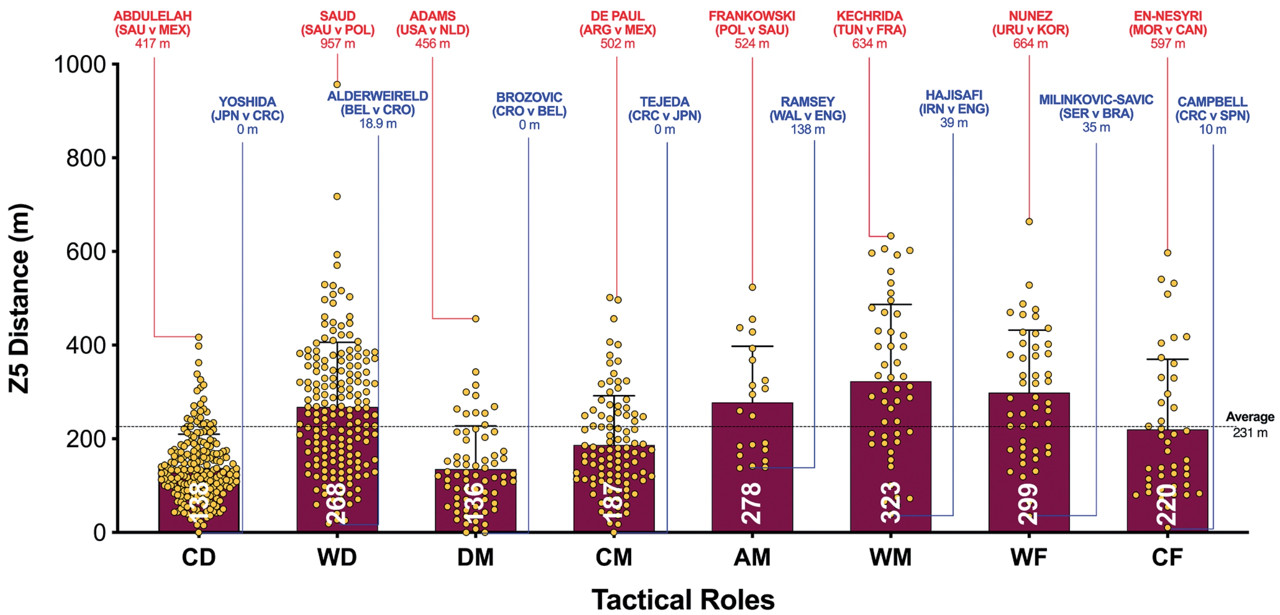

Fig. 1C. Sprint Distance (≥25 km·h^{-1}; Zone 5; Z5) and positional variation in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). CD = central defender, WD = wide defender, DM = defensive midfielder, CM = central midfielder, AM = attacking midfielder, WM = wide midfielder, WF = wide forward, CF = centre forward. Red = max, Blue = min.

association was observed between an AM total and high-intensity game distances ($r = 0.23$; $P > 0.05$), and it was clear that they did not occupy any specific quadrant (LLQ = 19%, LRQ = 24%, ULQ = 24% and URQ = 33%).

Figure 2C highlights the most specialised offensive roles, with WF demonstrating a moderate association ($r = 0.32$; $P < 0.05$), whilst CF illustrated a large strength correlation between the total and high-intensity game distances ($r = 0.58$; $P < 0.01$). The WF were predominantly spread across the upper-left and right quadrants (LLQ = 23%, LRQ = 4%, ULQ = 31% and URQ = 42%), whilst CF were principally located in the lower-left quadrant (LLQ = 53%, LRQ = 5%, ULQ = 14% and URQ = 28%). Both offensive positional roles rarely entered the lower-right quadrant.

In-Possession & Out-of-Possession

Those players with a vital defensive duty in the team such as CD, WD, DM, CM and WM covered a greater proportion of their overall distance out-of-possession compared to more offensive positions such as WF (48–49% vs 44%; $P < 0.01$; ES: 0.6–0.8). In contrast, WF covered a higher proportion of their overall distance covered in-possession compared to CD, WD, AM and WM (48% vs 43%; $P < 0.01$; ES: 0.7–0.8). Defensive positional roles such as CD and DM cover a greater proportion of their distance at higher intensities (≥20 and ≥25 $km \cdot h^{-1}$) out-of-possession than offensive positional roles such as AM, WF and CF (71–77% vs 40–44%; $P < 0.01$; ES: 1.7–3.0 and 73–83% vs 31–37%; $P < 0.01$; ES: 1.4–3.0). In contrast, AM, WF and CF covered a higher proportion of their distance at higher intensities (≥20 and ≥25 $km \cdot h^{-1}$) in-possession compared to CD and DM (55–58% vs 21–28%; $P < 0.01$; ES: 1.8–3.3 and 62–68% vs 15–23%; $P < 0.01$; ES: 1.6–3.1).

Half-by-Half Differences

Figures 3A-C highlight the half-by-half differences for each of the positional roles on a per min basis. Figure 3A illustrates that all positions demonstrated a second half reduction in total distance covered compared to the first half ($P < 0.01$; ES: 0.8–1.3). Figure 3B demonstrates that a decline between halves for high-intensity distance (≥20 $km \cdot h^{-1}$) was evident for WD, DM, CM, AM, WM and CF ($P < 0.01$; ES: 0.3–0.7) but not for CD and WF ($P > 0.05$; ES: 0.1–0.2). Figure 3C indicates that the decline between halves for sprinting distance (≥25 $km \cdot h^{-1}$) was evident for WD, AM and WM ($P < 0.05$; ES: 0.3–0.4) but not for CD, DM, CM, WF and CF ($P > 0.05$; ES: 0.0–0.2).

DISCUSSION

This study was the first to contextualise and physically benchmark eight specialised positional roles during the FIFA World Cup Qatar 2022. Thus, this section will attempt to integrate the present findings with a contextual narrative to aid interpretation. Data revealed that central and defensive midfielders covered the greatest total distance

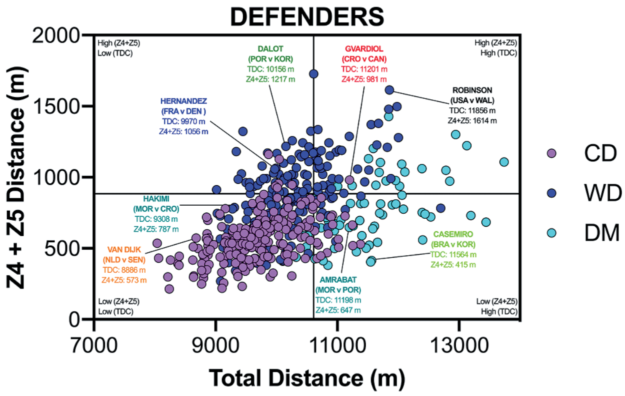

Fig. 2A. Defenders Total versus High Intensity Distance (≥20 $km \cdot h^{-1}$; Zone 4 and 5; Z4+Z5) in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Crosshairs were based on the average for all tactical roles. CD = central defender, WD = wide defender, DM = defensive midfielder. Text colour aligns with each position's national colours.

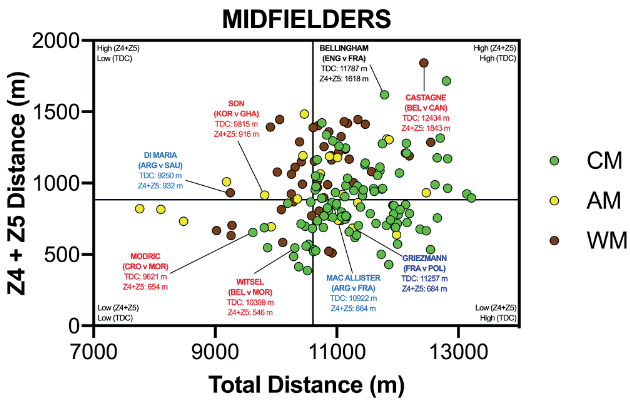

Fig. 2B. Midfielders Total versus High Intensity Distance (≥20 $km \cdot h^{-1}$; Zone 4 and 5; Z4+Z5) in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Crosshairs were based on the average for all tactical roles. CM = central midfielder, AM = attacking midfielder, WM = wide midfielder. Text colour aligns with each position's national colours.

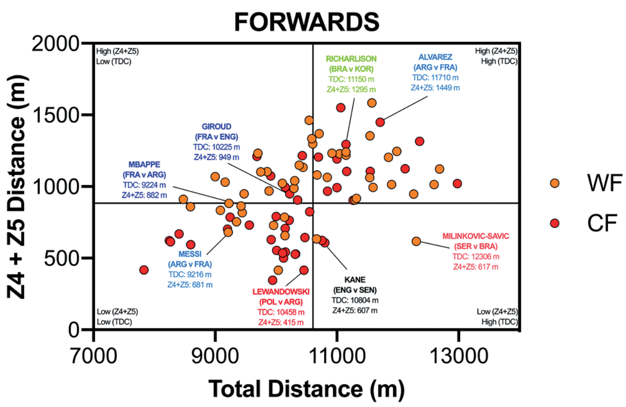

Fig. 2C. Forwards Total versus High Intensity Distance (≥20 $km \cdot h^{-1}$; Zone 4 and 5; Z4+Z5) in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Crosshairs were based on the average for all tactical roles. WF = wide forward, CF = centre forward. Text colour aligns with each position's national colours.

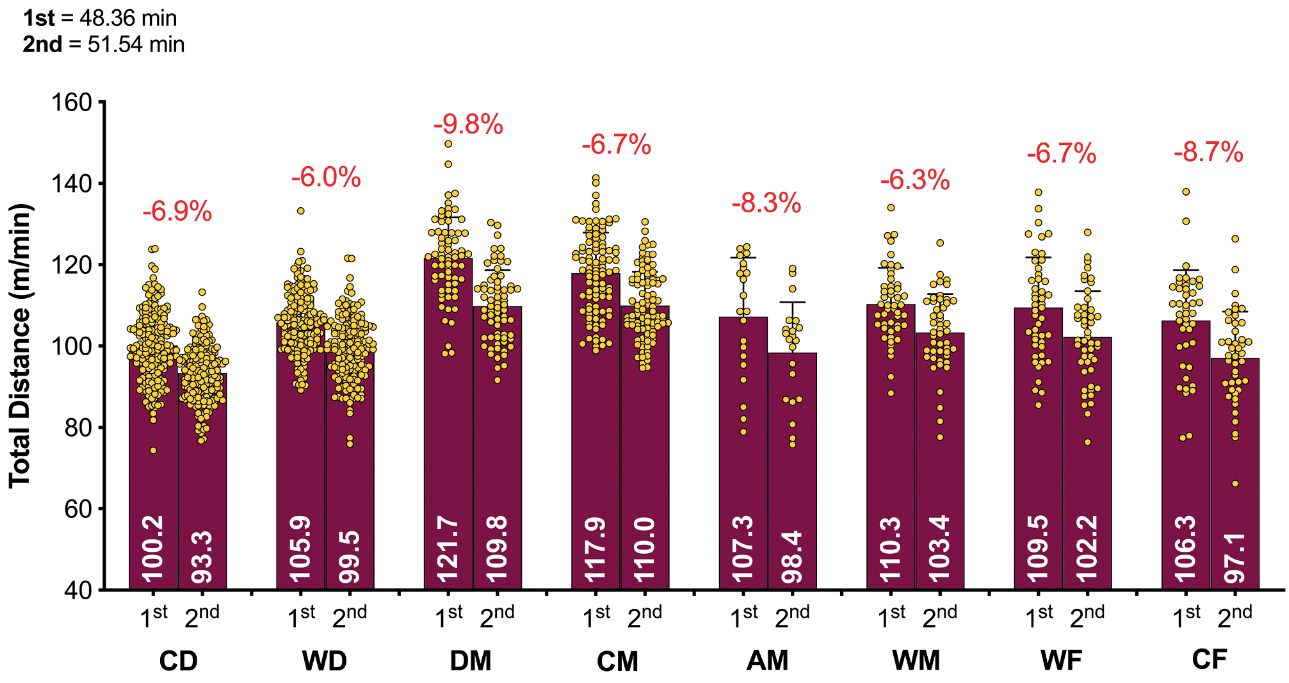

Fig. 3A. Positional half by half Total Distance in the Qatar FIFA World Cup 2022. Data normalized per min and only players completing 90+ min (excludes extra time). CD = central defender, WD = wide defender, DM = defensive midfielder, CM = central midfielder, AM = attacking midfielder, WM = wide midfielder, WF = wide forward, CF = centre forward. Red = a second half decline, Blue = no second half decline.

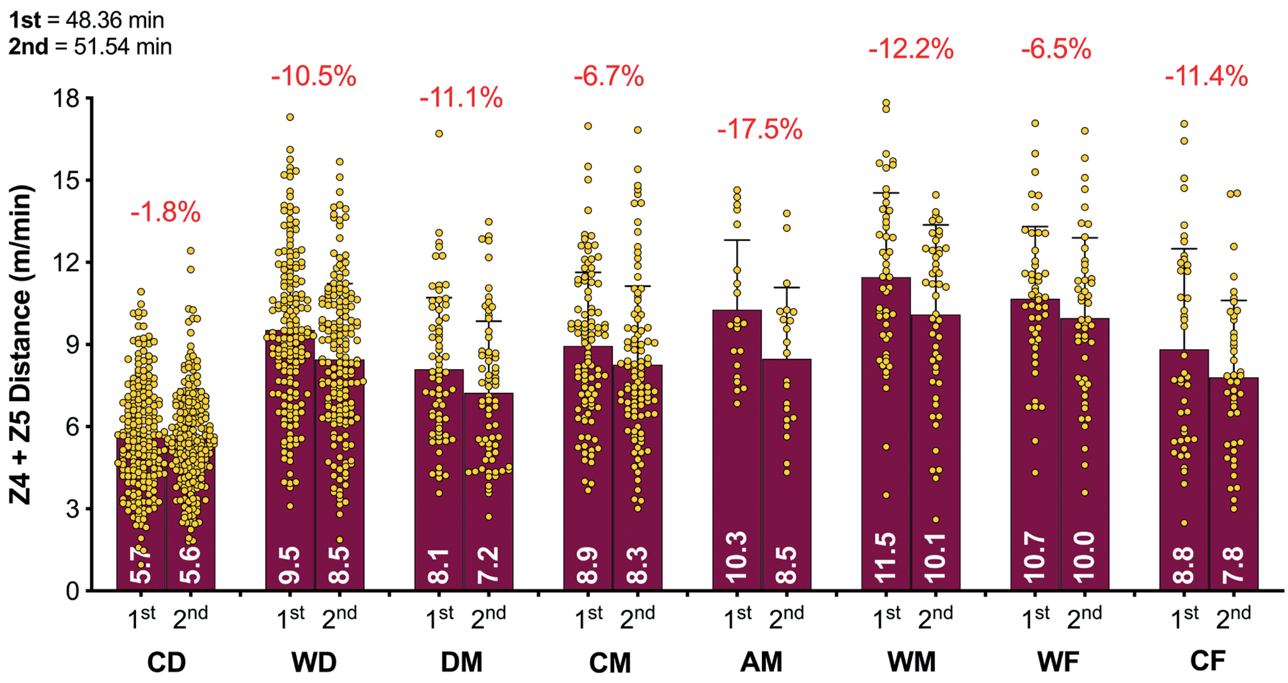

Fig. 3B. Positional half by half High Intensity Distance (≥20 km·h^{-1}; Zone 4 and 5; Z4+Z5) in the Qatar FIFA World Cup 2022. Data normalized per min and only players completing 90+ min (excludes extra time). CD = central defender, WD = wide defender, DM = defensive midfielder, CM = central midfielder, AM = attacking midfielder, WM = wide midfielder, WF = wide forward, CF = centre forward. Red = a second half decline, Blue or Black = no second half decline.

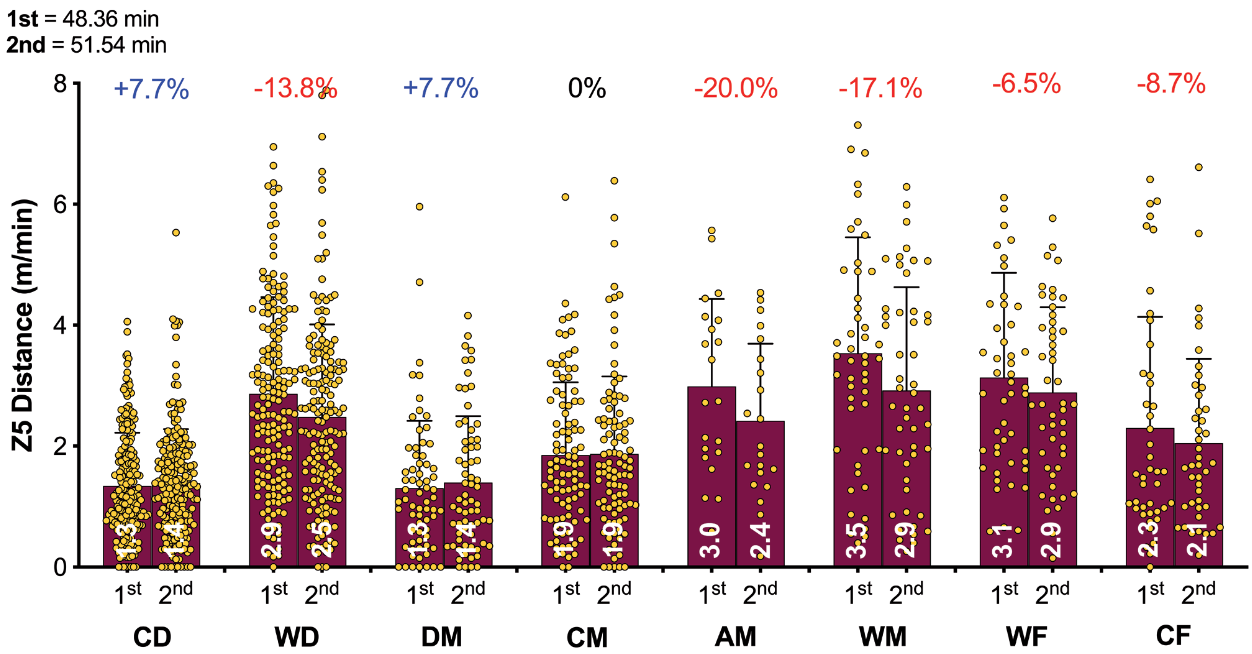

Fig. 3C. Positional half by half Sprint Distance (≥25 km · h^{-1}; Zone 5; Z5) in the Qatar FIFA World Cup 2022. Data normalized per min and only players completing 90+ min (excludes extra time). CD = central defender, WD = wide defender, DM = defensive midfielder, CM = central midfielder, AM = attacking midfielder, WM = wide midfielder, WF = wide forward, CF = centre forward. Red = a second half decline, Blue or Black = no second half decline.

and central defenders covered the lowest in the FIFA World Cup Qatar 2022. As similar findings have been documented in elite domestic football [13, 20], this current finding verifies that this trend also occurs at the highest standard of international football. Midfielders are renowned for their all-round industrious and versatile nature [2], and as such they covered the most ground during World Cup games. To further contextualise this trend, Croatia's Brozović and Tunisia's Skhiri covered > 13 km during World Cup games and thus set the upper benchmark for contemporary international midfielders. Midfielders have been found to be highly active during all phases of play [10]. Thus, unsurprisingly the present study found they covered the greatest in- and out-of-possession distances of the tournament. In contrast, central defenders are primarily active during out-of-possession phases [21], hence the lower total distance covered. However, due to the ever-changing demands placed on central defenders, they increasingly receive the ball from their goalkeeper to play out from the back or from teammates to (re)start build-up play [2, 10, 22]. To place this finding into a football context, it is imperative the reader is aware that the opposition's quality and work rate can have a direct bearing on a central defenders' activity profile [23]. For instance, Wales central defender Mepham covered > 11 km during the USA match, which was the upper benchmark for this positional role in the whole tournament. This can be attributed to the USA's extreme work rate alongside their frequent progressions and final-third entries during this game (e.g., highest ranked team for overall and high-intensity distance covered, see Part 2 for more detail). In contrast, Brazilian central defender Silva covered the lowest total distance of 8 km for this positional role against Switzerland. Despite similar work-rate profiles between teams, this may have been due to Brazil's attacking dominance throughout the match and the lack of threat from Switzerland, resulting in this sedate work-rate profile for Silva.

A focal point of researchers is usually the distances covered at higher intensities (≥20 km · h^{-1}), due to its instrumental role in game-changing moments [16]. In the present study, wide positional roles, such as wide midfielders and forwards, clearly covered more distance at the higher intensities compared to players in central positional roles, such as central defenders and midfielders. This falls in line with a plethora of studies using elite domestic populations [2, 24], but scant evidence exists on international samples. In the present study, both wide positional roles attained an average high-intensity distance (≥20 km · h^{-1}) of around 1.0–1.1 km. However, at the upper-level Belgium's Castagne and Iran's Taremi covered around 1.6–1.8 km, highlighting how demanding these wide roles are in the modern game. Some could attribute this finding to superior physical characteristics for wide versus central players [25], but it could simply be related to the extra space afforded to wide players along the flanks that enabled them to accelerate up to higher speeds when tactically required [11]. Wide players may also have been more active as teams utilised the flanks heavily in Qatar 2022 vs Russia 2018, as evidenced by a much greater number of goals from crosses (45 vs 25 goals). In contrast, central defenders and midfielders operate in pitch regions that are highly dense with players, which may limit their ability to accelerate into space at higher speeds when tactically required [2, 10]. This may have resulted in central positional roles covering much lower high-intensity distances during games of between 0.5–0.8 km. Data from the present study supports this assertion as the top ten fastest sprints in the FIFA World Cup Qatar 2022 were primarily by players in wide positional roles and they attained speeds > 35 $km \cdot h^{-1}$.

Translating match demands into positional drills is of the utmost importance to practitioners [26]. Precisely an overload stimulus that taxes the relevant physical attributes to enable players to fulfil their positional duties across the 90 min (volume) and during intensified periods (intensity). Thus, the current data were viewed from a unique perspective by correlating these two distinct dimensions of physical performance using quadrant plots. This may allow practitioners to determine which positional roles were more volume-based and which were more intensity-based by plotting the total distance against the distances covered at higher intensities (≥20 $km \cdot h^{-1}$). Unsurprisingly, central defenders and centre forwards primarily occupied the lower-left quadrant (53–85%), thus they generally exhibited low volume and intensity characteristics during games. Centre forwards and central defenders covered > 70% of their high-intensity distance in- and out-of-possession, respectively. Accordingly, the work rate profiles of these two positional adversaries are inextricably connected [27]. Interdependency is exhibited as centre forwards run into offensive areas to attack space or to run with the ball, whilst central defenders react through various runs to defensively press, cover or track back [9, 10–11]. Although one could extrapolate from such trends, the degree of physical preparation needed for these two roles, caution is still needed given the large coefficient of variation that exist in their physical profiles. This is especially evident for centre forwards, as 28% of the sample also resided in the upper-right quadrant (high volume and intensity), illustrating the greatest coefficient of variation across any positional role. Given such data spread, conditioning practices should always align with the age and capabilities of the players in these roles, in addition to the playing style(s) adopted by each nation [28]. To exemplify this point from a forward's perspective, three of the greatest modern-day forwards fall within the lower-left quadrant (Messi, Mbappé & Lewandowski), in which the game model provides more freedom for them to be selective when exerting themselves. At the opposite end of the physical continuum, wide midfielders mainly occupied the upper-right quadrant (55%), exhibiting both volume and intensity characteristics. Research demonstrates a potential reason for this upper-right quadrant dominance, as they are highly active throughout games during both in-possession and out-of-possession phases (volume) and are also instrumental during defensive and offensive transitions (intensity) during peak game periods [9, 29]. Interestingly, central midfielders exhibit dual tendences as they occupied both the lower- and upper-right quadrants (40–43%), clearly highlighting their volume characteristics to support teammates in-possession but to also to press, cover and track back when out-of-possession [9, 11]. During intensified periods, some central midfielders exhibit box-to-box qualities and produce significant amounts of intensity to run with the ball, move to receive, support, attack the space in behind and to break into the box [29]. This is unlike more volume based defensive midfielders that were mainly found in the lower-right quadrant (60%), and were very active but mainly at low to moderate speeds (e.g., Zones 1–3). Whilst attacking midfielders did not occupy any specific quadrant and were uniformly spread across quadrants. Thus, it might be prudent for practitioners to adopt high-intensity training drills that not only mimic each positional role but also the individual characteristics of each player. This type of training has been found to tax both the aerobic and anaerobic systems and thus create desirable adaptation to develop players physiological capacities [30–32].

The distance covered in total and at higher intensities (≥20 $km \cdot h^{-1}$) generally declines from the first to the second half of a match [1, 14], although some studies have observed minimal half-by-half differences [13]. This trend is based on a reasonably similar duration played in the two halves. However, FIFA's new approach to added time in the World Cup Qatar 2022 resulted in much longer second halves. Consequently, the absolute distances covered by players in total and across most speed zones in the second half (i.e., m or km), were either similar to or even greater than the distances covered in the first half. To allow more appropriate comparisons to be drawn between halves, the physical data was adjusted to account for this and was represented as the relative distance covered per minute of match play (i.e., $m \cdot min^{-1}$). Collapsing all positional roles together resulted in a reduction of around 7% in the second half compared to the first in terms of the relative total distance covered. However, this reduction was more pronounced for defensive midfielders (9.8%), and least prominent for wide defenders (6.0%). Similarly, the relative distance covered at higher intensities (≥20 and ≥25 $km \cdot h^{-1}$) decline by 8–10% in the second half. Attacking midfielders demonstrated the most pronounced second half reduction at higher intensities (17.5–20.0%). Second half distance deficits have been reported in various domestic football competitions, albeit at much lower magnitudes than that reported in the present study [14, 23]. Although previous studies used broad positional role categories making direct comparisons challenging. Furthermore, these competitions did not adopt this new FIFA approach to added time that resulted in much longer games and particularly second halves. Thus, this additional time could have resulted in some fatigue across various positional roles. A multitude of mechanisms have been proposed to explain fatigue development in football, but researchers have failed to identify its precise cause [33]. Some have attributed this second-half decline to fatigue, as studies have reported depleted muscle glycogen stores at the end of a match and reduced creatine phosphate availability after intense periods [34]. However, football is a complex sport and second-half performance declines are impacted by much more than just fatigue because the changing game state and match importance can decrease or even increase a players physical output as well as many other factors [35].

Although this study was a detailed contemporary match analysis of the highest level of international football, it has numerous limitations that the reader should be cognisant of. Firstly, the data provider and not the author assigned the specialised positional roles which are based on the tactical systems adopted at the start of the game. Secondly, the physical data is limited to locomotor metrics and thus omits crucial information on position-specific acceleration and change of direction profiles [9, 36]. Moreover, one challenge for practitioners is linking each positional roles physical profile with various tactical phases or scenarios [11]. Unfortunately, this physical-tactical integration was not possible for this analysis thus limiting insights. Thus, at every opportunity the author layered the data with a contextual narrative to aid interpretation. Finally, this tournament offered a unique competition context compared to other tournaments that may have some impact on physical outputs and thus warrants further investigation (e.g., no long or medium-distance travel due to proximity of stadia, allocation of substitutes, more consolidated use of the Video Assistant Referee etc).

CONCLUSIONS

The present data demonstrate the physical demands placed on various positional roles in contemporary international tournaments such as the FIFA World Cup Qatar 2022. Given the large variations in demands between and within each positional role, practitioners should ideally design high-intensity drills that replicate both position- and individual-specific characteristics that fully prepare players for the match demands. The reader should also be cognisant of how these positional trends align with team data from the tournament [37], so a more rounded view of match demands can be formulated.

Conflict of interest

The author would like to thank FIFA High Performance Division for supporting and funding this important research study.

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'Setting the Benchmark' Part 2: Contextualising the Physical Demands of Teams in the FIFA World Cup Qatar 2022

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ABSTRACT: This study aimed to contextualise and benchmark the physical demands of teams in the FIFA World Cup Qatar 2022. With FIFA's official approval, all sixty-four games were analysed during the competition (n = 32 teams) using a multi-camera computerised tracking system. On average, teams during Qatar 2022 covered around 108.1 ± 3.6 km in total, with 9.0 ± 0.9 and 2.3 ± 0.3 km covered at the higher intensities (≥20.0 and ≥25.0 km · h^{-1}), respectively. Compared to the FIFA World Cup Russia 2018, national teams in Qatar 2022 covered only 3% more total distance but 16–19% more distance at the higher intensities ($P < 0.01$; Effect Size [ES]: 0.9–2.0). When the data was adjusted based on the number of minutes played, tournament differences at the higher intensities were less pronounced (9–12%; $P < 0.01$; ES: 0.7–1.3). The United States, Canada, Saudi Arabia, Germany and IR Iran covered 19–34% more high-intensity distance than Argentina, Ecuador, Qatar, Poland and Costa Rica during the 2022 tournament ($P < 0.01$; ES: 3.2–3.5). Match-to-match variation of each team in Qatar 2022 revealed Ecuador and Uruguay were particularly consistent for the distances covered at higher intensities (Coefficient of Variation [CV]: 2–3%), whilst Japan demonstrated considerable variation (CV: 23–29%). Teams generally covered more total distance on a per-minute basis in the first versus the second half ($P < 0.01$; ES: 1.2), but no differences existed at higher intensities ($P > 0.05$; ES: 0.0–0.1). Correlations between the number of high-intensity runs and various phase of play events across all teams were strongest for defensive transitions and recoveries, in addition to progressions up the pitch and into the final third (r = 0.63–0.75; $P < 0.01$). The present findings provide valuable context into the contemporary team demands of international football. This information could be useful for practitioners to benchmark team performances and to potentially understand the myriad of factors impacting physical performances.

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Match Analysis
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INTRODUCTION

The highly changeable nature of football results in players continually alternating between brief bouts of high-intensity running and longer periods of low-intensity activity [1]. Researchers have extensively examined this activity profile but primarily from an individual and positional point of view [2–4], as opposed to a team perspective. Football is a team sport whereby the activities of players are mutually dependent upon the actions of their teammates and the opponent [5–6]. Thus, this necessitates the need for more research on team physical performances, particularly on the myriad of factors that up or down regulate physical outputs. Although some team physical benchmarking has occurred for various domestic leagues [7–9], scant evidence exists for international competitions such as the FIFA World Cup Qatar 2022. This information would certainly serve as an important point of reference for practitioners regarding the contemporary team demands of international football.

Football is an ever-changing game with research highlighting that the physical match demands have evolved significantly in the last decade, especially from a high-intensity perspective [10]. This type of evolution has been found in the English Premier League [3], Spanish La-Liga [11], Chinese Super League [9], and the FIFA Women's World Cup [12]. Despite this, no published work has established if this trend exists at recent international tournaments (e.g., FIFA World Cup Russia 2018 versus Qatar 2022). This is particularly relevant given new directives employed in Qatar 2022 that increased the number of substitutes compared to Russia 2018 [13]. This rule modification may contribute to even greater evolutionary changes from a team physical perspective (e.g., moving from three to five substitutes). Moreover, new directives to account for all time loss activities in the FIFA World Cup Qatar 2022 [14], resulted in much longer second halves than previous tournaments. Consequently, the team distances covered across halves in total and at higher intensities may have been modified and this warrants further investigation.

A powerful modulating factor influencing a team's physical output is the tactical approach that they employ [15]. A major challenge for practitioners is synchronising the physical and tactical metrics together to determine this. This is accomplished through simultaneously aligning the physical efforts with the tactical phases of play or scenarios [16–20]. Unfortunately, this type of integration can be immensely complex, so some authors simply determine noteworthy associations between physical-tactical-technical metrics [21]. Thus, correlating the physical data with FIFA's Enhanced Football Intelligence metrics may provide much-needed context as to why teams physically exerted themselves during FIFA World Cup matches. Therefore, this study aimed to contextualise and benchmark the team demands during the FIFA World Cup Qatar 2022.

MATERIALS AND METHODS

Sample

With FIFA's official approval, all games during the FIFA World Cup Qatar 2022 were collected and analysed. Team analyses involved the summation of all match physical performance values of outfield players who participated in games, including substitutes (goalkeeper data excluded). Thus, data trends are the sum of all individual outfield player values presented as team totals. Team data consisted of all 32 nations across 64 game observations. As this data are freely available [22], no ethical approval was required.

Match Analysis System

All FIFA World Cup Qatar 2022 games were analysed using a multi-camera computerised tracking system (TRACAB, Chyron Hego). All player movements were captured by high-definition cameras operating at 25 Hz. This systems validity has been quantified to verify the capture process and subsequent accuracy of the data [23]. After system calibration and various stringent quality control processes, the data captured were analysed using match analysis software. This produced a data set on each team's activity patterns during a match using specified speed zones.

Speed Zones

Players' activities were coded into the following:

- Zone 1 (0.0–6.9 $km \cdot h^{-1}$),
- Zone 2 (≥7.0–14.9 $km \cdot h^{-1}$),
- Zone 3 (≥15.0–19.9 $km \cdot h^{-1}$),
- Zone 4 (≥20–24.9 $km \cdot h^{-1}$),
- Zone 5 (≥25.0 $km \cdot h^{-1}$).

Total distance represented the sum of the distances covered above. High-intensity activity consisted of the aggregation of Zones 4 and 5 (≥20.0 $km \cdot h^{-1}$), whilst sprinting exclusively included Zone 5 activity (≥25.0 $km \cdot h^{-1}$). Similar classifications for the upper two Zones have been employed in elite football for over a decade [24]. Moreover, the speed demarcations used for the FIFA World Cup Qatar 2022 were identical to those employed at the FIFA World Cup Russia 2018 [25], thus allowing tournament comparisons to occur.

Enhanced Football Intelligence Metrics

To further contextualise the physical trends, FIFA's Enhanced Football Intelligence metrics were also adopted [26], specifically the phases of play metrics that captured the tactical behaviours of teams during games. FIFA's algorithms quantified different in-possession phases (build up, progression, final third, attacking transition, counter-attack, long ball and set piece) and out-of-possession phases (low, mid, high block/press, counter-press, recovery and defensive transition) using the tracking data obtained from the previously described system. It used various features (spatial and physical) to identify and classify the various phases of play. For instance, it extracted ball and player pitch locations in relation to each other, in addition to the speed and direction of play. If teams entered a certain phase of play for a selected period of time, then the algorithms recorded this as a frequency count or an accumulated fraction of in-possession or out-of-possession time. Detailed definitions for all in- and out-of-possession phases of play can be found in freely available documentation [26].

Statistical Analyses

All statistical analyses were conducted using SPSS (SPSS Inc., Chicago, USA). Descriptive statistics were calculated on each variable and z-scores were used to verify normality. Performance differences across teams and halves were determined using paired-samples and independent t-tests. Statistical significance was set at $P < 0.05$. The coefficient of variation (CV) was calculated to determine the data spread across each metric. Effect sizes (ES) were computed to determine the meaningfulness of any differences and corrected for bias using Hedges formula. . The ES magnitudes were classed as trivial (< 0.2), small (> 0.2–0.6), moderate (> 0.6–1.2) and large (> 1.2). Pearson's coefficients were used for correlation analyses and the magnitudes of the associations were regarded as trivial ($r \leq 0.1$), small ($r > 0.1$–0.3), moderate ($r > 0.3$–0.5), large ($r > 0.5$–0.7), very large ($r > 0.7$–0.9), and nearly perfect ($r > 0.9$). Values are presented as means and standard deviations unless otherwise stated.

RESULTS

Benchmarking & Match-to-Match Variation

On average, teams during the FIFA World Cup Qatar 2022 covered 108.1 ± 3.6 km in total, with 9,001 ± 850 m and 2,345 ± 314 m covered at the higher intensities (≥20.0 and ≥25.0 $km \cdot h^{-1}$), respectively. The physical performances of teams at the upper and lower extremes also revealed some interesting trends. Figure 1A demonstrates that the top five ranked teams for total distance (United States, IR Iran, Australia, Canada, Serbia) covered 8–14% more in games compared to the bottom five ranked teams (Qatar, Brazil, Argentina, Mexico, Ecuador) during the FIFA World Cup Qatar 2022 ($P < 0.01$; ES: 2.0–4.5). In Figure 1B, it is noteworthy that the top five ranked teams from a high-intensity running perspective (United States, Canada, Saudi Arabia, Germany, IR Iran) covered 19–34% more distance than the bottom five ranked teams (Argentina, Ecuador, Qatar, Poland, Costa Rica) during the competition ($P < 0.01$; ES: 3.2–3.5). Figure 1C illustrates that the top five ranked sprinting teams (United States, Saudi Arabia, Canada, Uruguay, Germany)

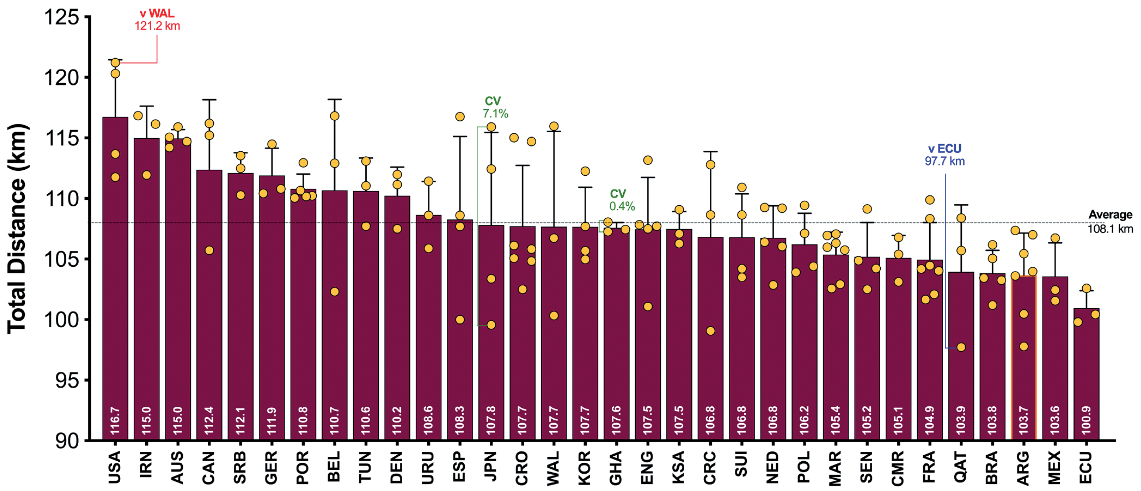

FIG. 1A. Total Team Distance and match-to-match variation in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Red = max, Blue = min, Green = variation.

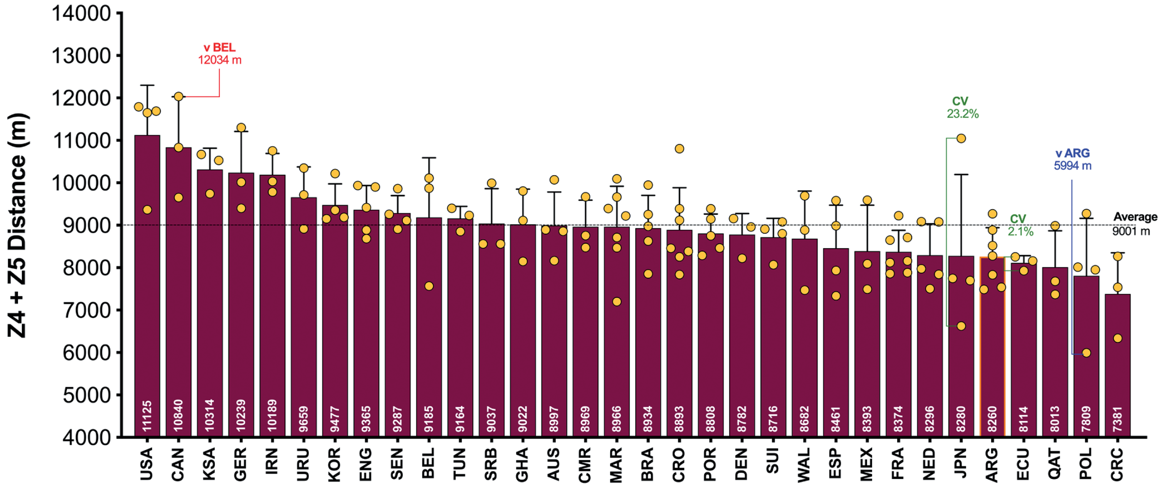

FIG. 1B. Team High Intensity Distance (≥20 km·h^{-1}; Zone 4 and 5; Z4+Z5) and match-to-match variation in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Red = max, Blue = min, Green = variation.

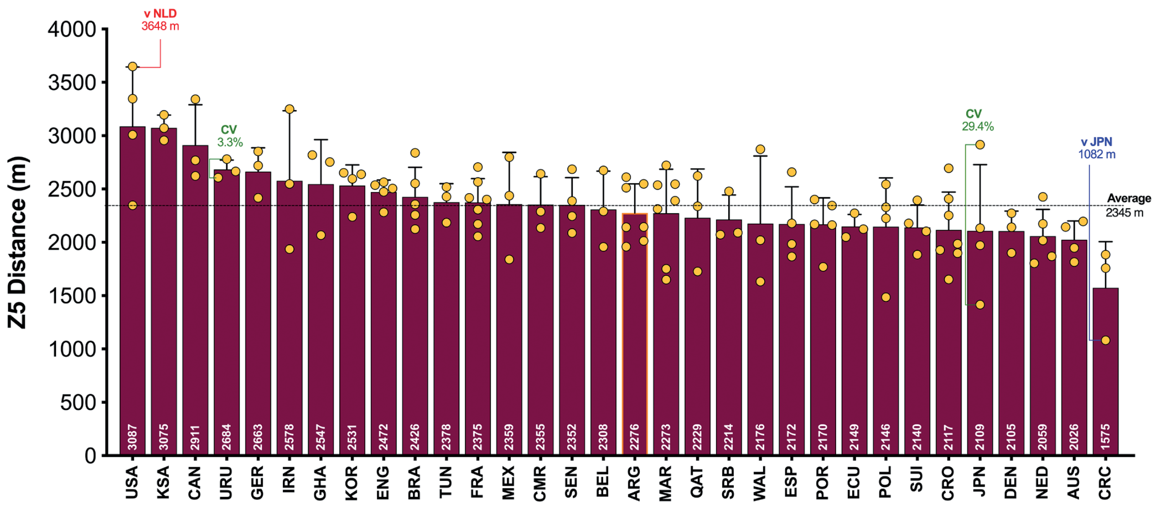

FIG 1C. Team Sprint Distance (≥25 km·h^{-1}; Zone 5; Z5) and match-to-match variation in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Red = max, Blue = min, Green = variation.

covered 21–49% more distance than the bottom five ranked teams (Japan, Denmark, Netherlands, Australia, Costa Rica) during the tournament ($P < 0.01$; ES: 1.2–3.0).

Figures 1A–C also depict the match-to-match variation of each team in the FIFA World Cup Qatar 2022. On average, teams match-to-match CV's during the tournament for total and the distance covered at higher intensities (≥20.0 and ≥25.0 km · h^{-1}) were 3.2%, 9.1% and 13.9%, respectively. The most consistent team from a physical perspective was highly dependent on the metric. For instance, Ghana, Ecuador and Uruguay were particularly consistent for total distance (CV: 0.4%), high-intensity distance (CV: 2.1%) and sprint distance (CV: 3.3%), respectively. It is noteworthy that Japan exhibited the most variation from match-to-match for the distance covered in total (CV: 7.1%) and that covered at higher intensities (CV: 23.2–29.4%).

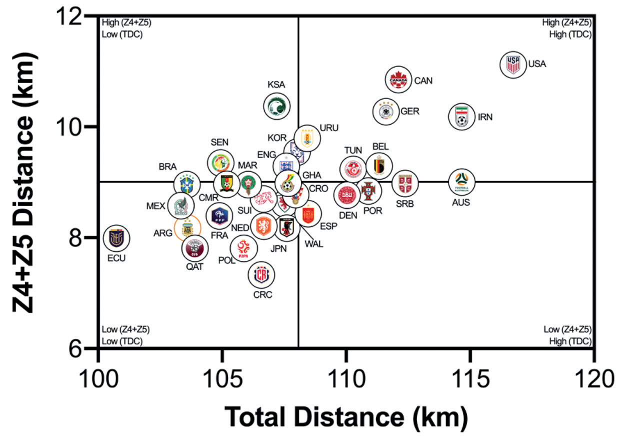

FIG. 2A. Team Total versus High Intensity Distance (≥20 km · h^{-1}; Zone 4 and 5; Z4+Z5) in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Crosshairs were based on the average for all teams.

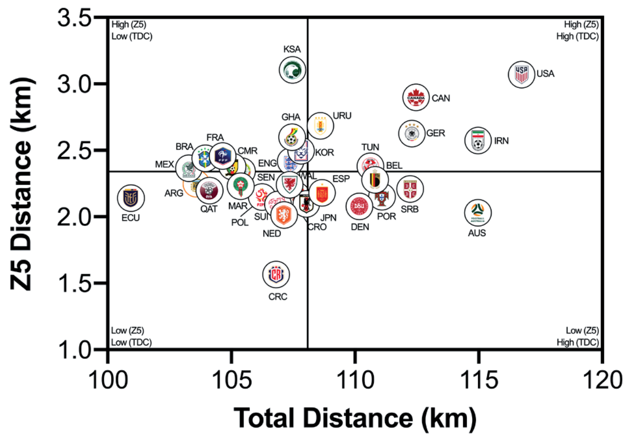

FIG. 2B. Team Total versus Sprint Distance (≥25 km · h^{-1}; Zone 5; Z5) in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Crosshairs were based on the average for all teams.

Quadrant Plots

The data presented in Figures 2A–B correlates two distinct dimensions of physical performance using quadrant plots to compare each team against one another. Figure 2A demonstrates a large association between a team's total and high-intensity game distances ($r = 0.65$; $P < 0.01$). The distribution of teams in each quadrant indicated that ~50% were in the lower-left quadrant (Ecuador, Costa Rica, Qatar, Poland, Argentina, France, Netherlands, Japan, Wales, Croatia, Ghana, Switzerland, Morocco, Cameron, Brazil, Mexico), ~16% were in the lower-right quadrant (Serbia, Australia, Portugal, Denmark, Spain), ~13% were in the upper-left quadrant (Saudi Arabia, Korea Republic, England, Senegal) and ~22% were in the upper-right quad- rant (United States, Canada, Germany, IR Iran, Belgium, Tunisia, Uruguay). Figure 2B demonstrates a moderate association between a team's total and sprint game distances ($r = 0.33$; $P > 0.05$). The distribution of teams in each quadrant indicated that ~34% were in the lower-left quadrant (Costa Rica, Ecuador, Argentina, Qatar, Mo- rocco, Switzerland, Poland, Wales, Croatia, Japan, Netherlands), ~19% were in the lower-right quadrant (Australia, Serbia, Portugal, Belgium, Denmark, Spain), ~28% were in the upper-left quadrant (Saudi Arabia, Ghana, Korea Republic, England, Cameron, France, Brazil, Mexico, Senegal) and ~19% were in the upper-right quadrant (Uruguay, Tunisia, Germany, Canada, IR Iran, United States).

Physical Evolution

Figures 3A–C demonstrate teams covered only 3% more total distance in the FIFA World Cup Qatar 2022 than in Russia 2018 ($P < 0.01$; ES: 0.9). However, the distances at higher intensities (≥20.0 and ≥25.0 km · h^{-1}) were 16–19% greater in Qatar 2022 than Russia 2018 ($P < 0.01$; ES: 1.2–2.0). When the data was adjusted based on the number of minutes played in each tournament, the trends for the overall distance covered actually reversed (3% lower in Qatar 2022 versus Russia 2018; $P < 0.01$; ES: 0.8). Although the demands were still greater in Qatar 2022 for the distances covered at higher intensities, they were less pronounced when adjusted for minutes played (9–12% higher in Qatar 2022 versus Russia 2018; $P < 0.01$; ES: 0.7–1.3).

Half-by-Half Differences

Figure 4A–C highlighted teams generally covered less total distance on a per-minute basis in the second half than in the first half ($P < 0.01$; ES: 1.2). Although Ecuador, Mexico, Qatar, Cameron and Canada covered similar distances across halves, more pronounced half-by-half differences were evident for Wales, France and Costa Rica. However, no half-by-half deficits existed for the distance on a per-minute basis at higher intensities (≥20.0 and ≥25.0 km · h^{-1}) in the FIFA World Cup Qatar 2022 ($P > 0.05$; ES: 0.0–0.1). Outliers such as Wales and Portugal covered much more distance at the

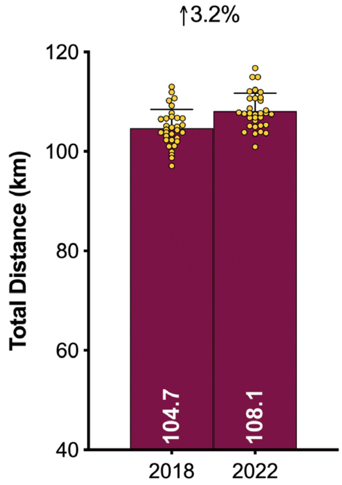

FIG. 3A. Evolution of the physical demands between FIFA World Cup 2018 vs 2022: Total Distance

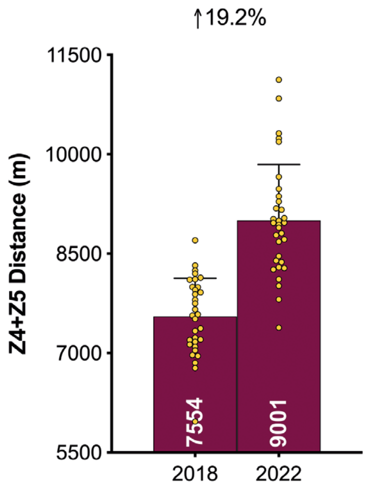

FIG. 3B. Evolution of the physical demands between FIFA World Cup 2018 vs 2022: High-Intensity Distance (≥20 km·h^{-1}; Zone 4 and 5; Z4+Z5).

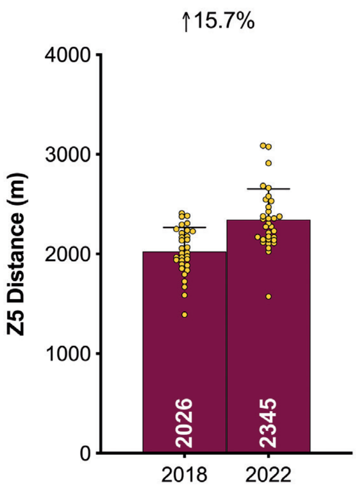

FIG. 3C. Evolution of the physical demands between FIFA World Cup 2018 vs 2022: Sprinting Distance (≥25 km·h^{-1}; Zone 5; Z5).

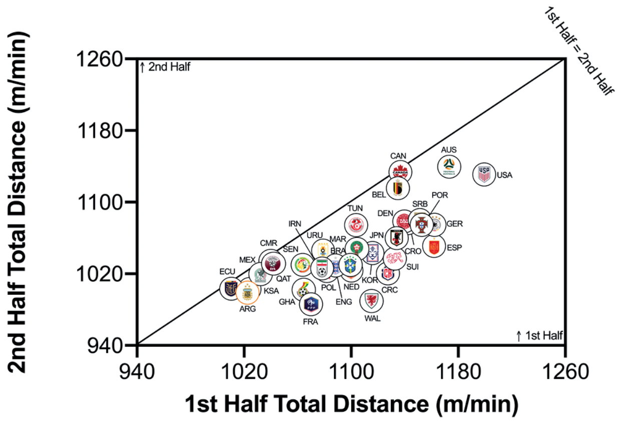

FIG. 4A. Team half by half Total Distance in the Qatar FIFA World Cup 2022. Data normalized per min and for 90+ min (excludes GK and extra time). Teams on the centre line covered the same distances in the 1st and 2nd half. Teams in the bottom triangle cover more distance in the 1st half and teams in top triangle cover more in the 2nd half.

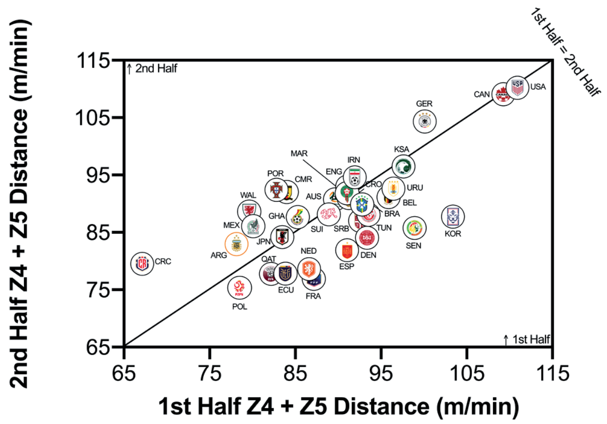

FIG. 4B. Team half by half High Intensity Distance (≥20 km·h^{-1}; Zone 4 and 5; Z4+Z5) in the Qatar FIFA World Cup 2022. Data normalized per min and 90+ min (excludes GK and extra time). Teams on the centre line covered the same distances in the 1st and 2nd half. Teams in the bottom triangle cover more distance in the 1st half and teams in top triangle cover more in the 2nd half.

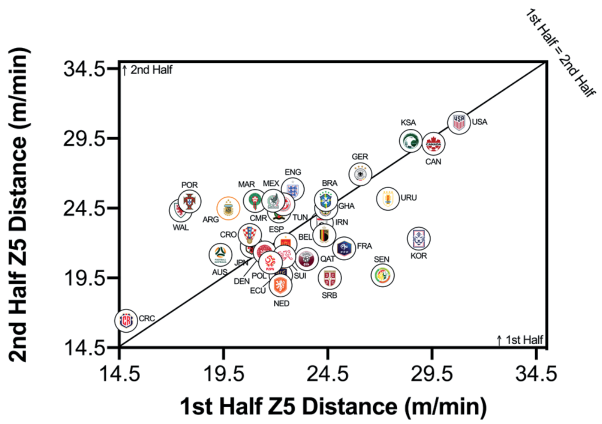

FIG. 4C. Team half by half Sprint Distance (≥25 km·h^{-1}; Zone 5; Z5) in the Qatar FIFA World Cup 2022. Data normalized per min and only players completing 90+ min (excludes GK and extra time). Teams on the centre line covered the same distances in the 1st and 2nd half. Teams in the bottom triangle cover more distance in the 1st half and teams in top triangle cover more in the 2nd half.

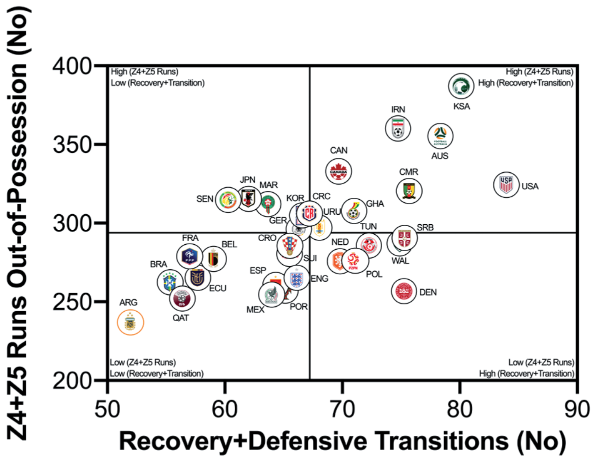

FIG. 5A. Team Recovery and Defensive Transition Count versus Out of Possession High Intensity Runs (≥20 km·h^{-1}; Zone 4 and 5; Z4+Z5) in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Correlation; r=0.63; P<0.01.

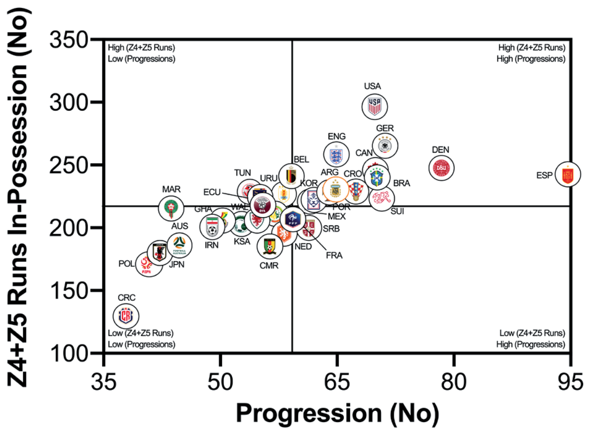

FIG. 5B. Team Progression Count versus In Possession Runs (≥20 km·h^{-1}; Zone 4 and 5; Z4+Z5) in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Correlation; r=0.73; P<0.01

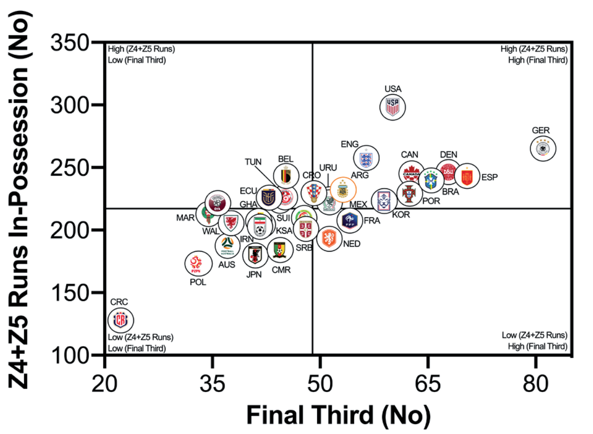

FIG. 5C. Team Final Third Count versus In Possession Runs (≥20 km·h^{-1}; Zone 4 and 5; Z4+Z5) in the Qatar FIFA World Cup 2022. Data normalized for 90+ min (excludes GK and extra time). Correlation; r=0.75; P<0.01.

higher intensities in the second half of matches, whilst Senegal and Korea Republic covered much more in the first half of matches.

Correlations Between Physical and Tactical Metrics

The number of high-intensity runs across teams were correlated against FIFA's Enhanced Football Intelligence metrics to determine any noteworthy associations (e.g., r > 0.60). Figure 5A indicates a large correlation between the number of high-intensity runs out-of-possession versus the combined number of events for defensive recoveries and transitions (r = 0.63; P < 0.01). Teams such as the United States, Saudi Arabia, Canada, IR Iran and Australia clearly fall within the upper-right quadrant as they performed a plentiful number of each. Figures 5B and 5C show a very large association between the number of high-intensity runs performed in-possession and the number of progression and final-third events (r = 0.73–0.75; P < 0.01). Teams such as the United States, Germany, Spain and Brazil were found in the upper-right quadrant, whilst Costa Rica, Poland, Australia and Japan are in the lower-left quadrant for both metrics.

DISCUSSION

This study was the first to physically benchmark all national teams competing at the FIFA World Cup Qatar 2022. On average, teams during the tournament covered around 108 km in total, with 9.0 and 2.3 km covered at the higher intensities (≥20.0 and ≥25.0 km·h^{-1}), respectively. Comparative team benchmarks from the FIFA World Cup Russia 2018 [25], revealed that national teams in Qatar 2022 covered only 3% more total distance but around 16–19% more distance at the higher intensities. Although it is tempting to attribute this finding to elevated demands in contemporary international football, the reader should be cognisant of the complexities surrounding such comparisons. For instance, new directives for added time in Qatar 2022 [14], resulted in much longer game durations compared with Russia 2018. However, when the data was adjusted based on the number of minutes played, tournament differences were less pronounced (9–12% at higher intensities). New directives also allowed teams to make five substitutes in Qatar 2022, as opposed to three in Russia 2018 [13]. This could also have contributed to the greater team demands in Qatar 2022, as substitutes cover more distance on a per minute basis at higher intensities compared to those starting the game or those that were replaced [1, 27]. More second half substitutions may also account for the negligible between halve deficits observed for high-intensity metrics in Qatar 2022. Irrespective of the differences in match duration or the number of substitutes used between tournaments, modern international teams are now expected to cover substantial distances at higher intensities. Thus, greater importance should be placed on training modalities that optimally prepare players for the rigours of the modern international game [28–30].

This section will attempt to integrate the present findings with a contextual narrative to aid interpretation. Quadrant plots revealed that teams such as the United States exhibited both volume and intensity characteristics during FIFA World Cup Qatar 2022 matches, whilst the likes of Costa Rica were the antithesis of this. This finding may not necessarily be completely indicative of physical fitness differences, but could also be shaped by the style of play employed by each team and/or their opposition plus numerous other contextual factors [31–32]. This is understandable as the aim of any team's tactics is to ensure optimal organisation in order to best utilise their physical and technical capabilities [5]. There were some expectations that utilising FIFA's Enhanced Football Intelligence metrics would shed some light on the tactical factors that up or down regulate a team's physical exertions during games. Interestingly, the strongest associations between the number of high-intensity runs a team performed and the various phases of play occurred for game situations that had a real urgency attached to their outcome (e.g., risk/benefit). Out-of-possession, this included high-intensity efforts to defensively recover and transition. Due to the potential consequences of not tracking back, it is not surprising that teams work intensely out-of-possession during defensive recoveries and transitions [7, 15–20]. The United States, Saudi Arabia, Canada, IR Iran and Australia clearly resided within the upper-right quadrant as they performed a plentiful number of each. Similarly, in-possession, this included high-intensity efforts to progress quickly up the pitch and into the final third to be an attacking threat. This could suggest that teams like the United States, Germany, England, Spain and Brazil up their intensity once they progress the ball forward and/or into the final third via vertical passes or dribbling. Research has revealed that the greatest proportion of a team's high-intensity activity occurs during transition-based activities [17, 19–20]. Thus, the United States intensity could be associated with their frequent transitions to recover defensively and to progress offensively, which may require players to produce long linear high-intensity runs. Whilst Costa Rica frequently sat compactly in a defensive low- or mid-block for extended periods, and this may have reduced their opportunity to move into space to engage in high-intensity activities, hence their subdued game intensity.

The present study was the first to quantify the physical match-to-match variation of each team in the FIFA World Cup Qatar 2022. Research has revealed that from an individual/positional perspective, the total distance covered is relatively stable from match-to-match but the distance covered at higher intensities varies considerably [33–34]. The present findings confirm this assertion from a collective perspective as team match-to-match CV's during the tournament were only 3% for the total distance covered but 9–14% for the distance covered at higher intensities. The most consistent teams from a physical perspective were highly dependent on the metric. For instance, Ghana, Ecuador and Uruguay were particularly consistent for total distance, high-intensity and sprint distances, respectively. It is noteworthy that Japan exhibited the most variation from game to game across most physical metrics. The opposition that Japan played against at the upper and lower ends of the range provides much-needed context. Japan covered their greatest distances in total and at higher intensities against Germany because the duration of that match was much longer than their other games. Japan covered most of this distance while out-of-possession (22% possession) in a reactive attempt to press Germany and force turnovers. In contrast, Japan covered their lowest distances in total and across higher intensities against Costa Rica. Japan covered more distance while in-possession (49% possession) across metrics in this game due to the defensive low/mid-block tactics that Costa Rica employed. Thus, Japan was able to dictate play more, as evidenced by their highest number of build-ups, progressions and movements to receive of their tournament. Given the multi-facetted and variable nature of football performance, the identification of factors that up or down regulate physical outputs is incredibly challenging as the context changes considerably within and between games. Thus, practitioners may need to focus their lens on game-by-game trends to gain a more holistic understanding of the impact of contextual influences on team physical outputs.

Although the present study provides unique insights into the physical team demands at the FIFA World Cup Qatar 2022, the reader should be aware of various shortcomings. The physical data presented should ideally include acceleration and change of direction metrics to provide a more rounded overview of team demands. Moreover, presenting the physical data trends across intensified periods of play would have enabled greater translation into training drill formats. Despite identical speed zones adopted across tournaments, the evolutionary trends should be viewed with caution given technological factors could have been modified (e.g., filters used to quantify high-intensity runs). Finally, the direct integration of physical and tactical metrics was not possible for this study. As a correlational approach was adopted, it is important for the reader to be mindful that correlation does not equal causation when examining these trends. The reader should also be cognisant of connecting the dots between team and positional trends by viewing other sources [35], this will provide a more holistic understanding of match demands at the international level.

CONCLUSIONS

This study was the first to verify the upper and lower physical benchmarks for international teams competing at the FIFA World Cup Qatar 2022. The data demonstrated the high physical demands of contemporary international football, which could be a combination of improved physical preparation and new rule directives applied to this tournament (e.g., more added time and substitutes). Practitioners should be cognisant of the fact that a team's physical demands are shaped by a myriad of factors and this makes interpretations particularly challenging.

Conflict of Interest

The author would like to thank FIFA High Performance Division for supporting and funding this important research study.

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Associations between the Big Five personality traits, testosterone, and cortisol in adolescent male athletes

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ABSTRACT: Testosterone (T) has been conceptualized as a biomarker of individual differences, yet T associations with the Big Five personality traits are inconsistent. Athletes provide a suitable model for evaluation here, as T co-expresses traits related to male-to-male competition and fitness with cortisol (C) playing a moderating role. This study investigated associations between the Big Five traits, T, and C in adolescent male athletes. One hundred and twenty male ice hockey players (aged 14–19 years) were assessed for blood total (T, C) and free (FT, FC) hormones, body-size dimensions (i.e., body mass, height, body mass index [BMI]), the Big Five personality traits (i.e., extraversion, neuroticism, agreeableness, conscientiousness, openness), and trait anxiety. Correlational and regression (with age and BMI as covariates) analyses identified a positive effect of FT on extraversion, but a negative FT effect on neuroticism and anxiety ($p < 0.05$). Significant FT × FC interactions emerged for extraversion and agreeableness. Slope testing revealed that FT had a positive effect on extraversion at the FC mean and +1 SD, and a negative effect on agreeableness with FC at +1 SD. In conclusion, adolescent male athletes with a higher serum FT concentration tended to express higher extraversion, but lower neuroticism and anxiety. The FT association with extraversion was moderated by FC concentration, as was agreeableness. Therefore, high-FT athletes presented a behavioural disposition that favours dominance and resiliency, with some dependencies on FC availability. Since all association effect sizes were weak, replicate studies on larger adolescent samples are needed.

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INTRODUCTION

The androgen testosterone (T) has an established role in sport and exercise, with basal, exercise-induced, and adaptive shifts in T regulating the structural and functional development of the brain and neuromuscular system [1]. Unsurprisingly, T has been conceptualized as biological marker of individual differences from a behavioral perspective, exhibiting high stability over time [2] with a substantial genetic component [3]. As such, personality studies have attempted to identify a functional role for individual T differences, particularly with respect to the Big Five personality traits. While there are some reports of high-T men scoring higher on extraversion [4, 5, 6, 7], others have found a negative association [8, 9] or no relationship between these factors [2, 10]. This inconsistency extends to the remaining Big Five traits of neuroticism, openness to experience, agreeableness, and conscientiousness [2, 5, 8, 9, 10],

From an evolutionary perspective, T helps coordinate the co-expression of traits related to male-to-male competition, fitness, and reproductive success [11]. Therefore, athletic men may provide a more suitable model for evaluating the T relationship with status-relevant personality traits. Indeed, research has shown high-T male athletes exhibit trait behaviours (i.e., more extraversion, less neuroticism and anxiety) [12, 13] that favour dominance and stress resiliency. No such data exists on male athletes during adolescence, a key developmental period characterized by dramatic changes in T production and temporal variation in the Big Five personality dimensions [14, 15]. This is despite suggestions that between 70–85% of successful and unsuccessful athletes can be identified using general measures of personality and mood state [16]; hence, access to this information could enhance sports selection, training preparation, and monitoring among young developing athletes.

The glucocorticoid cortisol (C) also plays a prominent role in sports performance and training adaptation via pleiotropic nervous-system actions that both oppose, and complement, those of T [1, 17]. Another emerging role for C is moderation of the T effect at target tissue. Research on adolescent [18] and adult male athletes [19], for instance, showed that T was a poor independent predictor of physical performance, but significant T linkages to performance were found at different baseline C concentrations. Whether T relationships with personality traits are moderated by C remains unclear. Large meta-analytic studies found no significant T × C effect (a common test for moderation) on the Big Five dimensions [7, 8], or other status-striving traits [7], in adult men. However, the population samples consisted of primarily non-athletic college students, with testing conducted under neutral conditions. To our knowledge, this nuanced T and C interplay with the Big Five traits has not been examined in male athletes of any age.

To address these gaps, a cross-sectional study was conducted to investigate associations between blood hormone (T, C) concentrations and the Big Five personality traits in a homogenous cohort of adolescent male athletes. Consistent with research on athletic men [12, 13], we hypothesized that individual differences in T concentration would be positively associated with extraversion and negatively related to neuroticism. No hypotheses were made with regards to the remaining Big Five traits. We also tested whether C moderates any T and personality relationship, operationally defined as a significant T × C interaction, with follow-up tests to probe the T effect at different C concentrations. Since no comparable data on male athletes exists, we made no firm predictions regarding these associations.

MATERIALS AND METHODS

Participants

One hundred and twenty male ice hockey players (aged 14–19 years) were recruited for this study. Athlete pre-screening did not reveal any medical and health problems, including endocrine and psychiatric disorders, that would affect the ability of participants to complete the experimental protocols, as detailed below. The study participants gave written informed consent, after receiving a full explanation of the study goals, procedures, and benefits. For those athletes under 18 years of age, additional consent from a parent or guardian was obtained. Ethical approval (number KEBN-20-54-HM) was granted from the ethics committee at the Institute of Sport – National Research Institute, Warsaw, Poland.

Study procedures

Data were collected using a cross-sectional design, as part of a national testing programme for the Polish Ice Hockey Federation. During a one-day visit to the laboratory, the participants completed the following assessments (in order) after an overnight fast; blood collection at ~8 am and anthropometric measurements, before breakfast was eaten from ~9–10 am. Testing resumed with an exercise assessment (not part of this study) at around 11–12 am, followed by a full recovery period before lunch was eaten from ~2–3 pm. Finally, questionnaires were self-completed in the afternoon (3–4 pm) to identify the Big Five personality traits and trait anxiety. The selection and order of testing is based on established protocols at the Institute of Sport – National Research Institute. To eliminate the confounding effects of fatigue, the athletes refrained from any physical training in the previous 24 hrs. Test implementation was performed by the same technicians and standardized across participants.

Blood hormone assessment

A 10 mL sample of venous blood was drawn from the antecubital vein and transferred into a polystyrene tube. The sample was left to clot after collection, before centrifugation (2000 g for 10 mins) to separate the serum component, which was aliquoted into another tube and stored in a -80° C freezer. After thawing and centrifugation, the serum samples were tested in duplicate using commercial enzyme-linked immunoassay (ELISA) kits (DRG, Germany). The lower detection limits for the T and C ELISA kits were 0.69 $nmol \cdot L^{-1}$ and 5.5 $nmol \cdot L^{-1}$, respectively. Sample testing was extended to include the blood measurement of free C (FC) and free T (FT) concentrations, as they represent the smaller portion of each steroid (1–10% of total hormones) that is biologically active at target tissue [20].

To determine serum FC concentration, expressed in $nmol \cdot L^{-1}$, we used a Centrifree YM-30 ultrafiltration device (Millipore, USA) with a 30kDa cut-off. Briefly, the loaded sample was centrifuged (2000 g for 30 mins at 37°C) to isolate the steroid free portion in sample filtrate. Following the centrifugation procedure, the filtrate was assayed using an ELISA kit for salivary C (DRG, Germany) with a detection limit of 0.25 $nmol \cdot L^{-1}$. Serum FT concentration, expressed in $pmol \cdot L^{-1}$, was estimated from the concentration measures of T and sex-hormone binding globulin (SHBG) using a validated algorithm [21], whereby FT concentration = $24.00314 \times T/Log10(SHBG) – 0.04599 \times T^2$. Serum SHBG concentration was determined using a commercial ELISA kit (DRG, Germany) that had a detection limit of 4 $nmol \cdot L^{-1}$. The inter-assay kit CV's, based on internal controls, were less than 5% on average across all blood T, C, and SHBG assays, and the salivary C assay.

Anthropometric testing

Participant body mass was measured to the nearest 0.1 kg using digital scales (Tanita, Japan). Standing height was assessed to the nearest 1 cm with a freestanding stadiometer (Siber-Hegner, Switzerland). The participants wore shorts and a shirt, without shoes and socks, during this evaluation. As a general indicator of health status, we computed a body mass index (BMI) for each participant by dividing body mass by height (expressed in m^2).

Assessment of personality traits

The NEO-FFI Personality Questionnaire was chosen to examine the athletes' personality type with regards to the Big Five factor model [22]. The NEO-FFI Personality Questionnaire consists of 60 items that measure the five-factor model (12 items each) of: (1) neuroticism, (2) extraversion, (3) openness to experience, (4) agreeableness, and (5) conscientiousness. Trait anxiety was also measured, being a standard assessment in our laboratory, and one that correlates positively with neuroticism and/or negatively with extraversion among male athletes [12, 13]. The 20-item version of the Spielberger State-Trait Anxiety Inventory (STAI) was selected for this purpose [23]. Both inventories were completed in pen and paper format using the translated (English into Polish) versions of the NEO-FFI [24] and STAI [25].

Statistical procedures

The study data were prepared and analyzed in the R (version 4.1.1) programming environment [26] using several packages (i.e., easystats, readxl, psych, ggplot2, interactions, sjPlot). In the first instance, descriptive means and dispersion statistics were calculated for all demographic, body size, hormonal, and personality variables. Next, the zero-order, linear associations between variables were explored using Pearson correlations. Based on standard conventions, these correlations (absolute values) can be interpreted as being either a weak (0.10 to < 0.30), moderate (0.30 to < 0.50) or strong effect (0.50 to 1.00). The correlational results were also used to identify, and subsequently remove, strongly-related variables to avoid multicollinearity in the main regression analyses.

To determine if individual differences in T and C concentrations were related to each personality trait, we ran a series of hierarchical regression models. Each model was implemented as a two-step process. In step one, FT and FC were entered as predictors with age and BMI as covariates. In step two, the FT × FC interaction was entered into the model. We report all significant effects with an effect-size correlation (i.e., partial *r*), computed from model t values and degrees of freedom [27]. Following a significant interaction, simple slopes were examined for three values of the moderator: -1 SD, sample mean, and +1 SD [28]. Further probing was performed using Johnson-Neyman interval plots to identify the regions of significance [29]. Statistical significance was set at an alpha level of $p \leq 0.05$. Given that T x C personality relationships are generally underpowered [7], we applied a lower alpha threshold ($p \leq 0.10$) to establish a significant interaction. All assumptions of regression modeling were met, based on visual checks of model residuals.

RESULTS

Descriptive statistics for all variables are presented in Table 1. Correlational testing revealed positive relationships (weak to strong effects) between most body-size indicators, with BMI also found to be negatively related (weak effect) to FC concentration (all $p < 0.05$). The serum T and FT concentration measures were strongly and positively related, as were serum C and FC ($p < 0.001$). Both serum T and FT concentrations were negatively related to neuroticism and anxiety, but positively related to extraversion ($p < 0.05$), with weak effect sizes on these bivariate comparisons. Significant interrelationships also emerged, both positive and negative, between the Big Five personality dimensions and/or trait anxiety. These associations were generally weak, apart from a strong positive relationship between neuroticism and anxiety ($p < 0.001$).

The stage one regression models (see Table 2) yielded a significant negative effect of FT concentration on both neuroticism (partial $r = -0.23$) and anxiety (partial $r = -0.23$), along with a significant positive effect of FT on extraversion (partial $r = 0.23$), when controlling for other predictors and covariates. We found no significant FT relationships with openness, agreeableness, and conscientiousness at this level of analyses, whilst FC concentration was unrelated (all $p > 0.179$) to all personality traits. The fitted models were weak, explaining only 1–5% of personality trait variation, and only the neuroticism and anxiety predictions were significant. Stage two revealed significant FT × FC interactions when predicting

TABLE 1. Descriptive results for each variable and zero-order correlations between variables.

Variables	Mean	Range	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Age (years)	16.7	14.0 – 18.6	1	-0.06	**0.20**	**0.28**	0.12	0.08	0.00	-0.01	0.06	-0.03	0.04	**0.19**	0.03	-0.05
2. Height (m)	1.79	1.64 – 1.93		1	**0.51**	-0.07	-0.12	-0.10	0.02	0.00	0.02	-0.01	0.07	-0.02	0.01	0.12
3. Body mass (kg)	73.8	53.1 – 93.4			1	**0.82**	-0.04	-0.01	-0.15	-0.16	-0.04	-0.01	0.04	0.06	0.06	0.03
4. BMI ($kg \cdot m^2$)	23.1	17.6 – 28.2				1	0.04	0.06	-0.17	**-0.18**	-0.07	0.01	0.01	0.08	0.07	-0.05
5. Testosterone ($nmol \cdot L^{-1}$)	22.5	9.4 – 38.5					1	**0.92**	0.16	0.11	**-0.20**	**0.21**	0.09	-0.09	0.15	**-0.21**
6. FT ($pmol \cdot L^{-1}$)	342	131 – 686						1	0.16	0.08	**-0.23**	**0.23**	0.11	-0.06	0.16	**-0.25**
7. Cortisol ($nmol \cdot L^{-1}$)	518	264 – 835							1	**0.92**	-0.15	0.09	0.13	0.04	0.13	-0.18
8. FC ($nmol \cdot L^{-1}$)	63.8	17.9 – 215								1	-0.12	0.07	0.11	0.04	0.12	-0.13
9. Neuroticism (score)	20.7	2 – 42									1	**-0.41**	-0.01	-0.08	**-0.33**	**0.75**
10. Extraversion (score)	31.3	12 – 44										1	**0.23**	0.03	**0.48**	**-0.39**
11. Openness (score)	24.4	11 – 37											1	-0.12	0.16	-0.05
12. Agreeableness (score)	28.4	16 – 44												1	**0.42**	-0.07
13. Conscientiousness (score)	35.4	13 – 47													1	**-0.28**
14. Anxiety (score)	39.5	25 – 60														1

Key: BMI = body mass index, FT = free testosterone, FC = free cortisol. Significant correlations are highlighted in bold.

TABLE 2. Hierarchical regression models predicting the Big Five personality traits and trait anxiety.

Predictors	Neuroticism		Extraversion		Openness		Agreeableness		Conscientiousness		Anxiety	
	Est.	*Est.*	*Est.*	*Est.*	*Est.*	*Est.*	*Est.*	*Est.*	*Est.*	*Est.*	*Est.*	*Est.*
Age	1.111 (0.993)	1.098 (0.992)	-0.418 (0.756)	-0.403 (0.749)	0.205 (0.628)	0.214 (0.626)	1.219* (0.611)	1.201* (0.601)	-0.086 (0.789)	-0.086 (0.792)	-0.185 (0.952)	-0.195 (0.953)
BMI	-0.379 (0.340)	-0.374 (0.340)	0.049 (0.259)	0.043 (0.257)	0.038 (0.215)	0.035 (0.215)	0.089 (0.209)	0.094 (0.206)	0.244 (0.270)	0.244 (0.272)	-0.189 (0.326)	-0.186 (0.327)
FT	-0.020* (0.008)	-0.001 (0.018)	0.015* (0.006)	-0.007 (0.014)	0.005 (0.005)	-0.008 (0.011)	-0.005 (0.005)	0.017 (0.011)	0.010 (0.006)	0.011 (0.014)	-0.020** (0.008)	-0.006 (0.017)
FC	-0.027 (0.021)	0.066 (0.084)	0.008 (0.016)	-0.100 (0.063)	0.014 (0.013)	-0.049 (0.053)	0.007 (0.013)	0.115* (0.051)	0.022 (0.016)	0.026 (0.067)	-0.027 (0.020)	0.041 (0.080)
FT × FC		-0.000 (0.000)		0.000# (0.000)		0.000 (0.000)		-0.000* (0.000)		-0.000 (0.000)		-0.000 (0.000)
R^2 adjusted	0.049*	0.051*	0.024	0.041	0.011	0.007	0.014	0.046	0.012	0.004	0.045*	0.043
ΔR^2 adjusted		0.002		0.017		-0.004		0.032*		-0.008		-0.002

Note: Estimates are shown with standard errors (). BMI = body mass index, FT = free testosterone, FC = free cortisol. Significance levels are depicted as # *p ≤ 0.10 * p ≤ 0.05 ** p ≤ 0.01.*

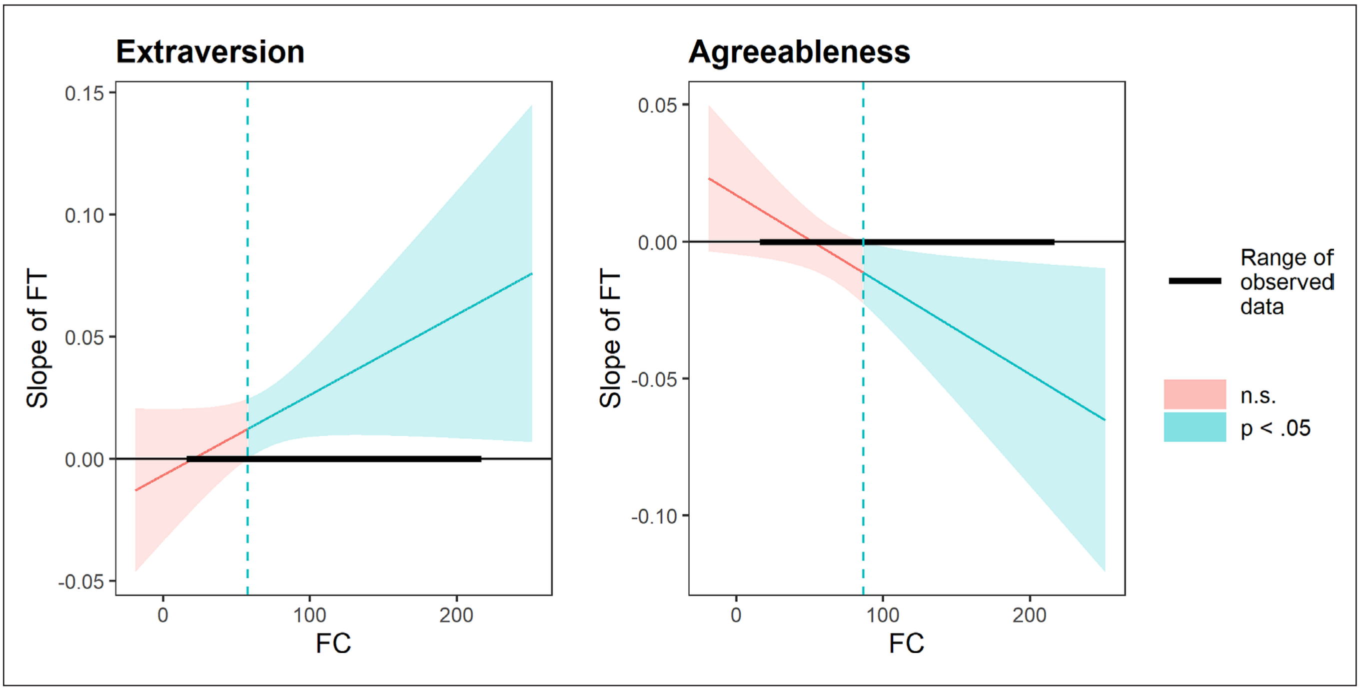

FIG. 1. Interactions between free testosterone (FT) and free cortisol (FC) concentrations in relation to extraversion and agreeableness.

extraversion ($p = 0.079$, partial $r = 0.16$) and agreeableness ($p = 0.030$, partial $r = -0.20$), once all lower-order main effects were controlled for. The fitted models were again relatively weak (1–5% variation explained) and largely non-significant, except for neuroticism and anxiety, and only agreeableness showed a significantly better fit ($\Delta R^2 = 3.2\%$) with the FT × FC term included.

When probing the FT × FC effect on extraversion, slope testing revealed a FT relationship at the FC mean (estimate = 0.014, SE = 0.006, $p = 0.019$) and +1 SD (estimate = 0.026, SE = 0.009, $p = 0.003$), but not at -1 SD (estimate = 0.002, SE = 0.009, $p = 0.817$). The Johnson-Neyman plot confirmed a positive and significant FT link to extraversion, but only when the FC interval was between 57.8 and 441.8 nmol·L^{-1} (Figure 1). Regarding agreeableness, simple slopes identified a FT relationship at a high (+1 SD) FC concentration (estimate = -0.016, SE = 0.007, $p = 0.026$), but not at the sample mean (estimate = -0.004, SE = 0.005, $p = 0.427$) or -1 SD (estimate = 0.008, SE = 0.008, $p = 0.281$). The Johnson-Neyman plot confirmed a significant negative effect of FT on agreeableness, but only when FC concentration was outside the interval of -104.3 to 86.5 nmol·L^{-1} (Figure 1).

As a robustness check, all regression models were repeated, but with the age and BMI covariates removed: see supplement Table S1. The emergence of significant FT associations with neuroticism (partial $r = -0.23$), extraversion (partial $r = 0.22$), and anxiety (partial $r = -0.24$) paralleled our main findings, as did a significant FT × FC effect on extraversion (partial $r = 0.17$) and agreeableness (partial $r = -0.20$). Follow-up analyses with simple slopes (Table S2) and Johnson-Neyman plots (Figure S1) revealed trends and regions of significance that are coherent with our initial results. Although the fitted outcomes were still weak in strength (1–6% explained variance), the explanatory models for neuroticism, extraversion and anxiety were all significant after covariate removal. Once again, only agreeableness showed a significantly better fit ($\Delta R^2 = 3.1\%$) with inclusion of the FT × FC interaction.

DISCUSSION

The purpose of this study was to investigate associations between the Big Five personality traits and morning blood T and C concentrations in adolescent male athletes. Complementary sets of analyses verified that individual differences in serum FT concentration were positively associated with extraversion, but negatively related to neuroticism and anxiety. No link between FC and any personality trait was, however, seen. Complex interplay also transpired for extraversion and agreeableness, with FT being positively related to extraversion and negatively related to agreeableness at a mean or higher FC concentration.

As hypothesized, adolescent males with an elevated serum FT concentration tended to express a higher level of extraversion, along with less neuroticism and anxiety. These findings parallel research on male athletes [12, 13], adult men [4, 6, 7], and mixed-sex cohorts [5]. For high-T males, higher scores on extraversion, coupled with lower neuroticism and anxiety, could reflect a general disposition for emotional stability, less tension, as well as stronger self-efficacy, positive affect, and motivation; all facets of dominance and stress resiliency. Nonetheless, it's not clear why T might preferentially relate to these dimensions and not others. One possibility is adaptive calibration of selected traits necessary for athletic performance. For example, stronger FT associations with training motivation and competitiveness were seen in elite than non-elite performers [30, 31, 32]. Our results could also reflect study specificities, such as the targeting of young talented athletes in a dominance-related sport, and data collection across a full day of physiological and psychological testing. The possible role of age-specific effects of T on the Big Five traits [14] is another open question. A replicate study on adolescent males representing different levels of athletic competition (i.e., elites, non-elites, controls), and varying age categories, would help answer these questions.

Serum FC concentration did not correlate with, or predict, any Big Five personality dimension or trait anxiety in our sample of adolescent athletes. Athlete studies in this area are equivocal, with reports of positive salivary FC linkages to some (i.e., extraversion, conscientiousness), but not all, of the Big Five personality traits [33, 34], while others found no serum C associations with neuroticism, extraversion or anxiety [12, 13]. This incongruency is perhaps not surprising, given reports of null or inconsistent results for the C or FC biomarkers are widespread in the general population [7, 8, 10, 35, 36, 37, 38]. These inconclusive findings extend to other hormones of the hypothalamic-pituitary-adrenal (HPA) axis (e.g., adrenocorticotropic hormone) and their relationship with the Big Five personality traits [39]. This equivocality could be attributed to study heterogeneity, in terms of differences in sample composition (e.g., blood, saliva, hair) and timing, the indices of HPA activity used (e.g., morning versus afternoon C, cumulative C, C awakening response), and assay procedures. An alternative viewpoint is that C, as a stress biomarker exerting pleiotropic actions on different target tissue and time scales [1, 17], functionally interacts with other biomarkers in such a way that independent testing of this variable fails to capture.

Finally, and as noted earlier, nuanced hormonal interactions emerged in relation to extraversion and agreeableness, with a higher FT concentration associated with more extraversion and less agreeableness when FC exceeded 57.8 nmol·L^{-1} and 86.5 nmol·L^{-1} respectively, which equates to the 55th and 78th percentile scores for FC. The latter result is reasonably consistent with work on androgen-deprived adult men, who reported higher agreeableness than controls [40]. Comparable data on adolescent athletic males does not exist; nevertheless, it may be considered that low agreeableness (among high-FT adolescent males) might not be viewed negatively in the context of athlete testing where cooperation and empathy are less relevant. Other T-connected traits, like physical fitness, have shown similar dependencies on C. For instance, salivary FC concentration moderated the FT effect on exercise performance in both male weightlifters [19] and ice hockey players [18]. Taken together, these results suggests that elevated FC secretion might be an important preconditioning factor, at least for athletic men and adolescent males. This position would also explain the lack of significant T × C interactions with the Big Five personality traits in larger studies on, primarily, college age students [7, 8]. Consequently, we propose that the presence of T (or FT) x C (or FC) interactions is contingent on many factors, like the studied population and personality trait measured, environmental or situational conditions, and potentially other (e.g., vitamin 25 [OH]D) steroid biomarkers [18].

Given the high proportion of successful and unsuccessful athletes that can be identified using general personality and mood state measures [16], we propose developing a psychological inventory for young male athletes that includes those Big Five personality traits deemed relevant to different team sports [41]. This information could form part of a broader testing strategy for talent identification, training and competition preparation, and seasonal monitoring. As one example, knowledge of behavioral tendencies might be used to assign mental training techniques, team communication, and tactical thinking skills to produce positive individual and team outcomes [41]. Supplementing this information with blood FT and FC data, or salivary FT and FC as a non-invasive alternative, could provide further insight regarding how a personality and biological disposition might affect athlete behavior in sport. With the advent of rapid hormone diagnostics [42, 43], it may be possible to intervene in relative real-time to promote a hormonal profile that exploits these psychological differences for athletic gain; see work on preconditioning strategies in sport [44]. Since sporting context can differentially activate T and C secretion, whilst inducing transient shifts in behavior, the concurrent assessment of relevant states (e.g., competitive state anxiety, situational motivation) would be prudent to capture context-related changes in these hormone-personality-behavior associations and thus, help refine the strategies prescribed.

One strength of this study is cohort homogeneity, although this does limit our ability to make broader conclusions for other athletic groups and non-athletes. Moreover, the effect sizes for the hormone-personality associations were weak and the current sample is considered small for testing interactions [7]. Further bias might arise from the time difference between the hormonal (morning) and personality (afternoon) assessment. Data collected within our laboratory does indicate that FT and FC measured in saliva are highly stable (Spearman $r = 0.87–0.97$) across the day (i.e., rank order is maintained), so we anticipated little bias in the modeled results. Temporal variation in the Big Five personality dimensions, from childhood up to early adulthood [14, 15], adds another level of complexity when attempting to characterize these linkages; however, it is known that trait stability remains relatively high across adolescence [15]. Finally, we acknowledge that T and C secretion can vary on a moment-to-moment basis, due to a myriad of situational and environmental cues in sport. Hence, a longitudinal study on a larger adolescent cohort is needed to ascertain the robustness of our findings across different contextual settings.

CONCLUSIONS

Adolescent male athletes with a higher serum FT concentration showed a tendency for higher extraversion, lower neuroticism, and less anxiety. The FT relationship with extraversion also depended on serum FC concentration, as did agreeableness. Therefore, high-FT athletes in this study displayed personality tendencies likely to favour dominance and stress resiliency, although complicated by more nuanced FT and FC interplay. These findings must be interpreted in light of weak association effect sizes and a lack of comparable research, which underscores the need for study replication on larger athlete samples.

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Data availability

The data is not publicly available, due to ethical restrictions.

Conflicts of interest

The authors declare no conflicts of interest

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Supplemental Materials.

TABLE S1. Hierarchical regression models predicting the Big Five personality traits and trait anxiety.

	Neuroticism		Extraversion		Openness		Agreeableness		Conscientiousness		Anxiety	
Predictors	***Est.***	***Est.***	***Est.***	***Est.***	***Est.***	***Est.***	***Est.***	***Est.***	***Est.***	***Est.***	***Est.***	***Est.***
FT	-0.020* (0.008)	-0.001 (0.018)	0.015* (0.006)	-0.007 (0.014)	0.005 (0.005)	-0.007 (0.011)	-0.004 (0.005)	0.018 (0.011)	0.011 (0.006)	0.011 (0.014)	-0.020** (0.008)	-0.006 (0.017)
FC	-0.023 (0.020)	0.072 (0.083)	0.008 (0.015)	-0.101 (0.062)	0.014 (0.013)	-0.050 (0.052)	0.006 (0.013)	0.114* (0.051)	0.019 (0.016)	0.023 (0.066)	-0.024 (0.019)	0.044 (0.080)
FT ´ FC		-0.000 (0.000)		0.000# (0.000)		0.000 (0.000)		-0.000* (0.000)		-0.000 (0.000)		-0.000 (0.000)
R^2 adjusted	0.049*	0.052*	0.038*	0.056*	0.004	0.009	-0.011	0.020	0.022	0.014	0.058*	0.056*
ΔR^2 adjusted		0.003		0.018		0.005		0.031*		-0.008		-0.002

Note: Estimates are shown with standard errors (). FT = free testosterone, FC = free cortisol. Significance levels are depicted as # *p ≤ 0.10 * p ≤ 0.05 ** p ≤ 0.01*

TABLE S2. Simple slope analyses for free testosterone (FT) and free cortisol (FC) concentrations in relation to extraversion and agreeableness.

Extraversion				**Agreeableness**			
Slope of FT when FC = 27.10 (-1 SD):				Slope of FT when FC = 27.10 (-1 SD):			
Est.	SE	t value	*p* value	Est.	SE	t value	*p* value
0.002	0.009	0.208	0.835	0.009	0.008	1.212	0.228
Slope of FT when FC = 63.83 (Mean):				Slope of FT when FC = 63.83 (Mean):			
Est.	SE	t value	*p* value	Est.	SE	t value	*p* value
0.014	0.006	2.367	0.020	-0.003	0.005	-0.583	0.561
Slope of FT when FC = 100.56 (+ 1 SD):				Slope of FT when FC = 100.56 (+ 1 SD):			
Est.	SE	t value	*p* value	Est.	SE	t value	*p* value
0.026	0.009	3.018	0.003	-0.015	0.007	-2.100	0.038

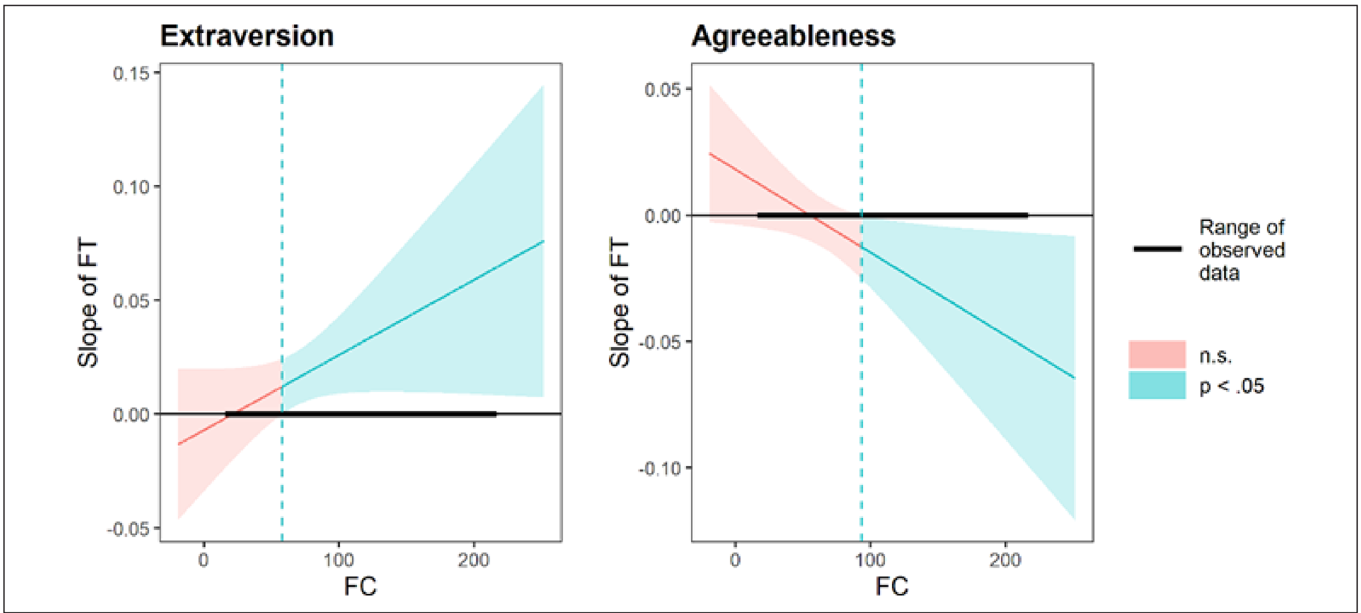

FIG. S1. Interactions between free testosterone (FT) and free cortisol (FC) concentrations in relation to extraversion and agreeableness.

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The effect of diminished metabolic acidosis on thermoregulatory response during exercise

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ABSTRACT: It was reported that metabolic acidosis inhibits the activity of warm-sensitive hypothalamic neurons. The present study was designed to test the hypothesis that metabolic alkalosis may improve heat loss during intensive exercise in men. Fifteen male subjects aged 22–24 years were submitted to incremental exercise on two randomized occasions one week apart. During the bicarbonate trial exercise was preceded by ingestion of $NaHCO_3$ at a dose 250 mg/kg whilst during the placebo trial lactose was administered. Exercise load was increased every 3 min by 30 W until volitional exhaustion. Ambient temperature was kept at 23–24°C and humidity 50–60%. Tympanic and skin temperatures were recorded and the rate of sweating was assayed by humidity measurement of nitrogen flowing through a capsule attached to the mid posterior chest. Total sweat loss was determined by the changes in body mass. Venous blood samples were taken before exercise and at the end of each workload for determination of acid-base parameters. The subjects attained similar maximal workload in the two tests (260 ± 6 W) with heart rate 185 ± 6 beats/min. Blood concentration of hydrogen ions was lower ($p < 0.001$) in the bicarbonate than in the placebo trial throughout the whole exercise period. There were no significant differences between these tests in tympanic and mean skin temperatures, sweating rate and total sweat loss. The present data showed that in men attenuation of metabolic acidosis by bicarbonate ingestion did not influence thermoregulation during incremental exercise performed until volitional exhaustion, possibly due to too short duration of exertional uncompensated metabolic acidosis.

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Temperature
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INTRODUCTION

Regulation of body temperature during exercise is achieved by both thermal and nonthermal factors. Increased body temperature triggers cutaneous vasodilation and sweating, but also causes hyperventilation which reduces arterial carbon dioxide partial pressure ($PaCO_2$) and cerebral blood flow [1]. Katagiri et al. found that metabolic alkalosis produced by sodium bicarbonate ingestion reduced hyperventilation and attenuated hypocapnia-related cerebral hypoperfusion during exercise [2].

The nonthermal factors include stimulation of the thermoregulatory neurons in the hypothalamus by impulses from motor centres of the cerebral cortex (central command) and stimulation of these neurons by afferent pathways originating in mechanoreceptors and metabolic receptors located in muscles. It is mediated by the superfamily of transient receptor potential (TRP) ion channels, which function as cellular sensors and are activated by several stimuli [3–5]. Among them, the transient receptor potential vanilloid (TRPV) subfamily members, namely TRPV1 and TRPV4, are gated by certain lipophilic molecules, extracellular protons (pH) and stimuli such as heat or osmotic pressure changes [6–8]. Heat and metabolic acidosis, the main physiological indicators modified by muscle contraction during exercise, activate TRPV1 in humans [4, 9]. At lower pH values (< 6.0) TRPV1 is directly activated by protons, whilst at the range of pH 6–9 protons modulate TRPV1 channels by sensitizing them to other stimuli [9, 10].

The firing rate of hypothalamic warm sensitive neurons in rodents is reported to be inhibited by metabolic acidosis [11, 12]. It was suggested that this effect may explain the impairment of the thermoregulatory mechanisms in hypercapnic respiratory acidosis, as well as in thermal stress (i.e. exertional heat stroke), which is usually accompanied by metabolic acidosis [13]. It may be speculated that metabolic acidosis induced by intensive exercise also contributes to the elevation of body temperature. This may partly explain the beneficial effect of training on thermoregulation and the relationship between internal body temperature and exercise loads expressed as percentage of maximal oxygen uptake [14]. It seems that the combination of TRPV channels' polymodal nature and stimulation sensitivity makes them ideal candidates for stress response proteins that merge signalling pathways and adjust intracellular Ca^{2+} levels as a response to induced stress, such as exercise-induced metabolic acidosis [15].

Therefore, the aim of the present study was to test the hypothesis that diminished metabolic acidosis may favourably affect thermoregulation during exhaustive exercise in men. For this purpose body temperature and sweating rate during exercise with increasing intensity were measured in healthy young men after sodium bicarbonate ingestion intended to diminish metabolic acidosis.

MATERIALS AND METHODS

Subjects

Fifteen healthy male students (age: 23.4 ± 0.6 years, body mass: 85.4 ± 2.1 kg, height: 184 ± 1.4 cm, VO_2peak 51 ± 3 mL/kg/min) participated in the study after giving informed consent. They were physically active but did not take part in any regular sports activity. None of them reported lactose, milk or other dairy product intolerance. The subjects were asked to hydrate properly and not to consume alcohol or perform vigorous exercise in the 24 h before testing and to consume no food or beverages (other than water) 2 h before testing. The study protocol was approved by the Ethical Committee of the Medical University in Warsaw (KB/175/2008).

Study protocol

A double-blind, placebo-controlled design was employed. The subjects performed an incremental exercise test on two occasions separated by a one-week interval. During the *bicarbonate trial* exercise was preceded by ingestion of $NaHCO_3$ at a dose 250 mg/kg of body mass, whilst during the *placebo trial* lactose was used. The dose was chosen in order to avoid the side effects of sodium bicarbonate ingestion, which are dose-dependent, whereas it provided the recommended 5–6 mmol/L increase in bicarbonates' blood concentration [16, 17]. Both substances were given wrapped in a wafer and ingested during 20–30 min. At that time the subjects in both trials drank 0.9–1.0 L of noncarbonated mineral water. The order of the trials was randomized. The $NaHCO_3$ ingestion procedure was similar to that described in previous papers [18].

Exercise started 90 min after bicarbonate or placebo ingestion. Room temperature was kept at 23–24°C, humidity at 50–60%, and the subjects were dressed in shorts and shoes only. Exercise commenced at 30 W and thereafter intensity was increased by 30 W every 3 min until volitional exhaustion. Body mass was measured to the nearest 10 g after voiding before exercise and immediately after its cessation. During exercise heart rate (HR), tympanic temperature (Ttymp) and skin temperature (Tsk) were recorded every 3 min. Tympanic temperature was measured using a thermocouple placed directly on the tympanic membrane (Ellab, Copenhagen, Denmark) and Tsk with an infra-red non-contact thermometer with laser alignment RayTemp3 (ETI, UK). Measurements of Tsk were made on the forehead, arm, trunk and thigh. Local sweating rate was assessed on the basis of relative humidity of nitrogen flowing at the rate of 2.0 L/min through the 20.5 cm^2 capsule fixed close to the centre of the mid posterior chest, as previously described [19]. During exercise the sweating rate increases significantly in all regions of the body, with the exception of the feet and ankles, and the central part of the posterior chest and lower back produce the highest sweat rates over the whole body during exercise [20]. Before $NaHCO_3$ or placebo ingestion and then immediately before exercise and at the end of each exercise load venous blood samples were taken through a venous catheter for determination of concentration of hydrogen ions, base excess, HCO_3^-, haemoglobin and haematocrit. The relative humidity of ambient air and nitrogen flowing through the capsule were measured with the Rotronic AG Hygrometer-Control 3 (Switzerland) computerized system with a 1% accuracy. Blood analyses were performed with a Cobas b 121 (Roche, Germany) analyser.

Calculations

Mean Tsk was calculated according to the following equation:

$$\text{Mean Tsk} = 0.6\ \text{Tsk trunk} + 0.1\ \text{Tsk arm} + 0.2\ \text{Tsk thigh} + 0.1\text{Tsk forehead};$$

Changes in plasma volume (ΔPV) were estimated from changes in blood haematocrit (Htc) and haemoglobin concentration [Hb] using the following formula [21]:

$$\%\Delta PV = 100\ [(Hb_0/Hb_t)\ (1\text{-}Htc_t)/(1\text{-}Hct_0)] - 100\%$$

Where subscripts t and 0 denote measurements at time t and at baseline, respectively. The venous Hct values are multiplied by 0.8736 to obtain values close to those of mean value in the whole vascular system.

The threshold of sweating was calculated using the log transformation method [22]. Total sweat loss during exercise was the difference in body mass measured before and immediately after exercise.

Statistics

Data are presented as mean ± SE, unless otherwise stated. The effects of treatment on thermoregulatory responses to exercise were tested by two-way ANOVA for repeated measures. Subsequent post-hoc pairwise comparisons were performed using the Student t-test. The null hypothesis was rejected when $p < 0.05$. For calculations Statistica version 6 (StatSoft Inc, Tulsa, OK, USA) was used.

RESULTS

In both trials duration of exercise ranged from 24 to 30 min and the maximal work loads ranged from 240 to 300 W. Maximal work load achieved by subjects during exercise after placebo and $NaHCO_3$ was almost identical (260.6 ± 6 and 264.8 ± 8 W, respectively, $p > 0.05$), as was maximal heart rate at the end of exercise (186 ± 2 and 184 ± 2 beats/min, $p > 0.05$).

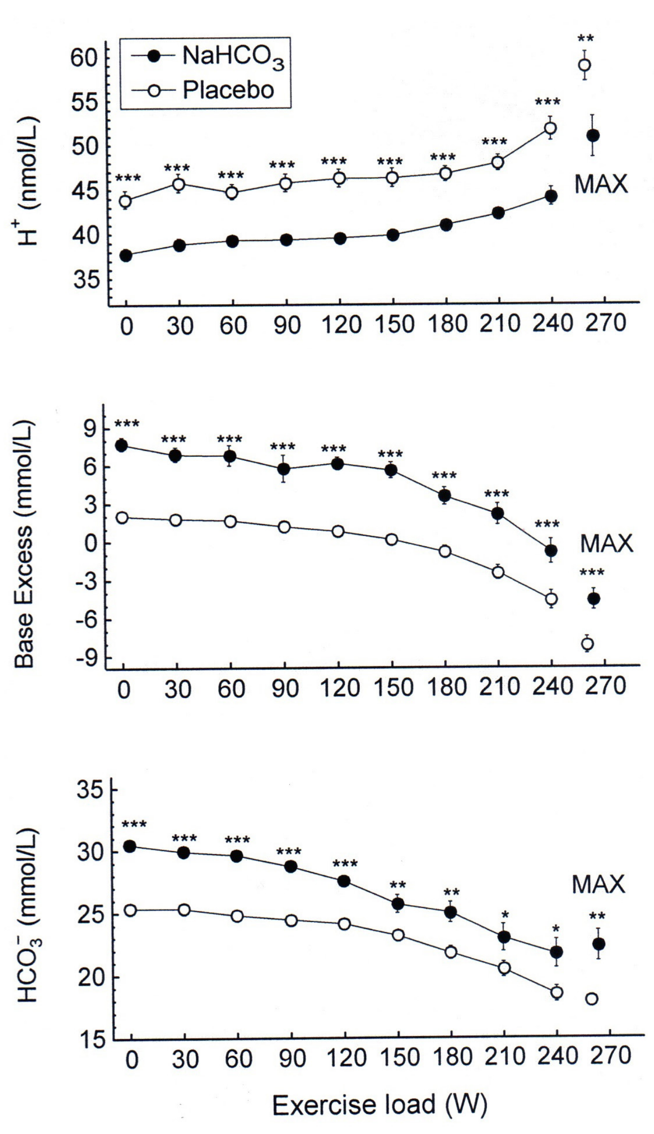

FIG. 1. Acid-base balance parameters during exercise in $NaHCO_3$ and placebo trials. MAX denotes mean values attained at the maximal exercise load; asterisks indicate a significant effect of $NaHCO_3$ ingestion evaluated by two-way ANOVA for repeated measures: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

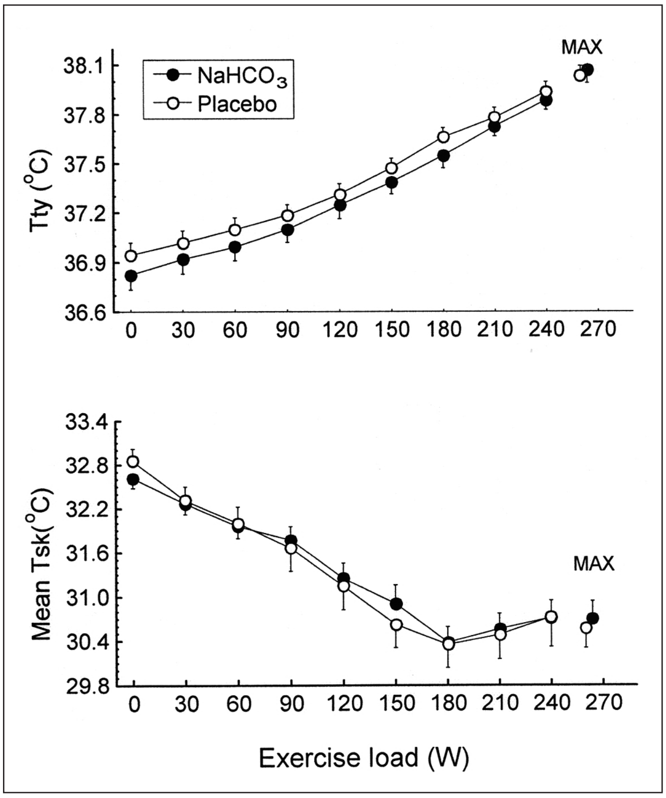

FIG. 2. Tympanic (Ttymp) and mean skin (Tsk) temperatures during exercise in $NaHCO_3$ and placebo trials. MAX denotes mean values attained at the maximal exercise load.

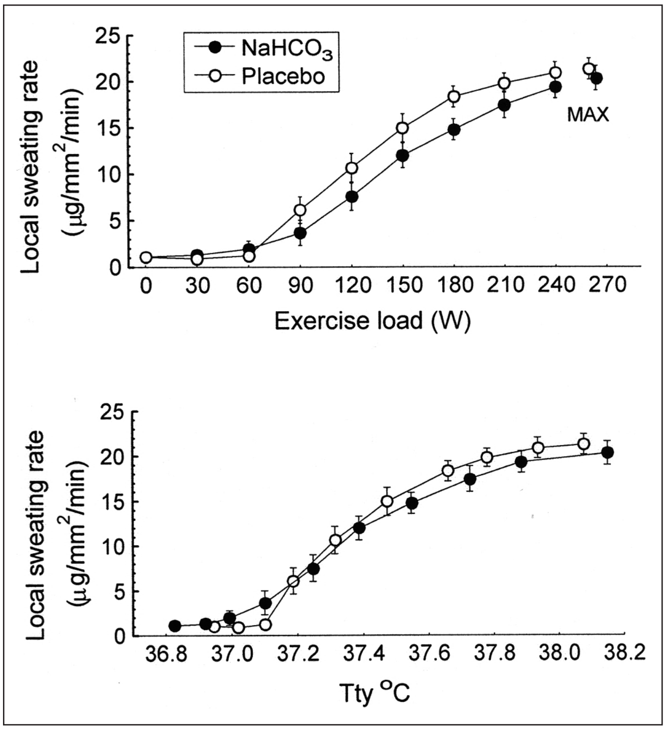

FIG. 3. Local sweating rate measured on the mid posterior chestrelated to exercise load and tympanic temperature (Ttymp). MAX denotes mean values attained at the maximal exercise load.

Blood acid-base status

As shown in Fig. 1, immediately before exercise blood concentration of H^+ was lower (by 6.1 ± 1.0 nmol/L, $p < 0.001$) and blood HCO_3^- and base excess were higher (by 5.1 ± 0.3 mmol/L and 5.1 ± 0.4 mmol/L, respectively, both $p < 0.001$) in the bicarbonate than in the placebo trial. During exercise the concentration of H^+ increased in both placebo and bicarbonate trials by 13.0 ± 2.1 nmol/L ($p < 0.001$) and 12.0 ± 2.2 nmol/L ($p < 0.001$), respectively, with no difference in the exertional increases between trials ($p > 0.05$). It corresponded to the decrease in blood pH from 7.34 ± 0.01 to 7.23 ± 0.01 and from 7.41 ± 0.01 to 7.30 ± 0.02 after placebo and bicarbonate ingestion, respectively (both $p < 0.001$), with no difference in deltas between trials ($p > 0.05$).

The repeated-measures ANOVA revealed that $NaHCO_3$ ingestion had a significant effect on H^+ concentration in blood ($p < 0.001$), although there was no significant interaction between effects of treatment and exercise. There was also a significant effect of $NaHCO_3$ on blood HCO_3^- ($p < 0.001$) and base excess ($p < 0.001$) without significant interactions of the effects of treatment and exercise.

Thermoregulation

There were no significant differences between trials in the resting tympanic temperature and the rate of its increase during exercise (Fig. 2). The mean exercise-induced increases in Ttymp were 1.1 ± 0.1°C and 1.2 ± 0.1°C in the placebo and bicarbonate trials, respectively, both $p < 0.05$. The initial values and the time course of mean skin temperature as well as local sweating rate measured on the centre of the mid posterior chest were also similar in both trials (Fig. 3). The threshold of sweating rate increase occurred at exercise loads of 96 ± 10 W and 100 ± 10 W ($p > 0.05$) and was associated with Ttymp of 37.25 ± 0.06°C and 37.20 ± 0.08°C ($p > 0.05$) in placebo and $NaHCO_3$ trials, respectively. There was no effect of bicarbonate ingestion on the slope of sweating rate increase in relation to Ttymp ($p > 0.05$). The total sweat loss during exercise calculated from changes in body mass was 0.440 ± 0.080 kg after placebo ingestion and 0.410 ± 0.050 kg ($p > 0.05$) after bicarbonate treatment.

Plasma volume

After bicarbonate ingestion, immediately before exercise plasma volume was increased by 2.9 ± 0.9% ($p < 0.05$), while after placebo it remained practically unchanged ($\Delta PV = 0.12 \pm 1.0\%$, $p > 0.05$). During exercise, plasma volume decreased to a similar extent in both trials: by 12.6 ± 1.4% and 11.5 ± 1.6% after bicarbonate and placebo ingestion, respectively (both $p < 0.05$), with no difference between trials ($p > 0.05$).

DISCUSSION

The present study failed to demonstrate any significant effect of diminished metabolic acidosis in blood induced by sodium bicarbonate ingestion on internal body temperature and sweating rate in men during maximal exercise, as well as on sweating threshold in relation to the tympanic temperature. We were not able, therefore, to confirm the hypothesis concerning the role of acid-base balance as a factor contributing to the regulation of body temperature during exercise in humans. However, this finding does not exclude the possibility that metabolic acidosis might adversely influence the heat dissipation mechanism during exercise and/or heat exposure.

Several questions should be considered to interpret the present results. It is not certain whether the hydrogen ion level in blood attained during exercise is high enough to induce the inhibitory effect on hypothalamic warm sensitive neurons or whether metabolic acidosis was maintained for a sufficiently long time to evoke this effect. Comparing metabolic acidosis which occurs during heat stroke with that during maximal exercise without prior alkalization, it appeared that the blood hydrogen ion concentrations were similar [23]. Assuming that metabolic acidosis contributes to the inhibition of heat loss during heat stroke, it seems likely that the exercise-induced metabolic acidosis is sufficient to evoke similar effect [13]. However, it may be speculated that longer duration of metabolic acidosis than that during our exercise test is necessary to influence the thermoregulatory centres. The total duration of exercise, which was 24–30 minutes, was long enough to increase tympanic temperature by more than 1.0°C, but exertional uncompensated metabolic acidosis was present only during the last 6–9 minutes.

Moreover, hypothalamic warm sensitive neurons are partly protected by the blood-brain barrier (BBB), which attenuates the severity of the impact of hydrogen ions. The brain pH results mostly from $PaCO_2$ and HCO_3^- concentrations in the brain interstitial fluid. $PaCO_2$ is the most potent regulator of cerebral blood flow, whereas alterations in arterial HCO_3^- during acute respiratory acidosis/alkalosis contribute to cerebrovascular acid–base regulation [24, 25]. In both metabolic acidosis and alkalosis in humans changes of pH in cerebrospinal fluid are much smaller than in blood [26].

Lactate transport across the BBB is mediated by the proton-linked monocarboxylate transporter MCT1 that transports one H^+ for each lactate molecule and saturates near 2.5–3 mmol/L. During exercise or increased nervous activity, lactate production in the brain increases and it should increase efflux of lactate across the BBB. If lactate concentration in blood is also increased, like during exercise, this may not be possible, or even influx can be observed [26]. The extent of brain pH decrease in the present study is hard to determine, but the duration of uncompensated exercise seems to be too short to affect the thermoregulatory neurons.

A similar conclusion was presented by Caldwell et al., who reported unaltered trans-cerebral $[HCO_3^-]$ exchange during the metabolic acidosis induced by the progressive cycling exercise to exhaustion in humans [27].

However, there are some studies suggesting that BBB integrity might be impaired during exercise, as indicated by the presence of the protein S100β in blood, which is specific for the central nervous system [28, 29]. The factors that may be responsible for transient dysfunction of the BBB during exercise include: development of hyperthermia [30], increase in plasma concentration of adrenaline and acute hypertension [31], increased plasma level of proinflammatory cytokines [32], oxidative stress [33], and changes to the brain serotonin [34]. Interestingly, both TRPV1 and TRPV4 channels are expressed in the subfornical organ area lacking the BBB, which is considered to be the systemic osmosensing region [35, 36].

The transient receptor potential family ion channels, acting as molecular thermometers, are present in many tissues and are influenced by multiple factors, including basic and acidic solutions. Moreover, some other channels, such as the TWIK-related K^+ channel (TREK1, TREK2) and TWIK-related arachidonic acid stimulated K^+ channel (TRAAK), are sensitive to both physical and biological stimuli (mechanical forces during pressure changes or cell swelling, lipids, temperature and pH), so the effects of temperature on membrane tension, thickness or curvature may influence channel gating [6, 37]. There is high expression of TREK1, TREK2 and TRAAK in the nervous system, especially in sensory neurons, where they modulate neuronal sensitivity in a highly temperature-dependent manner; channel activity increases with rising temperature [6]. Intracellular and extracellular pH differentially influences the channels: the TREK2 channel is activated by lower pH, whereas TREK1 and TRAAK are inhibited [37].

The time course of these actions and possible interactions during exercise in humans are hard to predict at the current stage of knowledge, constituting an obvious direction for the future research.

Another reason why diminished metabolic acidosis does not modify the thermoregulatory responses to exercise is that the effect of metabolic acidosis occurring during incremental exercise is overwhelmed by several other, nonthermal factors stimulating the hypothalamic heat dissipation centre. Humoral factors, such as an increase of plasma and cerebrospinal osmolality, elevation of sodium ions and a decrease in calcium ion concentrations adversely affect thermoregulation [6, 38–41].

The last question which should be discussed is the possible direct effect of sodium bicarbonate or placebo ingestion prior to exercise on thermoregulation due to the increases in extracellular fluid volume, which may improve thermoregulation [42] and elevation of sodium ion concentration, which in turn may exert an opposite effect [43, 44]. Previous studies demonstrated that hypervolaemia caused by sodium loading using $NaHCO_3$ or sodium citrate has a beneficial effect on endurance performance and thermoregulation [45–47]. The beneficial effect of diminished metabolic acidosis on thermoregulation was not taken into consideration in these studies. Our study demonstrated that before exercise plasma volume was increased by approximately 3% after bicarbonate ingestion, indicating that the water pool from which sweat can be drawn was greater in this trial than in the placebo trial, but no differences between the trials in sweating rate or body temperature were found. It might be speculated that either the increase in plasma volume was too small to exert any significant effect on thermoregulation or that the improvement of thermoregulation was prevented by an increase in the availability of sodium ions to the thermoregulatory centres. It should be mentioned, however, that some authors did not find any effect of hypervolaemia on sweating rate or body temperature during exercise [48].

It does not exclude the hypothesis that attenuated metabolic acidosis may improve heat loss during exercise. The observations obtained from cell cultures do not always simply extrapolate to whole organisms, and the total thermoregulatory effect is a complex result of several independent components.

CONCLUSIONS

The present data showed that in men attenuation of metabolic acidosis by bicarbonate ingestion did not influence thermoregulation during incremental exercise performed until volitional exhaustion, possibly due to too short duration of exertional uncompensated metabolic acidosis.

Limitations of the study

The experimental design tested a relatively short duration of exercise and mild thermal strain. It does not answer what would happen during prolonged exercise with greater thermal strain or during environmental heat stress.

The focus on male subjects only is obviously a limitation. The majority of physiological phenomena observed in male subjects are simultaneously true for females, whereas possible disturbances caused by the menstrual cycle are avoided.

In the case of application of bicarbonates, possible adverse events should be considered (especially gastrointestinal in chronic supplementation), which limits the applicability of this intervention to help with heat stroke.

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Conflict of interest declaration

The authors did not report any potential conflicts of interest.

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Association between polymorphism rs6295 of *HTR1A* serotonin receptor gene and personality traits among athletes of combat sport

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ABSTRACT: *HTR1A* (5-hydroxytryptamine receptor 1A) and its polymorphic variants are highly important for athletes in different aspects, allowing us to hypothesize their biological influences. Hence, to investigate at least part of the relationship mentioned in the case literature, it was decided to study the association of the selected *HTR1A* polymorphism with personality traits measured by the Temperament and Character Inventory (TCI). The participants consisted of 250 mixed martial arts (combat sport) athletes and 209 healthy male participants (control group). The personality traits were measured for the Revised Temperament and Character Inventory (TCI-R). Genetic material was isolated from whole blood collected from patients, and then all samples were genotyped using the real-time PCR method. Statistical analysis was performed using a 2×3 factorial ANOVA. The research revealed a statistically significant effect of a complex factor of rs6295 of the *HTR1A* serotonin receptor gene with combat sport/control and with Novelty Seeking ($F_{2,453} = 6.126$; $p = 0.0024$; $\eta^2 = 0.026$) and Harm Avoidance ($F_{2,453} = 3.709$; $p = 0.0252$; $\eta^2 = 0.016$). The presence of the *HTR1A* GG genotype (rs6295) was found to be associated with higher scores in self-management and lower scores in harm avoidance, indicating genetic predispositions in the strength group towards better results in combat sports.

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INTRODUCTION

The serotonin family includes at least 14 different 5-HT receptors [1]. The serotonin receptor 5-HTR1A (5-hydroxytryptamine receptor 1A) is a protein that regulates the release of serotonin by acting both as a presynaptic autoreceptor in the serotonergic neurons of the dorsal and medial raphe nuclei and as a postsynaptic heteroreceptor in non-serotonergic neurons. The 5-HTR1A receptor is encoded by a gene located on chromosome 5 (5q11.2–13) [2]. There is a common functional single nucleotide polymorphism (rs6295) in the promoter of the *HTR1A* gene, C (-1019) G. The G allele was associated with higher receptor expression, which led to increased negative feedback inhibition in the serotonergic neurons of the raphe nucleus (mediated by 5-HTR1A autoreceptors) and thus reduced serotonergic activity [3].

The 5-hydroxytryptamine 1A receptor gene (*HTR1A*) is located on chromosome 5 (5q12.3). In the central nervous system, the 5-HT1A receptor subtype is expressed in the cerebral cortex, hippocampus, septum, amygdala and other limbic system structures in the raphe nucleus on the soma and dendrites of 5-HT neurons or postsynaptic receptors, basal ganglia and thalamus [4]. This gene is known for its functional rs6295 polymorphism, located in the promoter region, and regulates *HTR1A* transcription and region-specific modification of *HTR1A* expression [5]. In particular, the rs6295 G allele leads to higher expression of the *HTR1A* gene, leading to an increase in 5-HTR1A autoreceptors and a decrease in the level of the postsynaptic 5-HTR1A receptor [6]. The rs6295 polymorphism may therefore explain the risk of developing a mental illness. Haslacher et al. [7] noted that the C allele might protect against depressive mood in older endurance athletes (risk of development in the control group 30% vs. 2% of athletes carrying the C allele).

Given that athletes' cognitive and psychological skills are critical factors in their ability to achieve a successful sports career, it is imperative to understand the involvement of serotonergic gene polymorphisms [8]. The serotonin 1A receptor is involved in memory and plays a crucial role in learning. It is found at high levels in the hippocampus and the raphe nucleus [4]. CC carriers also have better working and episodic memory [9].

The Temperament and Character Inventory (TCI) provides a comprehensive description of personality traits by measuring seven personality dimensions that are moderately heritable and associated with distinct brain networks and psychological characteristics [10]. The model measures four dimensions of temperament, which include basic emotional drives modulated by the hypothalamus and related limbic structures, and three dimensions of character, which rely on the self-regulation of emotions and attention to achieve the intended goals and values regulated mainly in the neocortex [10]. For example, high levels of self-targeting are associated with the executive attention system involving bipolar neurons in the anterior, frontal, and anterior cingulate [11]. Low Harm Avoidance is associated with diminished functional connectivity in the island's projection network (i.e., the right anterior island with anterior cingulate gyrus and dorsolateral prefrontal cortex) [12]. Greater novelty seeking and less harm avoidance are associated with greater white matter volumes bilaterally in the cerebellum and cortex. Higher novelty scores are associated with larger caudate and bilateral pale nuclei volumes, while lower harm avoidance is related to reduced crust diffusivity as measured by diffusion tensor imaging [13].

HTR1A and its polymorphic variants are highly important for athletes in different aspects, allowing us to hypothesize their biological influences. Hence, to show at least part of the relationship mentioned in the case literature, it was decided to present the association of the selected *HTR1A* polymorphism with personality traits measured by the TCI test

TABLE 1. Fundamental biological features of tested combat sports group and control group.

Feature	Combat sport *n* = 250 (M ± SD)	Control *n* = 209 (M ± SD)
Age (years)	26.16 ± 8.34	23.35 ± 5.35
Body mass (kg)	79.78 ± 13.76	81.85 ± 10.89
Height (cm)	178.34 ± 7.37	181.81 ± 6.22
BMI (kg/cm^2)	24.62 ± 4.21	24.33 ± 4.30

n – number of subjects, M – mean, SD – standard deviation, BMI – Body Mass Index.

MATERIALS AND METHODS

Research groups

Both athletes and controls were of Caucasian origin and living in one Polish region. The experiment was based on a group of 250 healthy Polish males (no prior history of substance dependency or psychosis) practising mixed martial arts (combat sports) aged 26.16 ± 8.34; mixed martial arts (MMA), n = 86; judo, n = 52; boxing, n = 52; karate, n = 26; kickboxing, n = 21; ju-jitsu, n = 13). Controls included 209 healthy (non-dependent and non-psychotic) Polish male volunteers aged 23.35 ± 5.35. All athletes and controls were white to reduce the possibility of racial bias and overcome any potential problems resulting from population stratification (Table 1). The study was supported by the National Science Centre of Poland (No. UMO-2017/27/B/NZ7/00204). The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Bioethics Committee for Clinical Research of the Regional Medical Society in Szczecin, Marii Skłodowskiej-Curie 11 Street (protocol no. 13/KB/VI/2016, 8 December 2016).

DNA Isolation and Genotyping

A standard procedure of collecting venous blood was applied to obtain genomic DNA used for genotyping by the real-time PCR method. According to the standard manufacturer's protocols, the genotyping of the rs6295 *HTR1A* gene was performed with fluorescence resonance energy transfer in the LightCycler 480 II System (Roche Diagnostic, Basel, Switzerland).

Psychometric Tests

All participants in this study were asked to perform a psychometric test, precisely the Revised Temperament and Character Inventory [NO_PRINTED_FORM]. TCI-R is a self-report questionnaire assessing four temperaments (Harm Avoidance, Novelty Seeking, Reward Dependence, and Persistence) and three character higher-order dimensions (Self-Directedness, Cooperativeness, and Self-Transcendence) [14, 15]. Temperament refers to individual differences in percept-based habits and skills that are regulated by the limbic system [16, 17] and measured by four independently inherited dimensions that are moderately stable throughout life: Novelty Seeking (NS) refers to a tendency toward exploratory activities in response to novelty and is hypothesized to be mediated by a dopaminergic behavioural activation system; Harm Avoidance (HA) refers to pessimistic worrying in anticipation of problems that are hypothesized to be mediated by a serotonergic behavioural inhibition system; Reward Dependence (RD) is defined as a tendency to maintain behaviours in response to reward by others and is mediated by a noradrenergic behavioural maintenance subsystem; Persistence (PS) is an independent dimension and refers to a tendency to perseverance despite frustration and fatigue.

Statistical Analysis

The distribution of rs6295 of the *HTR1A* serotonin receptor gene was tested by Hardy-Weinberg equilibrium (HWE) with the HWE software http://www.oege.org/software/hwe-mr-calc.html.

The variables that were analysed did not have a normal distribution. The results of the Mann-Whitney U test were used to determine the difference in the investigated features of Novelty Search, Harm Avoidance, Reward Dependence, Self-management, Cooperation abilities, and Self-transcendence skills.

Not all assumptions required for the ANOVA analysis were met. The speculation about the normal distribution was not fulfilled for all dependent variables, but the variance was the same (Levene's test $p > 0.05$). Because the number of subjects in groups was also significant, it was decided to use multivariate analysis: 2×3 factorial ANOVA. The test was used to show an association between Novelty Seeking, Harm Avoidance, Reward Dependence, Self-management, Cooperation abilities, Self-transcendence skills results and the combat sport and control group, and the rs6295 of *HTR1A* polymorphism (personality traits × control and combat sports subjects × genetic feature).

The frequencies of genotypes and alleles of the rs6295 polymorphism of *HTR1A* in analysed groups were compared by the chi-square test. All analyses were performed using STATISTICA 13 (Tibco Software Inc, Palo Alto, CA, USA) for Windows (Microsoft Corporation, Redmond, WA, USA).

RESULTS

The frequency distributions accorded with the HWE. There was no significant difference between combat sports subjects and control subjects (Table 2).

Association analysis of genotypes and alleles of the *HTR1A* rs6295 polymorphisms and combat sport revealed statistically significant differences only in the co-dominant model in frequencies of genotypes (G/G 0.30 vs. 0.21; G/C 0.54 vs. 0.54; C/C 0.16 vs. 0.24; $\chi^2 = 6.495$; $p = 0.039$). In contrast, there was a statistically significant difference between the control group and combat sport group in the additive model (Cochran-Armitage trend test) in *HTR1A* rs6295 polymorphisms ($Z = -2.539$ $p = 0.011$). Significant differences in the frequency of *HTR1A* rs6295 gene alleles between combat sport subjects and the control group were found (G 0.57 vs. G 0.49, C 0.43 vs. C 0.51, $\chi^2 = 5.900$, $p = 0.015$) (Table 3).

The means and standard deviations for Novelty Seeking, Harm Avoidance, Reward Dependence, Self-management, Cooperation abilities, and Self-transcendence skills in a group of combat sports subjects and control subjects are presented in Table 4. Compared to the controls, the case group subjects had significantly higher scores

TABLE 2. Hardy-Weinberg equilibrium of *HTR1A* rs6295 polymorphism in combat sports subjects and controls group.

Group	***HTR1A* rs6295**				
	Observed (Expected)		**Alleles frequency**	**χ^2**	***p* value**
combat sport, *n* = 250	GG	74 (80.1)	p allele freq (G) = 0.57 q allele freq (C) = 0.43	2.458	0.117
	GC	135 (122.8)			
	CC	41 (47.1)			
controls, *n* = 209	GG	45 (225.4)	p allele freq (G) = 0.49 q allele freq (C) = 0.51	1.413	0.234
	GC	113 (55.2)			
	CC	51 (3.4)			

p – statistical significance, χ^2 – Chi^2 test result, *n* – number of subjects.

TABLE 3. Frequency of genotypes and alleles of the rs6295 polymorphism of *HTR1A* in combat sports subjects and controls.

	Combat sport	**Controls**	**Co-dominant model χ^2 (*p* value)**	**OR (95% Confidence)**	**Additive model Cochran – Armitage trend test Z (*p* value)**
***HTR1A* rs6295**					
	n = 250 (%)	*n* = 209 (%)	6.495 (0.039)*	0.72 (0.46–1.14)	-2.539 (0.011)*
G/G	74 (30%)	45 (21%)			
G/C	135 (54%)	113 (54%)			
C/C	41 (16%)	51 (24%)			
G	283 (57%)	203 (49%)	5.900 (0.015)*	0.50 (0.29–0.87)*	
C	217 (43%)	215 (51%)			

p – statistical significance, χ^2 – Chi^2 test result, n – number of subjects, * – significant statistical differences. OR – Odds Ratio

TABLE 4. Analysis of Novelty Seeking, Harm Avoidance, Reward Dependence, Self-Management, Ability to Cooperate, and Self-transcendence results in combat sports subjects and controls.

Temperament and Character Inventory (TCI)	Combat sport (*n* = 250) M ± SD	Control (*n* = 209) M ± SD	U Mann-Whitney test	*p* value
Novelty Seeking	20.03 ± 4.72	20.45 ± 4.36	-0.717	0.473
Harm Avoidance	9.66 ± 4.92	11.60 ± 4.57	-4.594	< 0.00001*
Reward dependence	10.03 ± 3.03	10.44 ± 2.95	-1.173	0.241
Self-management	26.30 ± 4.37	24.01 ± 5.03	4.850	< 0.00001*
Cooperative abilities	20.59 ± 4.59	19.83 ± 4.59	1.949	0.051
Self-transcendence skills	6.94 ± 3.59	7.09 ± 3.63	-0.419	0.675

M – mean, SD – standard deviation, * – statistically significant between-group, n – number of subjects.

TABLE 5. The results of 2 × 3 factorial ANOVA for combat sports subjects and controls, incorporating: Novelty Seeking, Harm Avoidance, Reward dependence, Self-management, Ability to cooperate, Self-transcendence skills results and *HTR1A* rs6295.

Temperament and Character Inventory (TCI)	Group	*HTR1A rs6295* G/G (n = 119) M ± SD	G/C (n = 248) M ± SD	C/C (n = 92) M ± SD	ANOVA (interaction) Combat sport /Control × *HTR1A* rs6295; F (*p* value)	η^2
Novelty Seeking	combat sport; n = 250	20.73 ± 4.55	19.95 ± 5.09	19.00 ± 3.45	$F_{2,453}$ = 6.126 (*p* = 0.0024)*	0.026
	Control; n = 209	18.73 ± 1.97	20.78 ± 5.00	21.25 ± 4.02		
Harm Avoidance	combat sport; n = 250	8.12 ± 4.26	10.20 ± 5.14	10.63 ± 4.78	$F_{2,453}$ = 3.709 (*p* = 0.0252)*	0.016
	Control; n = 209	12.04 ± 4.30	11.53 ± 4.84	11.37 ± 4.22		
Reward dependence	combat sport; n = 250	9.99 ± 2.97	9.98 ± 3.03	10.29 ± 3.18	$F_{2,453}$ = 0.130 (*p* = 0.8777)	0.0006
	Control; n = 209	10.22 ± 3.01	10.31 ± 2.97	10.94 ± 2.87		
Self-management	combat sport; n = 250	25.88 ± 4.20	26.51 ± 4.49	26.39 ± 4.33	$F_{2,453}$ = 0.880 (p = 0.4154)	0.004
	Control; n = 209	24.60 ± 4.55	23.86 ± 5.01	23.82 ± 5.51		
Cooperative abilities	combat sport; n = 250	20.12 ± 4.57	20.60 ± 4.69	21.41 ± 4.25	$F_{2,453}$ = 0.115 (*p* = 0.8913)	0.0005
	Control; n = 209	19.62 ± 4.27	19.70 ± 4.85	20.33 ± 4.28		
Self-transcendence skills	combat sport; n = 250	6.40 ± 3.55	7.21 ± 3.62	7.02 ± 3.33	$F_{2,453}$ = 1.233 (*p* = 0.2923)	0.005
	Control; n = 209	6.55 ± 3.48	6.87 ± 3.80	8.05 ± 3.26		

M – mean, SD – standard deviation, n – number of subjects, *p* – statistical significance, * – significant statistical differences, η^2 – eta square

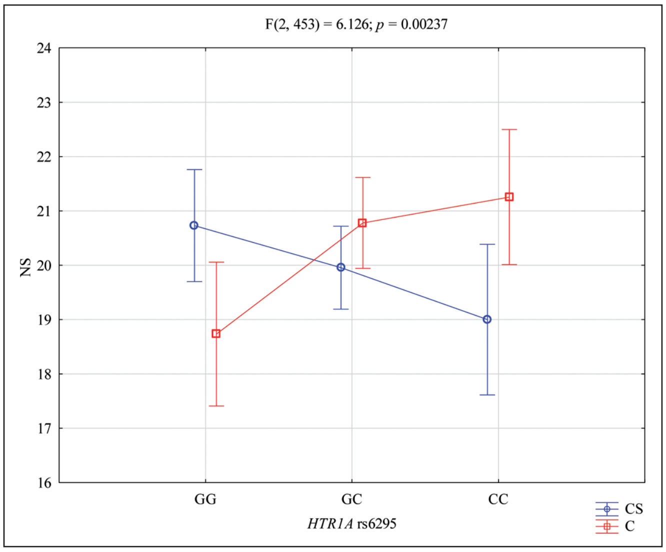

FIG. 1. Interaction between CS (combat sport)/C (control) and rs6295 of *HTR1A* and NS – Novelty Seeking scale.
NS – Novelty Seeking, *p* – statistical significance, CS – combat sport, C – control, GG and CC – genotypes (homozygotes), GC – genotype (heterozygote), G and C – alleles

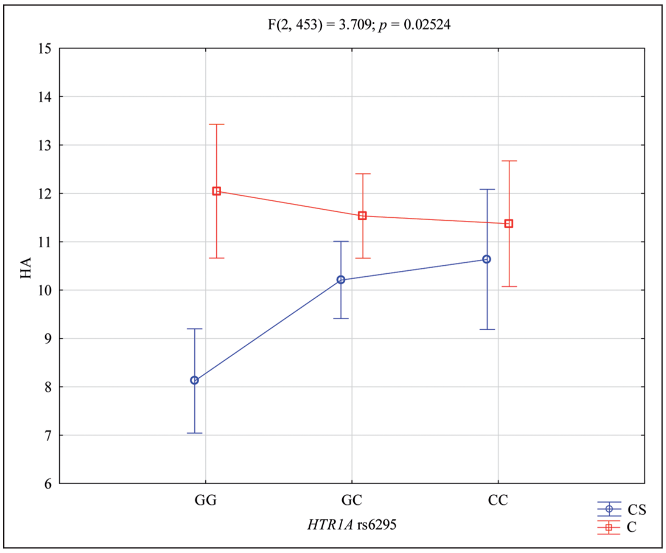

FIG. 2. Interaction between CS (combat sport)/C (control) and *HTR1A* rs6295 and HA – Harm Avoidance scale.
HA – Harm Avoidance, *p* – statistical significance, CS – combat sport, C – control, GG and CC – genotypes (homozygotes), GC – genotype (heterozygote), G and C – alleles

TABLE 6. Post hoc LSD (least significant difference) test of interactions between combat sport/controls, *HTR1A* rs6295, and the Novelty Seeking, Harm Avoidance scale.

***HTR1A* rs6295 and Novelty Seeking scale**						
	{1} 20.73	{2} 19.96	{3} 19.00	{4} 18.73	{5} 20.78	{6} 21.26
Combat sport *HTR1A* G/G {1}		0.2366	0.0498*	0.0198*	0.9422	0.5232
Combat sport *HTR1A* G/C {2}			0.2360	0.1166	0.1535	0.0807
Combat sport *HTR1A* C/C {3}				0.7846	0.0313*	0.0177*
Control *HTR1A* G/G {4}					0.0105*	0.0066*
Control *HTR1A* G/C {5}						0.5323
Control *HTR1A* C/C {6}						
***HTR1A* rs6295 and Harm Avoidance scale**						
	{1} 8.12	{2} 10.21	{3} 10.63	{4} 12.04	{5} 11.53	{6} 11.37
Combat sport *HTR1A* G/G {1}		0.0024*	0.0065*	0.00001*	0.000002*	0.0002*
Combat sport *HTR1A* G/C {2}			0.6125	0.0243*	0.0284*	0.1339
Combat sport *HTR1A* C/C {3}				0.1672	0.2980	0.4563
Control *HTR1A* G/G {4}					0.5376	0.4869
Control *HTR1A* G/C {5}						0.8424
Control *HTR1A* C/C {6}						

* – significant statistical differences. For these variables, G/G and C/C – genotypes (homozygotes), G/C – genotype (heterozygote), G and C – alleles, 1 – G/G, 2 – C/C, 3 – C/C, 4 – G/G, 5 – G/C, 6 – C/C, *HTR1A* – 5-hydroxytryptamine receptor 1A

on Self-management (M 26.30 vs. M 24.01; $p < 0.00001$) and lower scores on the scales of Harm Avoidance (M 9.66 vs. M 11.60; $p < 0.00001$) (Table 4).

Novelty Seeking and HTR1A rs6295

The 2 × 3 factorial ANOVA results showed a statistically significant effect of the interaction Novelty Seeking and *HTR1A* rs6295 genotype of combat sport/control ($F_{2,453} = 6.126$; $p = 0.0024$; $\eta^2 = 0.026$) (Table 5, Figure 1). Power calculation: the sample had more than 89% power to detect the combined factor of Novelty Seeking combat sport/control × *HTR1A* rs6295 and their interaction effect (about 2.6% of the phenotype variance). The results of the post hoc test are included in Table 6.

Harm Avoidance and HTR1A rs6295

The results of 2 × 3 factorial ANOVA showed a statistically significant effect of the interaction Harm Avoidance and *HTR1A* rs6295 genotype of combat sport/control ($F_{2,453} = 3.709$; $p = 0.0252$; $\eta^2 = 0.016$) (Table 5, Figure 2). Power calculation: the sample had more than 68% power to detect the combined factor of Harm Avoidance combat sport/control × *HTR1A* rs6295 and their interaction effect (about 1.6% of the phenotype variance). The results of the post hoc test are included in Table 6.

DISCUSSION

The present study focused on gene variants that potentially influence the modulation of emotion-regulating systems, particularly the gene responsible for encoding components of the serotonergic system.

Genetic factors are widely recognized to influence various phenotypic traits related to sports performance and the achievement of elite athletic status [18]. More than 200 genetic variants are associated with physical performance, and 155 are linked to elite athlete status [19]. Undoubtedly, psychological factors play a significant role, especially at the sport's highest level [20]. Between 70% and 85% of successful and unsuccessful athletes can be distinguished using the general psychological personality structure and mood state [21]. For example, the authors recently noted an association between the *DAT1* VNTR (Variable Number of Tandem Repeats) variant and lower anxiety levels in a group of tested athletes [22]. Also, it was observed that temperamental characteristics may indicate higher resilience of the nervous system in combat athletes in comparison to non-athletes [23]. However, the genetic foundation of the emotional and mental features predisposing to outstanding athletic performance is still elusive.

It was observed previously that mentally tough athletes effectively use motor skills in stressful situations to perform cognitive tasks better [24]. It is widely assumed that mental qualities such as planning skills, persistence, patience, mental strength, ambition and pursuit of leadership, stress-coping, preventing anxiety-like behaviour, and avoiding impulsivity and uncontrolled aggressiveness facilitate athletic training and success in competition [25]. Competition, especially its crucial moments, requires maximum physical and mental mobilization from the athlete. Training must comprise physical and psychological preparation to achieve a high level of sports efficiency. Since physical differences among top-level athletes are often barely noticeable, their ability to deliver optimal physical and mental performance precisely when required could be the decisive factor determining their actual standing [26].

Competition-facilitating behaviour and the low-stress response described above differentiate athletes from sedentary subjects [27]. Peplonska et al. [28], to search for the putative genetic background of mental characteristics, analysed 67 polymorphic variants in 28 genes potentially associated with behaviour, mood, and emotion expression plausibly related to competitiveness. These variants have previously been considered mainly in addiction, depression, suicidal tendencies, the aetiology of numerous psychosomatic and psychiatric disorders, and aggressive behaviour.

Both variants have been analysed previously, especially in the behavioural context. *HTR1B* rs11568817 has been associated with alcohol and drug abuse, whereas *HTR2C* rs3813929 has been associated with increased resistance to obesity and type II diabetes, but also migraine, schizophrenia, and depression [29]. Genetic association studies cannot point to particular molecular mechanisms underlying various phenotypes, as mentioned above, especially given the pleiotropic nature of genes. Mechanisms linking genetic variants with sport-related phenotypes, taking into account the function of genes bearing the variants, can only be hypothesized. It could be speculated that the common elements in such different behaviours as, e.g., addiction and sports competition, are based on a craving for excitement. However, explaining genotype-phenotype relationships requires in-depth functional studies [28].

In several studies of twins, the relative share of genetic factors in personality traits ranged from 40 to 60% [30]. In the biosocial theory of personality, Cloninger, using the Temperament and Character Inventory (TCI), found that temperament dimensions are especially related to activity in certain central neurotransmitter systems. However, the dimension of the character of self-transcendence is the most stable in the time dimension of TCI and the dimensions of TCI, showing the greatest variability among individuals [31]. TCI self-transcendence consists of three subscales: Spiritual Acceptance, Transpersonal Identification, and Self-Forgetting.

The polymorphism of the serotonin transporter (5-*HTTLPR*) promoter, consisting of a variable number of tandem repeats (VNTR), has been extensively studied in relation to personality disorders and mental disorders. Functional studies have shown that 5-*HTT* gene transcription is differently modulated by long and short 5-*HTTLPR* variants, where the short variant is associated with lower 5-*HTT* expression and lower 5-HT reuptake activity [32].

In this study, we report that the character of the self-transcendence personality, estimated using the Cloninger TCI, was significantly related to the genotype of the 5-*HTTLPR* gene polymorphism, as reported by Heils et al. [33], as well as to the variable repeat [CAAA] in the second intron of the AP-2β transcription factor gene described by Moser et al. [34]. The associations, however, occurred only in boys. Data supporting the results presented by Borg et al. [35] showed that 5-HT1A (11C) WAY100635 receptor-ligand binding was associated with the expression of Self-transcendence, but only in boys. The Self-transcendence dimension includes several aspects of religious behaviour, subjective experience, and individual worldview. In the Minnesota Study of Twins Reared Apart, religious heredity was found to be approximately 40% [36][34]. Links to multiple monoaminergic gene alleles further support genetic solid regulation of the character trait Self-transcendence (spiritual acceptance) with 5-HT1A receptor [34], 5-HT2A and 5-HT6 [37], and dopamine D4 polymorphisms.

Undoubtedly, psychological factors play a significant role, especially at the sport's highest level. Additionally, many reports emphasize the positive effect of exercise on the anti-depressant state [38]. Between 70% and 85% of successful and unsuccessful athletes can be distinguished using general psychological measures of personality structure and mood state [21]. However, the genetic foundation of the emotional and mental features predisposing to outstanding athletic performance remains elusive.

Several studies have investigated a potential association between the C(−1019)G polymorphism and various personality traits; using the revised five-factor Personality Inventory (NEO-PI-R) and the Tridimensional Personality Questionnaire (TPQ), higher scores for Neuroticism and Harm Avoidance were found in carriers of the G allele compared with C allele carriers [39], while other studies did not find any significant association between neuroticism and this SNP [40].

In a study of a Hungarian population, G/G carriers displayed significantly higher impulsivity levels than G/C and C/C carriers [40].

Furthermore, the C(-1019)G polymorphism was investigated in relation to personality traits. The G allele was associated with different anxiety- and depression-related personality traits in a nonclinical German population, such as neuroticism and harm avoidance [39]. However, such an association was not always supported. Another study also failed to report an association between the C(-1019)G polymorphism and different personality traits in a German population of suicide attempters and healthy controls and an Italian population of patients diagnosed with a mood disorder [16].

This study revealed that personality traits are an area of note in analysing genetics in a dispute. As it was observed in this analysis, the results of 2 × 3 factorial ANOVA showed a statistically significant effect of the interaction between Novelty Seeking and *HTR1A* rs6295 genotype of combat sport/control subjects. This relationship is clearly illustrated in Figure 1. However, another feature also deserves attention – Harm Avoidance – the results of 2 × 3 factorial ANOVA showed a statistically significant effect of the interaction between Harm Avoidance and *HTR1A* rs6295 genotype of combat sport/control subjects. There was more than 68% power to detect the combined factor of Harm Avoidance combat sport/control × *HTR1A* rs6295 and their interaction effect.

Genetic polymorphism may be used as an additional scientific tool to assist athletes and coaches in sport selection [17].

CONCLUSIONS

The study reveals the validity of analysing connections between personality traits and selected gene polymorphisms in athletes, a relatively new field. The presence of the *HTR1A* GG genotype (rs6295) is associated with higher self-management scores and lower harm avoidance scores, indicating genetic predispositions in the strength group for better results in combat sports. Despite limitations such as a small sample size and limited analysis of polymorphic variants, the findings already demonstrate significant associations. Further research with larger participant groups and expanded gene analysis is needed to explore these relationships more comprehensively.

Conflict of interest declaration

The authors declared no conflict of interest.

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DOFINANSOWANO ZE ŚRODKÓW BUDŻETU PAŃSTWA

Program Ministerstwa Nauki i Szkolnictwa Wyższego
Rozwój Czasopism Naukowych
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20 stycznia 2023