Proposed Title:

Submaximal Fitness Tests in Team-Sports: A Theoretical Framework for Evaluating Physiological State

Abstract-Only Word Count: ~315

Text-Only Word Count: ~7000

Authors:

Tzlil Shushan¹, Shaun J. McLaren^{2,3}, Martin Buchheit^{4,5,6,7}, Tannath J. Scott^{8,9}, Steve Barrett¹⁰ and Ric Lovell¹

¹ School of Health Sciences, Western Sydney University, Sydney, NSW, Australia

² Newcastle Falcons Rugby Club, Newcastle upon Tyne, UK

³ Department of Sport and Exercise Sciences, Durham University, Durham, UK

⁴ HIIT Science, Revelstoke, BC, Canada

⁵ French National Institute of Sport (INSEP), Laboratory of Sport, Expertise and Performance (EA 7370), Paris, France

⁶ Kitman Labs, Performance Research Intelligence Initiative, Dublin, Ireland

⁷ Institute for Health and Sport, Victoria University, Melbourne, VIC, Australia

⁸ Netball Australia, Victoria, Australia

⁹ Carnegie Applied Rugby Research (CARR) centre, Institute for Sport, Physical Activity and Leisure.

¹⁰ Department of Sport Science Innovation, Playermaker, London, United Kingdom

Corresponding Author:

Tzlil Shushan

School of Health Sciences, Western Sydney University

Email: Tzlil21092@gmail.com

ORCID

Tzlil Shushan 0000-0002-0544-1986

Shaun J. McLaren 0000-0003-0480-3209

Tannath J. Scott 0000-0003-4336-2370

Steve Barrett 0000-0002-6751-9937

Ric Lovell 0000-0001-5859-0267

Twitter Tag

Tzlil Shushan @shushan_tzlil

Shaun J. McLaren @Shaun_McLaren1

Martin Buchheit @mart1buch

Tannath J. Scott @TannathScott

Steve Barrett @SteveBarrett5

Ric Lovell @ric_lovell

Declarations

Authors Contributions TS conceived the idea for the article, performed the literature search and data analysis, wrote the first draft of the manuscript and all versions after. RL and SJM provided a significant writing content and revision to the manuscript. RL, SJM, MB, TJC and SB contributed substantially to the conceptual direction, content and provided edits and feedback to the manuscript. All authors read and approved the final manuscript. TS coordinated the submission and revision process.

Funding No sources of funding were used to assist in the preparation of this article.

Conflict of Interest All authors declare that they have no conflicts of interest directly relevant to the content in this article

Availability of data and material Supplementary materials for this paper are also available on the Open Science Framework at <https://osf.io/f9xwj/>

Ethics Approval Not applicable

This manuscript is a preprint version of a paper submitted in Sports Medicine. All authors agree to the sharing of this preprint on Open Science Framework (OSF).

Please cite as: Shushan T., McLaren J.M., Buchheit M., Scott J.S., Barret S., Lovell R., (2022). Submaximal Fitness Tests in Team-Sports: A Theoretical Framework for Evaluating Physiological State.

Abstract

Team-sports staff often administer non-exhaustive exercise assessments with a view to evaluating physiological state, to inform decision-making on athlete management (e.g., future training or recovery). Submaximal Fitness Tests (SMFT) have become prominent in team-sports settings for observing responses to a standardised physical stimulus, likely due to their time-efficient nature, relative ease of administration and physiological rationale. It is evident, however, that many variations of SMFT characteristics, response measures and monitoring purposes exist. The aim of this scoping review is to provide a theoretical framework of SMFT and a detailed summary of their use as proxy indicators of training effects in team-sports. Using a review of the literature stemming from a systematic search strategy, we identified five distinct SMFT protocols characterised in their combinations of exercise regimen (continuous or intermittent) and the progression of exercise intensity (fixed, incremental or variable). Heart rate (HR) derived indices were the most studied outcome measures in SMFT and included exercise (exercise HR) and recovery (HR recovery and vagal-related HR variability) responses. Despite the disparity between studies, these measures appear more relevant to detect positive chronic endurance-oriented training effects, whereas their role in detecting negative transient effects associated with variations in autonomic nervous system function is not yet clear. Subjective outcome measures such as ratings of perceived exertion were less common in team-sports, but their potential utility when collected alongside objective measures (e.g., exercise HR) has been advocated. Mechanical outcome measures either included Global-Positioning-System-derived locomotor outputs such as distance covered, primarily during standardised training drills (e.g., small-sided games) to monitor exercise performance, or responses derived from inertial-measurement units to make inferences about lower limb neuromuscular function. Whilst there is an emerging interest regarding the utility of these mechanical measures, their measurement properties and underpinning mechanisms are yet to be fully established. Herein, we provide a deeper synthesis of the available literature, culminating with evidence-based practical recommendations and directions for future research.

Key Points:

- Submaximal Fitness Tests (SMFT) provide a practical tool for team-sport practitioners to evaluate athlete's physiological state in a short-duration and non-exhaustive manner, whereby testing can be integrated within the training session.
- We propose a theoretical framework for SMFT in team-sports, encompassing an operational definition, five test protocol categories according to their exercise regimen and intensity parameters, and an evidence-based synthesis of protocols and outcome measures derived from three main response types: cardio-respiratory/metabolic, subjective and mechanical.
- Heart rate indices are most prevalent in the literature (57% of all outcome measures) and appear sensitive to detect positive endurance-oriented training effects. However, their utility in inferring negative transient effects associated with variations in autonomic nervous system function is questionable in team-sports.
- At present, limited evidence exists regarding the utility of ratings of perceived exertion to monitor training effects within SMFT in team-sports.
- Collecting outcome measures derived from inertial-measurement units during SMFT may be a promising approach to monitor transient changes in lower limb neuromuscular function. Further work to establish the underlying theoretical framework and measurement properties is warranted.

1. Background

Monitoring the training process and its outcomes within team-based sports requires a systematic approach that: 1) is grounded on a rigorous, conceptual framework; 2) can be implemented pragmatically on a frequent basis; 3) uses proxy outcome measures possessing sufficient measurement properties; and 4) is sensitive to identify acute (for example, post-match) and chronic (e.g., post training program) training effects [1–4]. Such an approach can be used to inform decision-making around athlete and training management, including future programming, adjustments to training delivery, or the implementation of recovery interventions [1].

Assessing aerobic-oriented training effects has traditionally been made via distinct, maximal effort, exhaustive tests. For example, improvements denoted in maximal intermittent field tests (e.g., 30-15 intermittent fitness test) can infer improved aerobic capacity (amongst other systems), whereas decreased values may be interpreted as a negative response or de-training [5,6]. However, given the nature of the in-season phase common to professional teams, which frequently experiences fixture congested periods, it is considered less feasible to expose athletes to serial exhaustive assessments [7,8]. With regards to neuromuscular function, a variety of test protocols are administered to quantify chronic training effects on athletic qualities such as strength and power, but more frequently as indicators of acute and transient responses (e.g., post-match recovery kinetics) [7,9]. Similarly, the practicability of such assessments in the team-sports environment is challenged by different factors such as the number of athletes, the time available for discreet testing protocols, and the numerous contextual and individual elements that may undermine inferences derived from the data (e.g., motivation, physical qualities, season stage) [1,7,8].

Submaximal Fitness Tests (SMFT) have been proposed to deliver a feasible alternative to evaluate athlete's physiological state, presumably due to their time-efficient nature, low physical/physiological burden and relative ease of administration [10]. In essence, SMFT provide a pragmatic and systematic approach of observing response(s) to a standardised physical stimulus [11,12]. Such assessments have been investigated since the late 1940's [13] and were mainly adopted among clinicians diagnosing

health conditions or physical fitness in non-athletic populations, whereby exposure to maximal or exhaustive activities was thought to be ill-advisable due to the health risk it posed to patients [13,14]. Over the years, a number of walking [15–19], cycling [14,20–22] and running [23,24] SMFT have been administered among clinical and healthy populations. These tests involve single or multiple continuous steady-state protocols, with some prescribing an absolute standardised intensity, while others include relative intensity ranges, or self-paced protocols (refer to Table 1 in Supplementary File S1).

1.1 Elite Sports

The implementation of SMFT in elite sports has been traditionally used for quantifying relevant physiological transitions between exercise intensity domains (for example, anaerobic threshold [i.e., the threshold indicates an equal rate of lactate production and disposal] and onset of blood lactate accumulation [$4 \text{ mmol} \cdot \text{L}^{-1}$ lactate threshold]) [26,27], often administered to inform training prescription or determine exercise economy. However, these tests generally necessitate a laboratory environment, are resource intensive and obtrusive, and therefore considered less feasible in the day-to-day field context, particularly with large cohorts of athletes [7].

Individual endurance sport practitioners were the first to develop and implement SMFT as part of their training monitoring processes [28,29]. Throughout the years, a broad range of cycling and running SMFT have been adopted across a variety of endurance sport athletes such as cyclists [28–32], runners [33–35] and triathletes [29,36,37]. Extensively used SMFT in endurance sports include exercise tasks prescribed by fixed internal intensities (% of an individual heart rate maximum) [32,34], while the outcome measures are considered both external (e.g., speed [34], cadence, power [32] collected throughout the test) and internal responses (heart rate recovery [38,39], ratings of perceived exertion [RPE] [32] collected immediately post-exercise). Alternatively, researchers have adopted tests using standardised external intensities (usually via absolute running speed values) [33,37]. Initially, the primary purpose of these SMFT was to predict performance (e.g., time-trial) or physiological capacities (i.e., maximal oxygen uptake) [32], however, more recently they have been used to identify impaired performance (for example, functional-overreaching) [40,41].

Due to the simplicity of implementing SMFT, their non-exhaustive nature, and their potential to provide information regarding both positive and negative training effects, SMFT have become common in team-sports. Indeed, the adoption of SMFT in team-sports research [8,10,42] and practice [43,44] has increased substantially over the last decade. However, given the broad range of SMFT adopted, including various protocols (continuous versus intermittent) [45,46], activity modes (running versus cycling) [47,48], intensities (fixed versus incremental, absolute versus individualised) [12,48], outcome measures (cardio-respiratory/metabolic, subjective or mechanical) [12,49,50], and purposes (monitoring positive versus negative effects) [47,51], a synthesis appears warranted. Accordingly, the aims of this scoping review were to 1) develop an operation definition of SMFT and protocol taxonomy, 2) identify previously used SMFT in the team-sports research and discuss their conceptual and methodical aspects, 3) provide an audit of outcome measures, collection methods and analytical processes, as well as evaluate the theoretical rationale underpinning their inclusion, 4) provide a narrative synthesis of the available research on SMFT as indicators of training effects in team-sports, and 5) conclude with practical recommendations and future directions.

2. Methods

Systematic searches of the electronic databases MEDLINE, Scopus, and Web of Science were used to identify relevant studies. From 2170 records identified in the original searches, we accepted 87 team-sport studies meeting our inclusion criteria. A detailed description of the searching strategy, screening process, and the inclusion–exclusion criteria are provided in the Supplementary File S2.

3. Results

3.1 Submaximal Fitness Tests Definition

A table presenting the characteristics of the included studies is provided in the Supplementary File S3. Based on the available literature, we defined Submaximal Fitness Tests (SMFT) as: a short exercise bout, undertaken at a standardised intensity that is intended to be non-exhausting, and performed with

the purpose of inferring an athlete's physiological state through the monitoring of relevant outcome measures. In this regard:

- *Exercise* is typically a cyclic activity involving large muscle groups. In team-sports settings, this is often administered as running activities, however, cycling has also been featured.
- *Standardised intensity* refers to a threshold(s) that is standardised based on an internal response or external intensity parameter, and can be either fixed for all athletes (i.e., absolute) or individualised to a capacity anchor (relative; e.g., fraction of heart rate maximum or maximal aerobic speed).
- *Non-exhausting* generally excludes frequent or prolonged 'all-out' maximal intensities, intensities that would cause voluntary cessation, or intensities that elicit an excessive training stimulus beyond that originally intended. From a practical standpoint, in team-sports, the test should not have negative carry-over effects for the subsequent training session (for instance, if administered during the warm-up), or elsewhere it is implemented as an integrated, standardised training component within the session plan (see for example section 3.2; intermittent-variable category).
- *Physiological state* can be defined as a particular condition or function of an individual's physiological system, or combination of systems—primarily, cardiovascular, respiratory, nervous and muscular—at a specific point in time. In the context of SMFT, it may be used to infer athlete's current (physical) performance capacity or training effects (i.e., training responses).

Training effects [4] indicate the direction (i.e., positive, negative) and the time course of the effect. Considering the challenges of dichotomising time course criteria, we opted to use commonly referenced durations [4,41] that align with the context and design of the included studies in our review, classified as either acute (i.e., immediate [48] and up to a 1-week duration [46,51]), short-term (typically 1–3 weeks; e.g., congested periods [52], training camps [53,54], exposure to extreme environments [55,56], season break [57]), and chronic (usually established over several weeks or months of training; e.g., pre-

season [50,58], training intervention [59,60]). The first two are commonly referred as transient effects, while the latter typically indicates more ‘persistent’ or ‘enduring’ changes [4].

- *Outcome measures* include cardio-respiratory/metabolic, subjective, mechanical, or combination of which, and are used as proxy (surrogate) measures that reflect (either directly or indirectly) the physiological systems they intend to assess. These are collected continuously within-exercise and then aggregated into a summary metric (e.g., mean heart rate, accumulated ground-impacts estimated via accelerometry-derived data), or measured immediately post-exercise (e.g., heart rate recovery, blood lactate, RPE).

Fig. 1 SMFT Protocol taxonomy. Each protocol category consists two level: 1) exercise intensity intermittency (continuous or intermittent) and 2) manipulation of exercise intensity (fixed, incremental or variable), together yielding five distinct SMFT protocol categories (shaded areas). Intermittent-variable can be further categorised into drill- and game-based formats. Each category further manipulated based on the movement pattern (linear, change of direction and multi-direction), activity mode (running or cycling) and exercise environment (closed, semi-open or open). *CoD* change of direction, *L* linear

3.2 Protocol Taxonomy

Information on SMFT protocols was extracted and categorised in reference to two main levels of classification: 1) exercise regimen (continuous or intermittent); 2) manipulation of exercise intensity (fixed, incremental or variable). Regarding exercise regimen characteristics, *continuous* activity represents a constant load exercise bout (typically for at least several minutes), without frequent alterations in velocity or rest periods [14,62]. Alternatively, *intermittent* is defined as an activity that is interrupted and restarts after a particular time span, characterised by alternated loads and rest intervals [63,64]. Considering all possible combinations of these categories, we subsequently identified five distinct SMFT categories from the available literature (Fig. 1), with each category further sub-divided based on the activity mode (running or cycling), movement pattern (linear, change of direction [CoD] or multi-directional), and exercise environment (closed, semi-open or open):

- **Continuous-Fixed** category represents a fixed intensity exercise bout which remains constant for the entire SMFT and intends to elicit a steady-state (for example, 4 minutes running at 12 km·h⁻¹) [65,66].
- **Continuous-Incremental** category is characterised by a progressive increase in intensity within (single) or between (multiple) exercise bout(s), whereas each bout lasting for several minutes (e.g., 4 minutes running with progressive increases in speed, 3 sets × 3 minutes bouts at 10, 11 and 12 km·h⁻¹, interceded by 1 minute rest periods) [11,67].
- **Intermittent-Fixed** category involves reoccurring activities performed at a constant intensity and rest intervals (for example, 4 running bouts × 50–60 meters at 18–22.5 km·h⁻¹, separated by 30 seconds of recovery) [49,68].
- **Intermittent-Incremental** category predominantly involves fixed rest periods, while intensity is increased between exercise bouts (e.g., 30 seconds shuttle runs at 10–14 km·h⁻¹, alternated by a 15 second rest periods and with 0.5 km·h⁻¹ increment after each bout) [60,69].
- **Intermittent-Variable** category represents specific and non-specific standardised drills, and therefore locomotive demands fluctuate during the exercise (i.e., multi-directional movements).

This category can be further categorised into drill- and game-based exercises. Drill-based exercises refer to exercises which do not include competition features (e.g., passing drills) [70], whereas game-based exercises are characterised with competition features (small-sided games [SSG]) [71,72].

3.2.1 Application of the taxonomy to the SMFT Team-Sports Literature

From the 87 included team-sport studies, we identified 100 independently described SMFT. As illustrated in Fig. 2, the majority of studies in the literature adopted continuous-fixed SMFT (37%), followed by intermittent-incremental (34%), intermittent-variable (15%), continuous-incremental (8%) and intermittent-fixed (6%). Table 1 provides a summary of these SMFT as described in these studies. Continuous-fixed protocols were administered in both running and cycling exercise modes and include linear and CoD (running protocols) movement patterns performed at absolute or relative standardised intensities. Continuous-incremental protocols comprised incremental exercises which were terminated when a specific internal (e.g., heart rate) or external (e.g., speed) intensity was achieved. Intermittent-fixed SMFT solely involved short-duration (8–12 seconds), high-intensity standardised bursts (~50–60 meters). Intermittent-incremental SMFT incorporated shorter versions of the most common intermittent shuttle fitness tests, such as the Yo-Yo Intermittent Recovery Tests (Yo-YoIR1&2) [46] and 30-15 Intermittent Fitness Test (30-15_{IFT}) [5]. Finally, intermittent-variable SMFT were mostly administered as game-based practices, including non-specific (handball, touchdown games) and specific (SSG of the sport) exercises, while drill-based practices included a variety of passing exercises (Table 1).

Fig. 2 Frequency of SMFT categories and their highlighted individual tests as identified in the team-sports literature. A detailed description of these tests is highlighted in Table 1. *30-15IFT* 30-15 intermittent fitness test, *HIR* high-intensity runs, *Int.* intensity, *ISRT* interval shuttle run test, *MSFT* multi-stage fitness test, *PCW* physical capacity work, *Yo-YoIR1* yo-yo intermittent recovery test level 1, *Yo-YoIR2* yo-yo intermittent recovery test level 2, *Yo-YoIE2* yo-yo intermittent endurance level 2

Table 1 SMFT described in the team-sports literature

SMFT				N Studies	Test description				Exe. Configuration
Category	Activity mode	Move. Patt.	Protocol		Dimensions	Stand. Volume		Stand. Intensity	
Continuous-Fixed	Running	Linear	5'-5'	1	Treadmill	5 minW/5 minR	833/917m	10/11 km·h ⁻¹	
			Mognomi's test	4	Track/Treadmill	6 min	1350m	13.5 km·h ⁻¹	
			5'-5'	2	Track	5 minW/5 minR	750m	9 km·h ⁻¹	
			Individualised run	1	NS	6 min	1150-1200m	60%V _{IFT}	
			Individualised run	1	Treadmill	10 min	NS	90% V _{AT}	
			Individualised run	1	NS	10 min	NS	75% HR _[RESERVE]	
	Cycling		5'-5'	4	Bicycle	5 minW/5 minR		130 watts/85 rpm	
			Individualised cycling	1	Bicycle	4 min		75%VO ₂ max/70 rpm	
	Running	CoD	5'-5' rectangle	2	20 × 20m	5 minW/5 minR	750m	9 km·h ⁻¹	≈37 turns 90°
			Rectangle course	3	100 × 50m	4 min	800m	12 km·h ⁻¹	≈10 turns 90°
			Short shuttle	5	20m	3-5 min	750-1000m	~9-12 km·h ⁻¹	≈38-50 shuttles 180°
			5'-5'	3	40m	5 minW/5 minR	833-1083m	~10-13 km·h ⁻¹	≈21-27 shuttles 180°
			Medium shuttle	2	40m	5 min	833-1000m	~10-12 km·h ⁻¹	≈21-25 shuttles 180°
			Long shuttle	3	80/100m	5/4 min	1000/800m	~12 km·h ⁻¹	12.5/8 shuttles 180°
			Long shuttle 5'-5'	2	≈80m	5 minW/5 minR	750-1000m	~9-12 km·h ⁻¹	≈9-12.5 shuttles 180°
			Individualised shuttle	1	57-68m	4 min	≈680-820m	75%MAS/~60%V _{IFT}	12 shuttles 180°
Continuous-Incremental	Running	Linear	Individualised run	1	Treadmill	NS	NS	S 8 km·h ⁻¹ ; F THR	↑ 1km·h ⁻¹ every 1min
			Absolute run	1	Treadmill	5 min	1000m	S 8; F 12 km·h ⁻¹	↑ 0.8km·h ⁻¹ every 1min
			Absolute run	1	Treadmill	3 min × 3 sets	1700m	9, 11, 14 km·h ⁻¹	3min continuous bouts
			Absolute run	2	Treadmill	12 min	750-900m	S 6/8; F 12 km·h ⁻¹	↑ 2km·h ⁻¹ every 3min
	Cycling		PCW170	1	Bicycle	3 min × 3 sets		F at 170 beats/min ⁻¹	120-170beats/min ⁻¹ stages
	Running	CoD	Short shuttle	1	20m	5 min	900m	~8, 10, 12 km·h ⁻¹	1min 8, 1min 10, 3min 12 km·h ⁻¹
			Short shuttle sets	1	20m	4 min × 3 sets	2000m	~9, 10, 11 km·h ⁻¹	≈100 shuttles 180°
			Medium shuttle sets	1	50m	2 min × 4 sets	≈1600m	~9.3, 11.1, 12.8, 14.6 km·h ⁻¹	≈32 shuttles 180°
Intermittent-Fixed	Running	Linear	High-intensity run	3	50m bursts	8 sec	50m	~18 km·h ⁻¹	3-4 reps
			High-intensity run	3	~60m bursts	12 sec	≈60m	18-24 km·h ⁻¹	4 reps
Intermittent-Incremental	Running	CoD	30-15 _{IFT}	1	40m shuttle	≈8:25 min/ individualised	≈960m/ individualised	F 13 km·h ⁻¹ / 25-75%V _{IFT}	≈24/individualised shuttles 180°
			Yo-YoIR1	19	20m shuttle	2-6:51 min	240-800m	S ~10; F ~13.5/14.5 km·h ⁻¹	11-40 shuttles 180°
			Yo-YoIR2	3	20m shuttle	2-8 min	240m-1040m	S ~13; F ~16.5-18 km·h ⁻¹	≈12-52 shuttles 180°
			Mod. Yo-YoIR2	1	18m shuttle	2-4 min	≈470m	S ~11.7; F ~14.9-15.8 km·h ⁻¹	
			Yo-YoIE2	2	20m shuttle	2-6 min	280-920m	S ~11.5; F ~13.5-14.5 km·h ⁻¹	14-46 shuttles 180°

Intermittent- Variable GB	Skating	MD	ISRT	1	20m shuttle	2–9 min	≈260–1225m	S ~10; F ~11–14 km·h ⁻¹	≈13–61 shuttles 180°
			Individualised ISRT	3	20m shuttle	9–12 min	1225–1700m	70% max of the test S ~10; F ~14–15 km·h ⁻¹	≈61–85 shuttles 180°
			MSFT	1	20m shuttle	≈5:30 min	≈800m	S ~8.5; F ~10.5 km·h ⁻¹	≈40 shuttles 180°
			30-15IFT ice	1	40m shuttle	≈3/6 min	≈390/870m	S ~10.8; F ~12.7/15.2 km·h ⁻¹	≈10/22 shuttles 180°
			Yo-YoIR1 ice	2	20m shuttle	6 min	≈700m	S ~10; F ~14.5 km·h ⁻¹	≈35 shuttles 180°
	Running		9v8 Handball	1	141m ² /player	8 min			similar game style
			4v4 Touchdown	1	150m ² /player	4 min of 1 set			score into the zone area
			4v4 SSG	1	80m ² /player	4 min × 3 sets			
			4v4 SSG	1	120m ² /player	1.5 min × 6 sets			with GK
			4v4 SSG	1		2 min × 4 sets			
			5v5–10v10 SSG	1	117±65m ² /player	NS			possession/with GK
			3v3–6v6 SSG	3	67.5–90m ² /player	3 min × 2 sets			with/without GK, limit/free touch
			5v5+5 SSG	1	135m ² /player	3 min × 4 sets			with GK, free play
			5v5 SSG	2	62.5/105m ² /player	3 min × 3–4 sets			without GK, free play
	Running		5-star drills	2	15–25m runs	4–5 min × 3 sets			kicking, handballing and marking
			Passing drill	1	~2/3 pitch	6 min × 2 sets			short and long distances

≈ approx., ~ mean, ↑ increase, ° CoD angle, *CoD* change of direction, *DB* drill-based, *F* finish, *GB* game-based, *GK* goalkeeper, $HR_{[RESERVE]}$ HR reserve, *ind.* Individualised, *ISRT* interval shuttle run test, *m* meters, *min* minute, *MAS* maximal aerobic speed, *MD* multi-direction, *Mod.* modified, *MSFT* multi-stage fitness test, *Mov. Patt.* movement orientation, *NS* not specified, *PCW170* physical work test, *rpm* rate per minute, *R* recovery, *reps* repetitions, *S* start, *sec* second, *SSG* small sided games, *THR* target HR = [(HR maximum – resting HR) * 80-85% intensity] + resting HR, V_{IFT} final velocity achieved in 30-15_{IFT}, V_{AT} velocity at anaerobic threshold, *W* work, *30-15_{IFT}* 30-15 intermittent fitness test, *Yo-YoIR1* Yo-Yo intermittent recovery test level 1, *Yo-YoIR2* Yo-Yo intermittent recovery test level 2, *Yo-YoIE2* Yo-Yo intermittent endurance level 2, *Mod.* Modified. SSG area per player was computed including GK

4. Outcome Measures

We identified 202 total outcome measures used in previous team-sports research. As shown in Fig. 3, cardio-respiratory/metabolic were the most used outcome measures (66%), followed by mechanical (28%) and subjective (6%). The following sections present the outcome measures corresponding to each response type, discuss their putative underlying mechanisms, and synthesise the current available evidence examining their changes within the SMFT framework.

Fig. 3 Frequency of SMFT outcome measures as identified in the team-sports literature. HR-derived indices are the most common cardio-respiratory/metabolic outcome measures and include variables represent exercises intensity (HReX) and recovery (HRR and HRV). Level 1–2 mechanical outcome measures represent locomotor activity variables collected during SMFT that are standardised by an internal stimulus or intermittent-variable exercise such as small-sided games. Level 3 mechanical outcome measures are response measures derived from inertial-measurement units (micro-electrical mechanical systems [MEMS]) for monitoring neuromuscular status. Subjective outcome

measures represent tolerance to effort and have been monitored solely via RPE. (+) positive, (-) negative, *AL* accelerometry-load, *AL_V* (*AU*) the vertical vector magnitude component of tri-axial *AL*, *AL_V* (%) percentage contribution of the vertical vector magnitude component to tri-axial *AL*, *ANS* autonomic nervous system, *CT* contact-time, *Force-load* (*fL*) sum of estimated ground-reaction forces during all foot impacts, *rMSSD* root mean square of the sum of all differences between successive normal heartbeats, *Ln rMSSD* natural log of rMSSD, *Ln SDI* log-transformed standard deviation of successive R spikes measured from Poincaré plots, *Velocity-load* (*vL*) sum of distance covered weighted by the speed of displacement (in SMFT refers to the actual mean velocity)

4.1 Cardio-Respiratory/Metabolic Outcome Measures

In team-sports settings, which can include a large number of individuals who may possess different aerobic capacities [8,12], it is difficult to implement SMFT that are standardised by internal intensity variables. Accordingly, the majority of the tests were applied by standardising the external intensity and measuring the corresponding internal responses [10,73]. A variety of cardio-respiratory/metabolic outcome measures have been used in the literature, with the most common being heart rate (HR) derived indices (Fig. 3). These include variables collected during (exercise heart rate [HR_{ex}]), immediately post (heart rate recovery [HRR]) and soon after (heart rate variability [vagal-related HRV]) the SMFT. Other measures include blood markers (e.g., blood lactate) [67,74–80] and oxygen consumption related parameters (e.g., oxygen uptake) [75,76,81,82]. Since blood and oxygen uptake outcome measures are time consuming, expensive and obtrusive, their viability to provide standardised and repeatable response measures is considered limited, particularly in team-sports [11,83]. Accordingly, here we focused on heart-rate derived indices.

4.1.1 Exercise Heart Rate

Exercise heart rate is collected during the SMFT and is either analysed in absolute (beats per minute; HR_{ex}[a]) [47,59,60,66,69,74–76,81,82,84–103], relative to maximal HR (HR_{ex}[%]) [6,11,45,46,48,51,54,56,57,59–61,66,67,70,73,79,83,84,89,95,97,104–119] or heart rate reserve (HR_{ex}[reserve]) [53] values. A variety of methods are used to derive HR_{ex}, with the majority calculating the mean HR during the last 10–60 seconds of the test [11,12,45–48,51,53–58,60,61,66,69,71,74,75,82,83,85–87,89,92,94,96,99,103,105–108,111,113–115,117,119–121]. Other approaches calculate mean HR during the overall test (particularly during intermittent-variable protocols such as SSG) [70,79,93,97,100,103,116], specific fixed time points [6,46,59,60,84,91,95,98,104,109,110,112,122], or peak values observed [90,107].

4.1.2 Heart Rate Recovery

Heart rate recovery can be defined as the rate at which HR declines after exercise cessation [10,39] and may be collected with athletes lying supine [123], sitting upright [12,45], standing [89,121] or walking

[94]. Similarly, HRR can be assessed as the absolute (HRR[*d*]) [45,47,48,53,54,57,60,66,88,99,102,107,114,119,121,123,124] or relative (HRR[%*d*]) [12,47,53,61,66,89,98,101,103,106,113,114,121] difference between HR_{ex} and HR value observed between 10–180 seconds post-test. Alternative approaches include the actual HR value observed at the end of the designated recovery period in absolute (HRR[*a*]) [66,74,94,98,121,125] or relative (HRR[%]) [66,109,110,113] values, or the overall mean HR during a variety of fixed time intervals [90,96,107]. Other approaches calculate time-based variables such as the time required to decrease from between fixed HR values (HRR[*s*]; e.g., time between 80% to 70% HR maximum) [79], or the time constant of HRR derived from mono-exponential modelling [107,126].

4.1.3 Heart Rate Variability

Vagal-related HRV is defined as the variability in the time intervals (usually in milliseconds) between adjacent heartbeats and reflects the regulation of cardiac autonomic nervous system (ANS) balance [10,127]. HRV indices are commonly collected in a seated or supine position and resting state in a laboratory or quiet room [10,42]; however, as the aim in SMFT is to monitor the response during and after a given submaximal workload, only HRV parameters observed immediately or soon after the test are relevant for SMFT in team-sports. These measures are usually analysed within a window of 3–5 minutes post-test cessation, and predominantly calculated as time-domain related variables such as the square root of the root mean square of the sum of all differences between successive normal heartbeats (rMSSD) [99,107] or its natural log (Ln rMSSD) [45,47,53,60,99,106,114], natural log of standard deviation of successive ‘R spikes’ (the peak of the QRS complex—reflective of ventricular depolarisation—recorded from an electrocardiogram wave) measured from Poincaré plots (Ln SD1) [57,105], and the standard deviation of mean interval differences between normal heartbeats (SDNN) [107].

4.1.4 Putative Mechanisms

HR-derived indices are commonly used to inform chronic aerobic-oriented training effects, attributed to the linear relationship between HR_{ex} and oxygen uptake during an intended steady-state activity

[10,42]. A reduction of HRex to a standardised submaximal stimulus may represent improved exercise economy, which may translated to the development of aerobic fitness [51,120], whereas an increment of HRex is considered to reflect a negative response (de-training of the cardio-respiratory system) [87], likely due to central adaptations (i.e. left-ventricular function) [128]. In addition, an increment of HRR or vagal-related HRV measures are considered as positive effects [60,106], reflecting the reactivation of the parasympathetic system and hemodynamic adjustments post-exercise [10]. That said, in addition to being more time consuming, these measures may be influenced by preceding exercise, with higher intensities eliciting increased blood acidosis that simulate the metaboreflex, and therefore may reduce HR decay post-exercise and alter HRR and vagal-related HRV results [10,47].

The use of HR-derived indices to infer negative transient training effects is inconclusive in the SMFT research. The theoretical basis for their inclusion is due to the potential influence of various training-induced physiological processes that originate in central (i.e., ‘central command’) and peripheral (for example, afferent feedback from skeletal muscles) body regions to alter cardiac ANS function (i.e., the balance between the sympathetic and parasympathetic systems), and subsequently HR activity [10,38,42]. It has been hypothesized that training-induced fatigue, or an incomplete recovery might result in a greater muscle activation at a given intensity [129], promoting increased oxygen demands [129] and yielding accelerated cardiac sympathetic activity that consequently increase HRex, and reduce HRR and HRV [114,129]. In contrast, previous research has proposed that increased training stress (leading at least to an overreaching state) may cause opposite responses—increased parasympathetic activity or blood plasma volume, consequently lowering HRex and increasing HRR and HRV [37,38,130].

4.1.5 Inferring Physiological State

Generally, across a standard micro-cycle, HR measures tend to stay relatively stable [45,47]. For example, studies among youth and senior athletes have observed no changes in the day-to-day variability of SMFT HRex [45,47,75] and HRR [45,47] derived from multiple SMFT administered throughout the week, despite substantial variations in training loads. Whilst vagal-related HRV indices

are considered to provide a better insight into the cardiac ANS [10,53], daily variations in training loads were associated with stable [45,47] and lower [53] responses. The disparity across studies maybe due to the differences in training loads and HRV variables [53], athlete's fitness levels [45], or simply reflective of measurement 'noise' (either measurement error or biological variations) [10,107], thus challenging between study comparisons.

The current research suggests that the use of HR-derived indices appear more relevant after acute (3–7 days) and short (~2 weeks) terms of altered training stress, albeit may cause misleading interpretations. In team-sports, 3–4 consecutive days of accumulated training loads have been associated with both increased [114] and decreased [54] SMFT HRex. Lower SMFT HRex values have been also observed after 2 weeks of intensified training [84], but also following a substantial decline in training loads due to season breaks [58]. Whilst the information in team-sports settings is limited, studies among various cohorts of individual endurance athletes (e.g., cyclists, triathletes) provide encouraging evidence that short-term intensified periods (1–3 weeks) of training-induced fatigue (incurring functional-overreaching) lowered SMFT HRex [36,38,130] and increased SMFT HRR [36,37,39]. These responses likely reflect a complex interplay between acute cardiac ANS function (usually referred to larger parasympathetic activity) and increased plasma volume [37,54,105], leading to an enhanced stroke volume for a similar cardiac output [10,131]. In summary, the use of HR-derived indices (especially HRex and HRR) to infer transient training effects associated with cardiac ANS dysfunction is currently questionable (at least, not straightforward), with no consensus around the underlying mechanisms and conflicting results in the literature.

Overall, SMFT HRex has small to very-large inverse relationships with performance indicators (i.e., maximal oxygen uptake, intermittent endurance capacity) when measured concurrently (lower HRex is associated with higher test results) [46,48,104], suggesting its validity as an indicator of individual's current endurance capacity. Indeed, it has been highlighted that a chronic exposure to internal (e.g., HR-based training impulse, session RPE) [86,90] and external (e.g., total distance covered, force-load) [71,120] loads is associated with reduced SMFT HRex. However, the studies examining training effects

within-athlete have reported contrasting findings. For example, studies in soccer players [46,91] have observed moderate to very-large relationships between SMFT HRex and intermittent endurance performance at different time points across the season, albeit with no interaction between the magnitude of these effects. Likewise, improved [59] or maintained [87] intermittent running ability did not necessarily coincide with reduced or stable SMFT HRex, respectively. In contrast, studies conducted on a variety of team-sports and age groups have observed significant relationships between changes in similar markers from pre-to-in-season [51,60], and across a full season [106]. Improved SMFT HRex were also largely correlated with the changes in running speed at 4 mmol·L⁻¹ blood lactate [11,83] or reduced oxygen uptake at fixed submaximal intensities (i.e., exercise economy) [81].

Research observations are more consistent where SMFT HRex has been administered to evaluate the adaptation time-course to changes in extreme environments (heat and altitude) during training camps or competitions [55–57,92,103,105,132]. Collectively, HRex displayed substantial deteriorations upon arrival and up to days of exposure [56,57,92,103], and generally return to baseline values within 6–10 [55,105] or 14 days [56], with quicker adaptations among highly trained individuals or across repeated exposures within-individuals [133,134]. Taken together, whilst it appears that SMFT HRex has the potential to serve as a valid and sensitive marker of positive training-induced effects, it remains questionable whether it can be used as a surrogate measure of within-athlete changes in maximal aerobic capacity. There is, however, considerable evidence suggesting its use during exposure to changes in environments for monitoring the athlete's acclimatisation.

The magnitude of correlations between cardiac parasympathetic related variables (HRR and vagal-related HRV) and performance indicators is less clear and ranged from no correlation to a very-large relationship [48,66,99]. The disparity could be the consequence of varied protocol intensities [10,35,42,45], collection time (e.g., 60, 180-second post-exercise) [48], analysis approaches [66], and fitness criterion measures [45,79]. Importantly, inferences regarding their long-term validity as proxy measures of chronic training effects can be somewhat impacted by SMFT intensity (i.e., HRex) [10]. The rate of the sympathetic withdrawal and parasympathetic reactivation post-exercise is altered when

the recovery period starts from different intensities. As an example, different absolute HRR ($HRR[d]$) values may be expected 60-second post SMFT if the exercise intensity varies (e.g., 90% versus 75% HR maximum). Hence, in theory, a significant reduction in HRex might influence the concurrent interpretation of post-exercise outcomes. Although this issue has been addressed by analysing HRR in relative values ($HRR[\%d]$) [61,114], time necessary to decrease from two fixed HR values ($HRR[s]$) [79], or employing individualised intensity protocols [12], these are not yet fully understood. In support of this, regardless of HRR analysis used, authors examining training-induced changes in both HRex and HRR did not always find congruent trends [61,101,107]. Other studies observed a lack of association between changes in HRR and endurance performance, despite significant relationships with HRex [60,106]. On the other hand, increased SMFT vagal-related HRV has been shown to be more appropriate, with studies reporting its validity for monitoring endurance-oriented training effects [60,106,107].

4.1.6 Considerations

Of critical importance when using HR-derived indices as proxies of training effects is the range of confounding factors, such as environmental (e.g., temperature), habitual (e.g., sleep, diet), circadian (time during the day), and psychological (e.g., emotions, stress). These could all contribute to the error of measurement of SMFT HR measures—HRex (CV: 1.0–3.5%) [12,45,48], HRR (CV: 2.8–13.8%) [45,48,66], and vagal-related HRV (CV: 6.6–19.0%) [45,105,107]—and should be considered (or standardised where pragmatic) when interpreting changes in HR-derived indices responses to SMFT [10,42].

Further research is warranted to explore the use of all HR-derived measures to infer acute-and-short-term effects, in particular, verifying the interaction between temporary changes in cardiac ANS function and plasma volume responses. In this respect, it should be highlighted that HR responses may still be less appropriate to denote peripheral neuromuscular fatigue, in which considered more important to monitor delayed recovery and injury risk mitigation in team-sports [49,135]. In the longer-term, HRex is probably the easiest to collect, most reliable HR measure, and its utility in observing positive changes

in aerobic capacity has stronger empirical support. Accordingly, the utility of adding post-exercise (HRR, vagal-related HRV) SMFT HR responses to infer chronic effects may be redundant. In order to enhance interpretations, future research should first determine meaningful changes in SMFT HR_{ex} (i.e., smallest worthwhile change) in reference to variations in physiological state.

Finally, when monitoring the responses to intermittent-variable SMFT (e.g., SSG), athlete's HR_{ex} may be influenced by their locomotor activity. These are likely to differ between tests and should be accounted for when interpreting data. Therefore, we recommend quantifying intermittent-variable SMFT locomotor activity for consideration. Given the reasonable association between internal and external measures during field-based sessions [136], it is also possible to standardise HR_{ex} to a given (fixed) external intensity parameter. Whilst some have attempted to achieve this by dividing the former by the latter, creating a ratio [137], there are complex statistical properties and assumptions associated with such indexes, presenting as a major validity concern [138]. To appropriately examine HR_{ex} while holding external intensity parameters constant, we recommend linear regression techniques, which do not violate statistical assumptions and achieve the desired outcome ratios [139].

4.2 Subjective Outcome Measures

Subjective measures are recognised by their ability to serve as gestalt measures that can be used across different exercise typologies, given their feasibility and low-cost [140]. These are commonly applied to quantify athlete's perception of intensity and training effects. The former is derived solely from RPE, while the latter are commonly referred as Athlete Reported Outcome Measures (AROMs) [141] of latent response constructs such as readiness, wellness, stress etc. [4,142]. Accordingly, RPE are the only subjective outcome measures that can be applied to SMFT, a notion supported by their exclusivity (albeit the limited number of studies) in the team-sport SMFT literature (Fig. 3). Among the available studies, different scales such as the Category-Ratio 10 (CR10 deciMax) [50,56,57,67,70,97,108], 100 (CR100[®] centiMax) [59] and 6–20 (Borg's 6–20) [75,76] have been adopted, using a variety of collection protocols (during the last 180 seconds, immediately and up to minutes post-exercise).

4.2.1 Putative Mechanisms

Perception of effort is defined as the ‘conscious sensation of how hard or strenuous a physical task is’ [142], and mainly depends on how easy or hard it is to breathe and drive the working muscles during exercise. [143]. As part of SMFT, the athlete provides a retrospective appraisal of perceived effort to a standardised stimulus that can be prescribed by either objective internal [32] or external [91] means. Since RPE is strongly associated with cardio-respiratory, metabolic and neuromuscular measures of exercise intensity [144,145], and influenced by mental state [142], changes in RPE may reflect positive [32,59] or negative [37,41] alterations in psycho-physiological state. However, given their gestalt nature, it is perhaps difficult to align RPE as a proxy to a single physiological system during SMFT. For example, RPE have been empirically associated with HR_{ex} during continuous exercise [144] and might therefore be used as a cardio-respiratory proxy measure. But spinal or supraspinal motoneuron inhibition, which is a neuromuscular phenomenon, can increase central motor command and subsequently RPE [146]. This is not to say that RPE cannot be used to infer physiological state during SMFT, but rather the mechanisms may be less precise. In addition, given that RPE have also been used to regulate exercise intensity [147], RPE can be used as an anchoring intensity variable (i.e., running or cycling at fixed RPE), whereby external outcomes such as velocity or power output are used as response measures [148]. However, to our authors knowledge, there is no published team-sports research evaluating the theoretical basis of such SMFT and their actual utility.

4.2.2 Inferring Physiological State

Whilst some evidence supports the use of SMFT RPE [58,59,97], it is difficult to support or refute their utility to determine training effects, given the limited data available in team-sports. In endurance athletes, RPE have been shown to detect negative transient effects associated with functional overreaching and disturbances in endurance performance [30,37,41], while their sensitivity to chronic positive effects is less certain [34,40]. In the team-sports context, one study [59] showed that reduced SMFT RPE (albeit maintained HR_{ex}[a]) were accompanied with enhanced intermittent running performance (Yo-YoIR1) and soccer match high-intensity running [59]. Another study [50] in professional soccer players did not observe any significant relationships between RPE collected

immediately post an individualised SMFT and AROMs across 6 in-season standard weeks. Despite the conflicting results, researchers have suggested the potential usefulness of SMFT RPE when measured concomitantly with other objective outcome measures (e.g., HRex) as part of a multivariate monitoring approach [37,42,130].

4.2.3 Considerations

It is noteworthy to highlight some of the challenges associated with collecting and interpreting RPE in team-sports, where interpretation is challenged by coach and peer presence biasing ratings, the application of unvalidated collection tools, lack of or inappropriate athlete familiarisation/education, and their gestalt nature [142,146,149]. Moreover, RPE may be confounded by other sensations associated with exercise, such as mood, discomfort, pain and enjoyment [142]. In view of these challenges, researchers may consider other perceptual measures such as ratings of fatigue [150], or techniques such as numerically-blinded [149] and differential [151] RPE, alongside the implementation of rigorous familiarisation processes to facilitate authentic and sensitive perceptual ratings associated with SMFT.

With this in mind, a benefit of SMFT in team-sports is to provide an assessment that can be seamlessly integrated into the training session such as the warm-up or standardised drills. The need to collect RPE from all athletes individually (~20–40) under controlled conditions is likely to be disruptive and impractical, which is perhaps why there are few studies using this practice. It is probably reasonable to assume that unless SMFT are completed as a discreet activity, with smaller groups, or RPE collection procedures are made more accessible (e.g., mobile devices, human resources), these outcome measures may be less pragmatic or sustainable in team-sports.

4.3 Mechanical Outcome Measures

Within the current monitoring schemes in sport, there is a broad classification of external load parameters. These indices represent kinematic outputs [152] performed by an athlete throughout an

exercise bout/session [153] and have been classified into three distinct levels, which we will use here to audit their implementation in the context of SMFT [8,154].

4.3.1 Level 1–2 Measures

Level 1 variables are typically the locomotor performance outputs including distance covered, time spent or count of efforts in different velocity zones, whilst *Level 2* variables reflect changes in velocity such as accelerations, decelerations (i.e., change of directions) [8]. Such kinematic parameters are routinely collected using global positioning systems (GPS) or other tracking technologies (i.e., semi-automated pixel tracking, local positioning systems). In the team-sports SMFT framework, the use of level 1–2 mechanical outcome measures can occur in two scenarios: 1) monitoring the speed achieved to a submaximal exercise that is standardised by internal intensity responses [50,155], and 2) monitoring the changes in these variables during intermittent-variable standardised drills [54,58,70–72,79,93,97,105,116,132,156], since they are standardised by a variety of other parameters such as duration, sets, recovery and unique constraints (e.g., number of players, rules modifications). Whilst the former is considered less practical in team-sports for many pragmatic reasons, the latter are implemented as a part of the training plan, encompassing sport specific actions and are perhaps the most feasible to apply routinely [8,131]. Conceptually, higher values (e.g., accumulated distance covered), coupled with stable or lowered internal responses are indicative of a positive effects (i.e., improved exercise performance) [8,58,97]. In fact, studies examining level 1–2 variables during drill (passing drills) and game (SSG) exercises have highlighted their pragmatic advantages to deliver information related to athlete's performance [58,71,72,97]. However, it should be noted that intermittent-variable SMFT are influenced by a variety of individual and contextual factors such as technical level, motivation and tactics [8,72], and have a higher degree of variation (test-retest reliability) compared to other SMFT modalities [70,72,156,157], and therefore, should not necessarily be interpreted in the aforementioned simplistic manner [8].

4.3.2 Level 3 Measures

Level 3 external load variables are derived from inertial-measurement units such as tri-axial accelerometers, magnetometers and gyroscopes [8] (collectively referred to as micro electrical mechanical systems [MEMS] [158,159]). Unlike level 1–2 variables, these outcome measures can be used for the majority of SMFT applied in the team-sport context and have been proposed to provide an insight into athlete's neuromuscular system, given their potential link with lower limb vertical stiffness [135,154,160–163]. Vertical stiffness is considered to affect several athletic parameters, including elastic energy storage and utilization (i.e., stretch shortening cycle) [164] and has traditionally been measured through a variety of jump assessments (counter-movement, hopping and drop jumps) using variables such as jump height, contact- and flight-time [52,165,166]. However, due to the limited viability of these assessments in field conditions and their lack of specificity (jumping activities may be less sensitive to detect changes in running strategy) [52,161], researchers and practitioners have started to collect proxy variables required to estimate vertical stiffness derived from MEMS during SMFT [49,52,55,65,68,72,167–169].

To date, studies have adopted accelerometer-derived vector magnitudes (collectively termed in this review as accelerometry-load [AL]) [49,52,72] and individual vector components (vertical AL [AL_V], antero-posterior AL [AL_{AP}], and medio-lateral AL [AL_{ML}]) using MEMS-embedded accelerometers [49,52,68,167,168], predominantly collected during intermittent-fixed protocols comprising high-intensity running bursts [49,52,55,68,168]. Generally, reduced AL in the vertical plane (AL_V [arbitrary units; AU]), or the percentage contribution of the AL_V to the overall tri-axial vector magnitude (AL_V [%]) during SMFT have been postulated as an indicator of reduced leg vertical stiffness and subsequently inferred a degree of lower limb neuromuscular fatigue [167,170]. Theoretically, reduced vertical stiffness may lead to reduced efficiency for the same speed through altered kinetic and kinematic parameters, such as reduced vertical ground-reaction forces and increased ground-contact time [161,170] which likely lead to decreased stride length [52,72] and elevated energy cost [162,170].

4.3.3 Inferring Physiological State

Studies investigating acute effects on mechanical outcome measures during SMFT are scarce, and those available are quite disparate in terms of protocols, variables, and their analytical processes [49,52,65]. Nonetheless, there is an emerging agreement from these studies that suggest AL measures can provide sensitive indicators of athlete's neuromuscular fatigue and efficiency. In a group of professional soccer players who performed an intermittent-fixed SMFT ($4 \times \sim 60$ meter runs, alternated by a ~ 30 second recovery) before and immediately after a training session, Buchheit et al. [49] found that various AL variables respond differently to different training modes (strength, speed, endurance-oriented conditioned sessions). Estimated vertical stiffness slightly increased after all training modes, whereas propulsion efficiency (the ratio between velocity loads and force load, vL/fL ; refer to Fig. 3 for variables) was session dependent (largely increased after strength, small and moderate decreases after endurance and speed, respectively), suggesting its sensitivity to detect changes in running strategy (hypothetically, horizontal force application capability) [8,49]. In a study [52] using a similar SMFT protocol and outcome measures among university rugby union players reported large relationships between the vector magnitude and vertical accelerometer components derived from the constant phase of the run, versus leg stiffness measured more directly via submaximal hopping test performed on a force platform [52]. Whilst only trivial effects were observed in leg stiffness over the week, the changes in SMFT AL data were large [52].

Similar trends were also found in a study investigating the alterations in triaxial AL data collected before, 48 and 96-h post an Australian football match [68]. A main finding reported in this latter study was that AL_V (AU) and AL_{ML} (AU) derived from the constant phase of the SMFT were still impaired 96-h post-match among players who were classified as 'fatigued' ($> 8\%$ reduced counter-movement jump at 48-h post-match) [68]. Finally, a within-individual longitudinal study among soccer players [72] showed reductions in $AL \cdot \text{min}^{-1}$ and $AL \text{ slow} \cdot \text{min}^{-1}$ collected during a standardised SSG (5v5+5) 1-day before a match were concomitant with a reduction in neuromuscular function (flight-time:contact-time ratio measured from counter-movement jump) and altered match running profile—increased AL_{ML} (%) and decreased AL_V (%) contribution to AL—indicative of potential neuromuscular fatigue [72,167]. Collectively, it appears that specific mechanical level 3 metrics may be useful for

identifying acute variations in performance (neuromuscular fatigue and efficiency) associated with changes in lower limb function.

Inferring longer-term training effects from mechanical variables ascertained during SMFT has received limited attention, and insights have been drawn exclusively from tracking locomotor outputs during intermittent-variable SMFT in the form of SSG. For example, moderate to very-large positive relationships have been reported between higher level 1–2 outputs during SSG and intermittent running capacity [97]. In addition, during intensified training camps (1–2 weeks), within-individual increases in running parameters (e.g., total and high-speed running distance) measured during intermittent-variable SMFT were also concordant with improved intermittent running capacity [54,105,132]. Of note, the utility of all mechanical outcome measures (levels 1, 2 & 3) derived during SMFT in detecting chronic training effects in neuromuscular function such as improved running efficiency (enhanced muscle-tendon unit recoil) is unknown.

4.3.4 Considerations

Most studies adopting mechanical outcome measures to denote acute neuromuscular effects have administered SMFT characterised by intermittent high-intensity bursts. These outcome measures are often sampled from the constant running velocity phases of the SMFT and using the vertical accelerometer component [52,68,167], perhaps owing to an enhanced association with vertical stiffness [52,68]. Typically, such techniques have demonstrated an inferior degree of reliability (CV: 6.7–17.5%, standardised TE: small to moderate [49,52,68]) versus maximal and non-running-based assessments of neuromuscular function (jump and force indices; CV: 2.9–6.1%, standardised TE: small [49,65,171]). One study [65] using a continuous-fixed SMFT and lower running intensity (mean velocity of 12 km·h⁻¹ compared to 18–22.5 km·h⁻¹), reported lower measurement noise (CV: 2.1–8.0%, standardised TE rated as small). Additionally, the changes found in AL_V (%) (decreased) and AL_{ML} (AU) (increased) 24-h post a strenuous soccer training session were greater than smallest worthwhile change (signal to noise ratio > ±1) [167]. Although these findings indicate enhanced reliability and sensitivity for SMFT involving lower running speeds in a more continuous fashion, this is based on only one study and the

utility of different SMFT protocols has not yet been compared in the available literature, and barriers to implementation should also be considered. Similarly, the questionable reliability of locomotor outputs recorded during intermittent-variable SMFT in the form of SSG (total distance CV: 2.3–11.7%, high-speed thresholds CV: 8.1–83.0% [70,72,93,97,156,157], small to moderate in magnitude [70,156,157], perhaps limits their utility to denote moderate to large effects only (i.e., larger CV may decrease the signal to noise ratio).

Although studies have suggested that changes in AL variables may reflect effects on lower limb stiffness [162,172,173], few have directly assessed stiffness [52,174]. Moreover, these studies have typically used MEMS mounted between the scapulae, which may be influenced by upper-body kinematics during running or dampening of ground-contact vibrations [172,175]. Whilst unit placement may have limited impact under standardised conditions, intermittent-variable SMFT may be more susceptible to positioning noise as changes in orientation of the MEMS devices are not considered in the quantification of accelerometer metrics. In addition to positioning, users should be cautious of other extraneous factors such as movement artifact within the device harness, running surface (e.g., ground stiffness), and footwear [158].

Future work should address the overall convergent validity of MEMS-derived data to obtain an accurate estimation of running strategy characteristics such as vertical stiffness. It is also necessary to investigate the theoretical framework for the sensitivity of these measures and their potential mechanisms (i.e., with respect to human tissue and gait mechanics). Furthermore, more research is required to examine whether protocol characteristics (e.g., exercise regimen, running intensity) and unit placement (for example, centre of mass, foot mounted MEMS unit) can enhance measurement properties, and therefore facilitate inferences regarding lower limb stiffness and ultimately neuromuscular fatigue or efficiency.

Table 2 Practical applications and Future directions

SMFT Protocol

- In team-sports, which comprise a large number of individuals, it is more practical to prescribe external (duration and velocity) rather internal intensity (e.g., fixed HR response) parameters.
- Whilst (theoretically) individualised prescription of SMFT intensities accounts for the potential variation of physiological capacities within team-sports squads, this may be less feasible as given the inherent requirement for periodic fitness assessments during seasonal stages.
- When HR-derived indices are monitored, notably HREx, we recommend the use of continuous (fixed, incremental) SMFT protocols, with a minimum dose of 3–4 minutes to attain more stable HR during data collection.
- Most studies administering intermittent-fixed, high-intensity SMFT to denote transient effects in lower limb function. This could be because researchers consider that higher velocities are required to examine neuromuscular status. Whilst no studies have explicitly examined this query, we encourage team-sport researchers to test the utility of continuous, lower-intensities SMFT.
- In the absence of strong evidence of regarding the optimal SMFT exercise intensity, we recommend the prescription of fixed intensities that serve the training purposes (e.g., integrated into the warm-up), without negatively impacting the subsequent session, and can be easily repeated over time (i.e., individual and resource constraints).
- Due to the notable influence of individual and contextual factors, practitioners should consider administering intermittent-variable protocols (e.g., SSG) in combination with more generic SMFT, rather than isolation. For example, continuous SMFT during the warm-up and SSG within the main parts of the session. This may provide insight into general versus sport-specific training effects.
- When monitoring the internal response to intermittent-variable SMFT (e.g., SSG HREx), we recommend quantifying and, if possible, controlling for external intensity parameters. The latter should be sought through linear regression techniques, with ratios (e.g., internal:external) being avoided.

HR-derived indices

- HREx is the most viable SMFT outcome measure to evaluate athlete's physiological state, principally to monitor chronic aerobic-oriented training effects.
- Considering that similar changes in HR-derived indices can infer positive and negative training effects, researchers and practitioners are advised to include more than a single outcome measure (e.g., HREx and RPE) and interpret the trends observed in relation to training aims and context.
- We recommend caution to practitioners when interpreting changes in cardiac parasympathetic outcome measures (e.g., HRR), given their direct link with exercise intensity (i.e., changes in HREx may influence HRR).

Subjective

- RPE may provide a useful adjunct to objective SMFT outcome measures such as HREx or accelerometry-load measures for monitoring physiological state, but data must be collected in an appropriate and standardised manner (appropriate anchoring and education, correct scales, in isolation, etc.) to mitigate the influence of conscious bias and habitual ratings.
- The practicality of collecting SMFT RPE in the originally intended manner from groups of team-sport athletes (~20–40) is logistically challenging. This may be however, feasible if SMFT is performed as a discreet session that is not integrated within training, when working with individuals (e.g., small group training, or the rehabilitation return-to-play phase), or if data collection procedures are made more accessible (e.g., mobile applications, human resources).
- Differential RPE (respiratory, muscular) may provide a more sensitive appraisal of perceived exertion in response to change in physiological state, but the utility of these measures requires further investigation.

Mechanical

- Monitoring locomotor outputs such distance covered and high-intensity efforts during SSG display larger magnitude of measurement error and therefore may compromise their sensitivity. We suggest future work scrutinizing whether modifications in game constraints can reduce physical performance variability, or alternatively explore the utility of drill-based exercises such as passing drills.

- MEMS devices used within SMFT may be a promising tool to monitor lower limb neuromuscular status (fatigue and efficiency). However, before confident inferences can be made, further research is necessary to address their validity as markers of changes in running mechanics. The technology and the associated analytical techniques used, as well as other aspects such as the SMFT properties, outcome measures collected, and unit placement should be also considered.

HR heart rate, *HRex* heart rate exercise, *HRR* heart rate recovery, *MEMS* micro electrical mechanical systems, *RPE* ratings of perceived exertion, *SMFT* submaximal fitness tests, *SSG* small-sided games

5. Summary and Conclusions

Our review provides an overview of the literature regarding SMFT in team-sports, including the development of SMFT definition, protocol categorisation, and a systematic audit of protocols and outcome measures. We also provide a narrative synthesis of the applications of SMFT within the training continuum of sport teams and future research directions (outlined in Table 2). In summary, SMFT have the potential to serve as time-efficient, non-exhaustive and feasible standardised tests that can be administered to a group of athletes simultaneously as a part of the warm-up and using specific drill(s) during the training session. Multivariate outcome measures such cardio-respiratory/metabolic (e.g., HR-derived indices), subjective (e.g., RPE), and mechanical (GPS and MEMS-derived data) can be collected simultaneously, and in theory, provide a multifactorial evaluation for athlete monitoring in team-sports. Collectively, the literature suggests that several outcome measures collected during and immediately post SMFT can inform on athlete's physiological state. HR-derived indices seem more appropriate to denote positive chronic training effects on endurance performance, whereas their role in detecting negative transient effects associated with variations in ANS function is questionable. Despite the lack of knowledge about the underlying mechanisms and the inconsistent findings between studies, their sensitivity appears to improve after days or over short periods that are characterised by substantial alterations in training stress, seemingly caused by an interaction between cardiac ANS status and plasma volume responses. Subjective outcome measures are less common in team-based sports and only global RPE have been adopted thus far. Although their validity and practicability has yet to be established, researchers have proposed their utility when measured concomitantly with other objective measures (e.g., HRex) as part of a multivariate monitoring system. Mechanical outcome measures are relatively novel and have been mostly investigated using intermittent-variable and intermittent-fixed protocols, whereby the former primarily involves GPS-derived kinematic variables (level 1–2) to monitor exercise performance, while the latter includes response measures derived from inertial-measurement units (level 3) to monitor lower limb neuromuscular function. Whilst monitoring locomotor outputs during standardised training drills is more feasible and has shown to provide valuable data on athlete's performance, practitioners should consider the large influence of various individual and contextual factors (e.g., technical/tactical level, motivation) that may undermine their interpretations.

Accelerometry-load parameters can provide sensitive indicators of acute changes in lower limb function and therefore neuromuscular fatigue and efficiency, albeit the overall validity of these outcome measures and the physiological mechanisms underpinning their changes has not yet been fully evaluated. Moreover, there is an absence of information on the use of all mechanical metrics (levels 1–3) to monitor chronic training effects. Finally, future research should also examine the methodical elements (e.g., protocol characteristics, collection and analytical processes) related to SMFT to derive the most appropriate protocol to capture reliable, valid and sensitive outcome measures that provide useful inferences regarding athlete's physiological state.

Acknowledgements

The authors would like to thank the authors who provided additional data for the studies included in our review. We would also like to thank the reviewers for their constructive comments and contribution.

References

1. Impellizzeri FM, Menaspà P, Coutts AJ *et al.* Training Load and Its Role in Injury Prevention, Part I: Back to the Future. *J of Athl Train* 2020;**55**:885–92; <https://doi.org/10.4085/1062-6050-500-19>.
2. Kalkhoven JT, Watsford ML, Impellizzeri FM. A conceptual model and detailed framework for stress-related, strain-related, and overuse athletic injury. *J of Sci Med Sport* 2020;**23**:726–34; <https://doi.org/10.1016/j.jsams.2020.02.002>.
3. Vanrenterghem J, Nedergaard NJ, Robinson MA *et al.* Training Load Monitoring in Team Sports: A Novel Framework Separating Physiological and Biomechanical Load-Adaptation Pathways. *Sports Med* 2017;**47**:2135–42; <https://doi.org/10.1007/s40279-017-0714-2>.
4. Jeffries AC, Marcora SM, Coutts AJ *et al.* Development of a Revised Conceptual Framework of Physical Training for Use in Research and Practice. *Sports Med* 2021:1–16; <https://doi.org/10.1007/s40279-021-01551-5>.
5. Buchheit M, Rabbani A. The 30-15 Intermittent Fitness Test versus the Yo-Yo Intermittent Recovery Test Level 1: relationship and sensitivity to training. *Int J Sports Physiol Perform* 2014;**9**:522–4; <https://doi.org/10.1123/ijsp.2012-0335>.
6. Bradley PS, Bendiksen M, Dellal A *et al.* The Application of the Yo-Yo Intermittent Endurance Level 2 Test to Elite Female Soccer Populations: Yo-Yo IE2 testing in female soccer players. *Scand J Med Sci Sports* 2014;**24**:43–54; <https://doi.org/10.1111/j.1600-0838.2012.01483.x>.
7. Carling C, Lacombe M, McCall A *et al.* Monitoring of Post-match Fatigue in Professional Soccer: Welcome to the Real World. *Sports Med* 2018;**48**:2695–702; <https://doi.org/10.1007/s40279-018-0935-z>.
8. Lacombe M, Simpson BM, Buchheit M. Monitoring Training Status With Player-Tracking Technology: Still on The Road to Rome. *Aspetar Sports Med Journal* 2018;**7**:54–63.
9. Norris D, Joyce D, Siegler J *et al.* Considerations in interpreting neuromuscular state in elite level Australian Rules football players. *J of Sci Med Sport* 2021;**24**:702–8; <https://doi.org/10.1016/j.jsams.2021.02.007>.
10. Buchheit M. Monitoring training status with HR measures: do all roads lead to Rome? *Front Physiol* 2014;**5**; <https://doi.org/10.3389/fphys.2014.00073>.
11. Buchheit M, Simpson BM, Lacombe M. Monitoring Cardiorespiratory Fitness in Professional Soccer Players: Is It Worth the Prick? *Int J Sports Physiol Perform* 2020;**15**:1437–41; <https://doi.org/10.1123/ijsp.2019-0911>.
12. Scott TJ, McLaren SJ, Caia J *et al.* The reliability and usefulness of an individualised submaximal shuttle run test in elite rugby league players. *Science and Medicine in Football* 2018;**2**:184–90; <https://doi.org/10.1080/24733938.2018.1448937>.
13. Bruce RA, Pearson R. Variability of respiratory and circulatory performance during standardized exercise. *J Clin Invest* 1949;**28**:1431–8; <https://doi.org/10.1172/jci102208>.
14. Åstrand P-O, Ryhming I. A Nomogram for Calculation of Aerobic Capacity (Physical Fitness) From Pulse Rate During Submaximal Work. *J Appl Physiol* 1954;**7**:218–21; <https://doi.org/10.1152/jappl.1954.7.2.218>.

15. Bassey EJ, Fentem PH, MacDonald IC *et al.* Self-paced walking as a method for exercise testing in elderly and young men. *Clin Sci Mol Med* 1976;**51**:609–12.
16. Guyatt GH, Sullivan MJ, Thompson PJ *et al.* The 6-minute walk: a new measure of exercise capacity in patients with chronic heart failure. *Can Med Assoc J* 1985;**132**:919–23.
17. McGavin CR, Gupta SP, McHardy GJ. Twelve-minute walking test for assessing disability in chronic bronchitis. *Br Med J* 1976;**1**:822–3; <https://doi.org/10.1136/bmj.1.6013.822>.
18. Kline GM, Porcari JP, Hintermeister R *et al.* Estimation of VO₂max from a one-mile track walk, gender, age, and body weight. *Med Sci Sports Exerc* 1987;**19**:253–9.
19. Ebbeling CB, Ward A, Puleo EM *et al.* Development of a single-stage submaximal treadmill walking test. *Med Sci Sports Exerc* 1991;**23**:966–73.
20. Broman S, Wigertz O. Transient dynamics of ventilation and heart rate with step changes in work load from different load levels. *Acta Physiol Scand* 1971;**81**:54–74; <https://doi.org/10.1111/j.1748-1716.1971.tb04877.x>.
21. Haber P, Schlick W, Schmid P *et al.* Estimation of the performance spectrum of healthy adolescents by using the PWC 170 (Physical Work Capacity). *Acta Med Austriaca* 1976;**3**:164–6.
22. Franks BD. *YMCA Youth Fitness Test Manual*. 6th ed. Champaign, IL : YMCA of the USA, 1989.
23. Singh SJ, Morgan MD, Scott S *et al.* Development of a shuttle walking test of disability in patients with chronic airways obstruction. *Thorax* 1992;**47**:1019–24; <https://doi.org/10.1136/thx.47.12.1019>.
24. Bruce RA. Exercise testing of patients with coronary heart disease. Principles and normal standards for evaluation. *Ann Clin Res* 1971;**3**:323–32.
25. Bruce RA, Kusumi F, Hosmer D. Maximal oxygen intake and nomographic assessment of functional aerobic impairment in cardiovascular disease. *Am Heart J* 1973;**85**:546–62; [https://doi.org/10.1016/0002-8703\(73\)90502-4](https://doi.org/10.1016/0002-8703(73)90502-4).
26. Ghosh AK. Anaerobic threshold: its concept and role in endurance sport. *Malays J Med Sci* 2004;**11**:24–36.
27. Wasserman K. The anaerobic threshold: definition, physiological significance and identification. *Adv Cardiol* 1986;**35**:1–23.
28. Barbeau P, Serresse O, Boulay MR. Using maximal and submaximal aerobic variables to monitor elite cyclists during a season. *Med Sci Sports Exerc* 1993;**25**:1062–9.
29. Urhausen A, Gabriel H, Weiler B *et al.* Ergometric and Psychological Findings During Overtraining: A Long-Term Follow-Up Study in Endurance Athletes. *Int J Sports Med* 1998;**19**:114–20; <https://doi.org/10.1055/s-2007-971892>.
30. Halson SL, Bridge MW, Meeusen R *et al.* Time course of performance changes and fatigue markers during intensified training in trained cyclists. *J Appl Physiol* 2002;**93**:947–56; <https://doi.org/10.1152/jappphysiol.01164.2001>.
31. Jeukendrup A, Hesselink M, Snyder* A *et al.* Physiological Changes in Male Competitive Cyclists after Two Weeks of Intensified Training. *Int J Sports Med* 1992;**13**:534–41; <https://doi.org/10.1055/s-2007-1021312>.

32. Lamberts RP, Swart J, Noakes TD *et al.* A novel submaximal cycle test to monitor fatigue and predict cycling performance. *Br J Sports Med* 2011;**45**:797–804; <https://doi.org/10.1136/bjsm.2009.061325>.
33. Wallace LK, Slattery KM, Coutts AJ. A comparison of methods for quantifying training load: relationships between modelled and actual training responses. *Eur J Appl Physiol* 2014;**114**:11–20; <https://doi.org/10.1007/s00421-013-2745-1>.
34. Vesterinen V, Nummela A, Äyrämö S *et al.* Monitoring Training Adaptation With a Submaximal Running Test Under Field Conditions. *Int J Sports Physiol Perform* 2016;**11**:393–9; <http://doi.org/10.1123/ijsp.2015-0366>.
35. Vesterinen V, Nummela A, Laine T *et al.* A Submaximal Running Test With Postexercise Cardiac Autonomic and Neuromuscular Function in Monitoring Endurance Training Adaptation: *J Strength Cond Res* 2017;**31**:233–43; <http://doi.org/10.1519/JSC.0000000000001458>.
36. Aubry A, Hausswirth C, Louis J *et al.* The Development of Functional Overreaching Is Associated with a Faster Heart Rate Recovery in Endurance Athletes. Sacchetti M (ed.). *PLoS ONE* 2015;**10**:e0139754; <https://doi.org/10.1371/journal.pone.0139754>.
37. Le Meur Y, Buchheit M, Aubry A *et al.* Assessing Overreaching With Heart-Rate Recovery: What Is the Minimal Exercise Intensity Required? *Int J Sports Physiol Perform* 2017;**12**:569–73; <http://dx.doi.org/10.1123/ijsp.2015-0675>.
38. Bosquet L, Merkari S, Arvisais D *et al.* Is heart rate a convenient tool to monitor over-reaching? A systematic review of the literature. *Br J Sports Med* 2008;**42**:709–14; <https://doi.org/10.1136/bjsm.2007.042200>.
39. Daanen HAM, Lamberts RP, Kallen VL *et al.* A Systematic Review on Heart-Rate Recovery to Monitor Changes in Training Status in Athletes. *Int J Sports Physiol Perform* 2012;**7**:251–60; <http://dx.doi.org/10.1123/ijsp.7.3.251>.
40. Capostagno B, Lambert MI, Lamberts RP. Analysis of a Submaximal Cycle Test to Monitor Adaptations to Training: Implications for Optimizing Training Prescription. *J Strength Cond Res* 2021;**35**:924–30; <https://doi.org/10.1519/jsc.0000000000003227>.
41. Decroix L, Lamberts RP, Meeusen R. Can the Lamberts and Lambert Submaximal Cycle Test Reflect Overreaching in Professional Cyclists? *Int J Sports Physiol Perform* 2018;**13**:23–8; <https://doi.org/10.1123/ijsp.2016-0685>.
42. Schneider C, Hanakam F, Wiewelhove T *et al.* Heart Rate Monitoring in Team Sports—A Conceptual Framework for Contextualizing Heart Rate Measures for Training and Recovery Prescription. *Front Physiol* 2018;**9**:639; <https://doi.org/10.3389/fphys.2018.00639>.
43. Akenhead R, Nassis GP. Training Load and Player Monitoring in High-Level Football: Current Practice and Perceptions. *Int J Sports Physiol Perform* 2016;**11**:587–93; <https://doi.org/10.1123/ijsp.2015-0331>.
44. Taylor K-L, Chapman DW, Cronin JB *et al.* Fatigue Monitoring in High Performance Sport: A Survey of Current Trends. *J Aust Strength Cond* 2012;**20**:12–23.
45. Buchheit M, Mendez-Villanueva A, Quod MJ *et al.* Determinants of the variability of heart rate measures during a competitive period in young soccer players. *Eur J Appl Physiol* 2010;**109**:869–78; <https://doi.org/10.1007/s00421-010-1422-x>.

46. Mohr M, Krstrup P. Yo-Yo intermittent recovery test performances within an entire football league during a full season. *J Sports Sci* 2014;**32**:315–27; <https://doi.org/10.1080/02640414.2013.824598>.
47. Thorpe RT, Strudwick AJ, Buchheit M *et al.* Tracking Morning Fatigue Status Across In-Season Training Weeks in Elite Soccer Players. *Int J Sports Physiol Perform* 2016;**11**:947–52; <http://dx.doi.org/10.1123/ijsp.2015-0490>.
48. Veugelers KR, Naughton GA, Duncan CS *et al.* Validity and Reliability of a Submaximal Intermittent Running Test in Elite Australian Football Players: *J Strength Cond Res* 2016;**30**:3347–53; <https://doi.org/10.1519/jsc.0000000000001441>.
49. Buchheit M, Lacome M, Cholley Y *et al.* Neuromuscular Responses to Conditioned Soccer Sessions Assessed via GPS-Embedded Accelerometers: Insights Into Tactical Periodization. *Int J Sports Physiol Perform* 2018;**13**:577–83; <https://doi.org/10.1123/ijsp.2017-0045>.
50. Haddad M, Chaouachi A, Wong DP *et al.* Influence of fatigue, stress, muscle soreness and sleep on perceived exertion during submaximal effort. *Physiol Behav* 2013;**119**:185–9; <https://doi.org/10.1016/j.physbeh.2013.06.016>.
51. Hulin BT, Gabbett TJ, Johnston RD *et al.* Sub-maximal heart rate is associated with changes in high-intensity intermittent running ability in professional rugby league players. *Science and Medicine in Football* 2019;**3**:50–6. <https://doi.org/10.1080/24733938.2018.1475748>.
52. Leduc C, Tee J, Lacome M *et al.* Convergent Validity, Reliability, and Sensitivity of a Running Test to Monitor Neuromuscular Fatigue. *Int J Sports Physiol Perform* 2020;**15**:1067–73; <https://doi.org/10.1123/ijsp.2019-0319>.
53. Thorpe RT, Strudwick AJ, Buchheit M *et al.* Monitoring Fatigue During the In-Season Competitive Phase in Elite Soccer Players. *Int J Sports Physiol Perform* 2015;**10**:958–64; <https://doi.org/10.1123/ijsp.2015-0004>.
54. Malone S, Hughes B, Roe M *et al.* Monitoring player fitness, fatigue status and running performance during an in-season training camp in elite Gaelic football. *Science and Medicine in Football* 2017;**1**:229–36; <https://doi.org/10.1080/24733938.2017.1361040>.
55. Buchheit M, Cholley Y, Lambert P. Psychometric and Physiological Responses to a Preseason Competitive Camp in the Heat With a 6-Hour Time Difference in Elite Soccer Players. *Int J Sports Physiol Perform* 2016;**11**:176–81; <https://doi.org/10.1123/ijsp.2015-0135>.
56. Buchheit M, Simpson BM, Garvican-Lewis LA *et al.* Wellness, fatigue and physical performance acclimatisation to a 2-week soccer camp at 3600 m (ISA3600). *Br J Sports Med* 2013;**47**:i100–6; <http://dx.doi.org/10.1136/bjsports-2013-092749>.
57. Buchheit M, Voss SC, Nybo L *et al.* Physiological and performance adaptations to an in-season soccer camp in the heat: Associations with heart rate and heart rate variability: Monitoring responses to training in the heat. *Scand J Med Sci Sports* 2011;**21**:e477–85; <https://doi.org/10.1111/j.1600-0838.2011.01378.x>.
58. Buchheit M, Morgan W, Wallace J *et al.* Physiological, Psychometric, and Performance Effects of the Christmas Break in Australian Football. *Int J Sports Physiol Perform* 2015;**10**:120–3; <https://doi.org/10.1123/ijsp.2014-0082>.
59. de Freitas VH, Pereira LA, de Souza EA *et al.* Sensitivity of the Yo-Yo Intermittent Recovery Test and Cardiac Autonomic Responses to Training in Futsal Players. *Int J Sports Physiol Perform* 2015;**10**:553–8; <https://doi.org/10.1123/ijsp.2014-0365>.

60. Aoki MS, Ronda LT, Marcelino PR *et al.* Monitoring Training Loads in Professional Basketball Players Engaged in a Periodized Training Program: *J Strength Cond Res* 2017;**31**:348–58; <https://doi.org/10.1519/jsc.0000000000001507>.
61. Buchheit M, Millet GP, Parisy A *et al.* Supramaximal Training and Postexercise Parasympathetic Reactivation in Adolescents: *Med Sci Sports Exerc* 2008;**40**:362–71; <https://doi.org/10.1249/mss.0b013e31815aa2ee>.
62. Continuous vs intermittent: what is the difference? 2021. <https://diffsense.com/diff/continuous/intermittent>. Accessed 15 Jan 2021.
63. Christensen EH, Rune H, Bengt S. Intermittent and Continuous Running (A further contribution to the physiology of intermittent work.). *Acta Physiol Scand* 1960;**50**:269–86. <https://doi.org/10.1111/j.1748-1716.1960.tb00181.x>.
64. Exercise, Intermittent | Encyclopedia.com. 2021. <https://www.encyclopedia.com/sports/sports-fitness-recreation-and-leisure-magazines/exercise-intermittent>. Accessed 15 Jan 2021.
65. Fitzpatrick JF, Hicks KM, Russell M *et al.* The Reliability of Potential Fatigue-Monitoring Measures in Elite Youth Soccer Players. *Strength Cond Res* 2019;**Publish Ahead of Print**; <http://dx.doi.org/10.1519/JSC.0000000000003317>.
66. Rabbani A, Kargarfard M, Twist C. Reliability and Validity of a Submaximal Warm-up Test for Monitoring Training Status in Professional Soccer Players: *J Strength Cond Res* 2018;**32**:326–33. <https://doi.org/10.1519/jsc.0000000000002335>.
67. Castagna C, Manzi V, Impellizzeri F *et al.* Validity of an On-Court Lactate Threshold Test in Young Basketball Players: *J Strength Cond Res* 2010;**24**:2434–9; <https://doi.org/10.1519/JSC.0b013e3181e2e1bf>.
68. Garrett J, Graham SR, Eston RG *et al.* A Novel Method of Assessment for Monitoring Neuromuscular Fatigue in Australian Rules Football Players. *Int J Sports Physiol Perform* 2019;**14**:598–605; <https://doi.org/10.1123/ijsp.2018-0253>.
69. Buchheit M, Lefebvre B, Laursen PB *et al.* Reliability, Usefulness, and Validity of the 30–15 Intermittent Ice Test in Young Elite Ice Hockey Players. *J Strength Cond Res* 2011;**25**:1457–64; <https://doi.org/10.1519/jsc.0b013e3181d686b7>.
70. Iacono AD, Beato M, Unnithan V. Comparative Effects of Game Profile–Based Training and Small-Sided Games on Physical Performance of Elite Young Soccer Players. *J Strength Cond Res* 2019;**9**; <https://doi.org/10.1519/jsc.0000000000003225>.
71. Lacombe M, Simpson B, Broad N *et al.* Monitoring Players' Readiness Using Predicted Heart-Rate Responses to Soccer Drills. *Int J Sports Physiol Perform* 2018;**13**:1273–80; <https://doi.org/10.1123/ijsp.2018-0026>.
72. Rowell AE, Aughey RJ, Clubb J *et al.* A Standardized Small Sided Game Can Be Used to Monitor Neuromuscular Fatigue in Professional A-League Football Players. *Front Physiol* 2018;**9**:1011; <https://doi.org/10.3389/fphys.2018.01011>.
73. Scott TJ. Testing, prescribing and monitoring training in team sports: The efficiency and versatility of the 30-15 Intermittent Fitness Test. *Sport Performance & Science Reports* 2018;**5**.

74. Delisle-Houde P, Reid RER, Insogna JA *et al.* Seasonal Changes in Physiological Responses and Body Composition During a Competitive Season in Male and Female Elite Collegiate Ice Hockey Players: *J Strength Cond Res* 2019;**33**:2162–9; <https://doi.org/10.1519/jsc.0000000000002338>.
75. Dillern T. Markers of the Aerobic Energy-Delivery System as Measures of Post-Match Fatigue and Recovery in Soccer; a Repeated Measures Design. *Asian J Sports Med* 2017;**8**, DOI: 10.5812/asjms.14425; <https://dx.doi.org/10.5812/asjms.14425>.
76. Dobbin N, Moss SL, Highton J *et al.* An examination of a modified Yo-Yo test to measure intermittent running performance in rugby players. *Eur J Sport Sci* 2018;**18**:1068–76. <https://doi.org/10.1080/17461391.2018.1475509>.
77. Ferioli D, Bosio A, La Torre A *et al.* Different Training Loads Partially Influence Physiological Responses to the Preparation Period in Basketball: *J Strength Cond Res* 2018;**32**:790–7; <https://doi.org/10.1519/jsc.0000000000001823>.
78. Iaia FM, Fiorenza M, Larghi L *et al.* Short- or long-rest intervals during repeated-sprint training in soccer? Csernoch L (ed.). *PLoS ONE* 2017;**12**:e0171462; <https://doi.org/10.1371/journal.pone.0171462>.
79. Reinhardt L, Schulze S, Kurz E *et al.* An Investigation into the Relationship Between Heart Rate Recovery in Small-Sided Games and Endurance Performance in Male, Semi-professional Soccer Players. *Sports Med - Open* 2020;**6**:43; <https://doi.org/10.1186/s40798-020-00273-8>.
80. Rampinini E, Donghi F, Martin M *et al.* Impact of COVID-19 Lockdown on Serie A Soccer Players' Physical Qualities. *Int J Sports Med* 2021, DOI: 10.1055/a-1345-9262. <https://doi.org/10.1055/a-1345-9262>.
81. Owen AL, Wong DP, Paul D *et al.* Effects of a periodized small-sided game training intervention on physical performance in elite professional soccer. *J Strength Cond Res* 2012;**26**:2748–54; <https://doi.org/10.1519/jsc.0b013e318242d2d1>.
82. Signorelli GR, Perim RR, Santos TM *et al.* A pre-season comparison of aerobic fitness and flexibility of younger and older professional soccer players. *Int J Sports Med* 2012;**33**:867–72; <https://doi.org/10.1055/s-0032-1311597>.
83. Altmann S, Neumann R, Härtel S *et al.* Using Submaximal Exercise Heart Rate for Monitoring Cardiorespiratory Fitness Changes in Professional Soccer Players: A Replication Study. *Int J Sports Physiol Perform* 2021:1–7; <https://doi.org/10.1123/ijspp.2020-0554>.
84. Bradley PS, Mohr M, Bendiksen M *et al.* Sub-maximal and maximal Yo–Yo intermittent endurance test level 2: heart rate response, reproducibility and application to elite soccer. *Eur J Appl Physiol* 2011;**111**:969–78; <https://doi.org/10.1007/s00421-010-1721-2>.
85. Brink MS, Visscher C, Coutts AJ *et al.* Changes in perceived stress and recovery in overreached young elite soccer players: Stress and recovery in overreaching. *Scand J Med Sci Sports* 2012;**22**:285–92; <https://doi.org/10.1111/j.1600-0838.2010.01237.x>.
86. Brink MS, Nederhof E, Visscher C *et al.* Monitoring Load, Recovery, and Performance in Young Elite Soccer Players: *J Strength Cond Res* 2010;**24**:597–603; <https://doi.org/10.1519/jsc.0b013e3181c4d38b>.
87. Brink MS, Visscher C, Schmikli SL *et al.* Is an elevated submaximal heart rate associated with psychomotor slowness in young elite soccer players? *Eur J Sport Sci* 2013;**13**:207–14; <https://doi.org/10.1080/17461391.2011.630101>.

88. Dobbin N, Highton J, Moss SL *et al.* The Effects of In-Season, Low-Volume Sprint Interval Training With and Without Sport-Specific Actions on the Physical Characteristics of Elite Academy Rugby League Players. *Int J Sports Physiol Perform* 2020;**15**:705–13; <https://doi.org/10.1123/ijsp.2019-0165>.
89. Doncaster G, Scott M, Iga J *et al.* Reliability of heart rate responses both during and following a 6 min Yo-Yo IR1 test in highly trained youth soccer players. *Science and Medicine in Football* 2019;**3**:14–20; <https://doi.org/10.1080/24733938.2018.1476775>.
90. Dubois R, Lyons M, Paillard T *et al.* Influence of Weekly Workload on Physical, Biochemical and Psychological Characteristics in Professional Rugby Union Players Over a Competitive Season. *J Strength Cond Res* 2020;**34**:527–45; <https://doi.org/10.1519/jsc.0000000000002741>.
91. Fanchini M, Schena F, Castagna C *et al.* External Responsiveness of the Yo-Yo IR Test Level 1 in High-level Male Soccer Players. *Int J Sports Med* 2015;**36**:735–41; <https://doi.org/10.1055/s-0035-1547223>.
92. Fanchini M, Castagna C, Coutts AJ *et al.* Are the Yo-Yo intermittent recovery test levels 1 and 2 both useful? Reliability, responsiveness and interchangeability in young soccer players. *J Sports Sci* 2014;**32**:1950–7; <https://doi.org/10.1080/02640414.2014.969295>.
93. Garvican LA, Hammond K, Varley MC *et al.* Lower Running Performance and Exacerbated Fatigue in Soccer Played at 1600 m. *Int J Sports Physiol Perform* 2014;**9**:397–404; <https://doi.org/10.1123/ijsp.2012-0375>.
94. Hulka K, Weisser R, Belka J *et al.* Stability of internal response and external load during 4-a-side football game in an indoor environment. *Acta Gymnica* 2015;**45**:21–5; <https://doi.org/10.5507/ag.2015.003>.
95. Hulse M, Morris J, Hawkins R *et al.* A Field-Test Battery for Elite, Young Soccer Players. *Int J Sports Med* 2012;**34**:302–11; <https://doi.org/10.1055/s-0032-1312603>.
96. Ingebrigtsen J, Bendiksen M, Randers MB *et al.* Yo-Yo IR2 testing of elite and sub-elite soccer players: Performance, heart rate response and correlations to other interval tests. *J Sports Sci* 2012;**30**:1337–45; <https://doi.org/10.1080/02640414.2012.711484>.
97. Natera AOW, Jennings J, Oakley AJ *et al.* Influence of Environmental Conditions on Performance and Heart Rate Responses to the 30-15 Incremental Fitness Test in Rugby Union Athletes. *J Strength Cond Res* 2019;**33**:486–91; <https://doi.org/10.1519/jsc.0000000000001865>.
98. Owen AL, Newton M, Shovlin A *et al.* The Use of Small-Sided Games as an Aerobic Fitness Assessment Supplement within Elite Level Professional Soccer. *J Hum Kinet* 2020;**71**:243–53; <http://dx.doi.org/10.2478/hukin-2019-0086>.
99. Owen C, Jones P, Comfort P. The reliability of the submaximal version of the Yo-Yo intermittent recovery test in elite youth soccer. *J Trainol* 2017;**6**:31–4.
100. Pereira LA, Abad CCC, Leiva DF *et al.* Relationship Between Resting Heart Rate Variability and Intermittent Endurance Performance in Novice Soccer Players. *Res Q Exerc Sport* 2019;**90**:355–61; <https://doi.org/10.1080/02701367.2019.1601666>.
101. Younesi S, Rabbani A, Manuel Clemente F *et al.* Session-to-session variations of internal load during different small-sided games: a study in professional soccer players. *Res Sports Med* 2021:1–13; <https://doi.org/10.1080/15438627.2021.1888103>.

102. Cornforth DJ, Robinson DJ, Spence I *et al.* Heart Rate Recovery in Decision Support for High Performance Athlete Training Schedules. *IJIKM* 2014;**9**:193–207.
103. Moreira A, Machado DG da S, Moscaleski L *et al.* Effect of tDCS on well-being and autonomic function in professional male players after official soccer matches. *Physiol Behav* 2021;**233**:113351; <https://doi.org/10.1016/j.physbeh.2021.113351>.
104. Meylan CMP, Bowman K, Stellingwerff T *et al.* The Efficacy of Heat Acclimatization Pre-World Cup in Female Soccer Players. *Front Sports Act Living* 2021;**3**:614370; <https://doi.org/10.3389/fspor.2021.614370>.
105. Araújo M, Baumgart C, Freiwald J *et al.* Contrasts in intermittent endurance performance and heart rate response between female and male soccer players of different playing levels. *Biol Sport* 2019;**36**:323–31. <https://doi.org/10.5114/biol sport.2019.88755>.
106. Buchheit M, Racinais S, Bilsborough JC *et al.* Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players. *J of Sci Med Sport* 2013;**16**:550–5; <https://doi.org/10.1016/j.jsams.2012.12.003>.
107. Buchheit M, Simpson MB, Al Haddad H *et al.* Monitoring changes in physical performance with heart rate measures in young soccer players. *Eur J Appl Physiol* 2012;**112**:711–23; <https://doi.org/10.1007/s00421-011-2014-0>.
108. Buchheit M, Simpson BM, Schmidt WF *et al.* Predicting sickness during a 2-week soccer camp at 3600 m (ISA3600). *Br J Sports Med* 2013;**47**:i124–7; <https://doi.org/10.1136/bjsports-2013-092757>.
109. Deprez D, Fransen J, Lenoir M *et al.* The Yo-Yo intermittent recovery test level 1 is reliable in young high-level soccer players. *Biol Sport* 2015;**32**:65–70; <https://doi.org/10.5604/20831862.1127284>.
110. Deprez D, Coutts AJ, Lenoir M *et al.* Reliability and validity of the Yo-Yo intermittent recovery test level 1 in young soccer players. *J Sports Sci* 2014;**32**:903–10; <https://doi.org/10.1080/02640414.2013.876088>.
111. Francini L, Rampinini E, Bosio A *et al.* Association Between Match Activity, Endurance Levels and Maturity in Youth Football Players. *Int J Sports Med* 2019;**40**:576–84; <https://doi.org/10.1055/a-0938-5431>.
112. Lignell E, Fransson D, Krstrup P *et al.* Analysis of High-Intensity Skating in Top-Class Ice Hockey Match-Play in Relation to Training Status and Muscle Damage: *J Strength Cond Res* 2018;**32**:1303–10; <https://doi.org/10.1519/jsc.0000000000001999>.
113. Rabbani A, Kargarfard M, Twist C. Fitness Monitoring in Elite Soccer Players: Group vs. Individual Analyses. *J Strength Cond Res* 2020;**34**:3250–7; <https://doi.org/10.1519/jsc.0000000000002700>.
114. Thorpe RT, Strudwick AJ, Buchheit M *et al.* The Influence of Changes in Acute Training Load on Daily Sensitivity of Morning-Measured Fatigue Variables in Elite Soccer Players. *Int J Sports Physiol Perform* 2017;**12**:S2-107-S2-113; <https://doi.org/10.1123/ijsp.2016-0433>.
115. Vigh-Larsen JF, Beck JH, Daasbjerg A *et al.* Fitness Characteristics of Elite and Subelite Male Ice Hockey Players: A Cross-Sectional Study. *J Strength Cond Res* 2019;**33**:2352–60; <https://doi.org/10.1519/jsc.0000000000003285>.

116. Younesi S, Rabbani A, Clemente FM *et al.* Relationships Between Aerobic Performance, Hemoglobin Levels, and Training Load During Small-Sided Games: A Study in Professional Soccer Players. *Front Physiol* 2021;**12**:649870; <https://doi.org/10.3389/fphys.2021.649870>.
117. Nakamura FY, Pereira LA, Moraes JE *et al.* Physical and physiological differences of backs and forwards from the Brazilian National rugby union team. *J Sports Med Phys Fitness* 2017;**57**:1549–56. <https://doi.org/10.23736/s0022-4707.16.06751-7>.
118. Hulin BT, Gabbett TJ, Pickworth NJ *et al.* Relationships Among PlayerLoad, High-Intensity Intermittent Running Ability, and Injury Risk in Professional Rugby League Players. *Int J Sports Physiol Perform* 2020;**15**:423–9; <https://doi.org/10.1123/ijsp.2019-0139>.
119. Ryan S, Pacecca E, Tebble J *et al.* Measurement Characteristics of Athlete Monitoring Tools in Professional Australian Football. *Int J Sports Physiol Perform* 2019:1–7; <https://doi.org/10.1123/ijsp.2019-0060>.
120. Rago V, Krstrup P, Martín-Acero R *et al.* Training load and submaximal heart rate testing throughout a competitive period in a top-level male football team. *J Sports Sci* 2020;**38**:1408–15; <https://doi.org/10.1080/02640414.2019.1618534>.
121. Fox R, Patterson SD, Waldron M. The relationship between heart rate recovery and temporary fatigue of kinematic and energetic indices among soccer players. *Science and Medicine in Football* 2017;**1**:132–8; <https://doi.org/10.1080/24733938.2017.1329590>.
122. Ingebrigtsen J, Brochmann M, Castagna C *et al.* Relationships Between Field Performance Tests in High-Level Soccer Players: *J Strength Cond Res* 2014;**28**:942–9; <https://doi.org/10.1519/jsc.0b013e3182a1f861>.
123. Harry K, Booyesen MJ. Faster Heart Rate Recovery Correlates With High-Intensity Match Activity in Female Field Hockey Players—Training Implications. *J Strength Cond Res* 2020;**34**:1150–7; <https://doi.org/10.1519/jsc.0000000000003073>.
124. Starling LT, Nellesmann S, Parkes A *et al.* The sensitivity of the Fatigue and Fitness Test for Teams (FFITT) to measure the demands of a rugby match. *Eur J Sport Sci* 2021;**21**:803–10; <https://doi.org/10.1080/17461391.2020.1780327>.
125. Prajapat A, Ahmad I, Khan Z *et al.* Cardiac Autonomic Profile of Soccer, Field Hockey and Basketball Players: A Comparative Study. *Asian J Sports Med* 2018;**9**, DOI: 10.5812/asjrm.62492; <http://dx.doi.org/10.5812/asjrm.62492>.
126. Vachon A, Berryman N, Mujika I *et al.* Tapering and Repeated High-Intensity Effort Ability in Young Elite Rugby Union Players: Influence of Pretaper Fatigue Level. *Int J Sports Physiol Perform* 2021;**16**:993–1000. <https://doi.org/10.1123/ijsp.2020-0639>.
127. Ernst G. Heart-Rate Variability—More than Heart Beats? *Front Public Health* 2017;**5**:240; <https://doi.org/10.3389/fpubh.2017.00240>.
128. Stone NM, Kilding AE. Aerobic Conditioning for Team Sport Athletes: *Sports Med* 2009;**39**:615–42; <https://doi.org/10.2165/00007256-200939080-00002>.
129. Kuipers H, Keizer HA. Overtraining in Elite Athletes: Review and Directions for the Future. *Sports Med* 1988;**6**:79–92; <https://doi.org/10.2165/00007256-198806020-00003>.

130. ten Haaf T, Foster C, Meeusen R *et al.* Submaximal heart rate seems inadequate to prescribe and monitor intensified training. *Eur J Sport Sci* 2019;**19**:1082–91; <https://doi.org/10.1080/17461391.2019.1571112>.
131. Laursen P, Buchheit M eds. *Science and Application of High-Intensity Interval Training*. Human Kinetics, 2019.
132. Racinais S, Buchheit M, Bilsborough J *et al.* Physiological and Performance Responses to a Training Camp in the Heat in Professional Australian Football Players. *Int J Sports Physiol Perform* 2014;**9**:598–603; <https://doi.org/10.1123/ijsp.2013-0284>.
133. Pryor JL, Johnson EC, Roberts WO *et al.* Application of evidence-based recommendations for heat acclimation: Individual and team sport perspectives. *Temperature* 2019;**6**:37–49; <https://doi.org/10.1080/23328940.2018.1516537>.
134. Racinais S, Alonso JM, Coutts AJ *et al.* Consensus recommendations on training and competing in the heat. *Br J Sports Med* 2015;**49**:1164–73; <https://doi.org/10.1111/sms.12467>.
135. Garrett JM, Gunn R, Eston RG *et al.* The effects of fatigue on the running profile of elite team sport athletes. A systematic review and meta-analysis. *J Sports Med Phys Fitness* 2019;**59**:1328. <https://doi.org/10.23736/s0022-4707.19.09356-3>.
136. McLaren SJ, Macpherson TW, Coutts AJ *et al.* The Relationships Between Internal and External Measures of Training Load and Intensity in Team Sports: A Meta-Analysis. *Sports Med* 2018;**48**:641–58; <https://doi.org/10.1007/s40279-017-0830-z>.
137. Akubat I, Barrett S, Abt G. Integrating the internal and external training loads in soccer. *Int J Sports Physiol Perform* 2014;**9**:457–62; <https://doi.org/10.1123/ijsp.2012-0347>.
138. Atkinson G, Batterham AM. The use of ratios and percentage changes in sports medicine: time for a rethink? *Int J Sports Med* 2012;**33**:505–6; <https://doi.org/10.1055/s-0032-1316355>.
139. Wiseman RM. On the use and misuse of ratios in strategic management research. *Research Methodology in Strategy and Management*. Emerald Group Publishing Limited, 2009, 75–110.
140. Coyne JOC, Gregory Haff G, Coutts AJ *et al.* The Current State of Subjective Training Load Monitoring—a Practical Perspective and Call to Action. *Sports Med - Open* 2018;**4**:58; <https://doi.org/10.1186/s40798-018-0172-x>.
141. Jeffries AC, Wallace L, Coutts AJ *et al.* Athlete-Reported Outcome Measures for Monitoring Training Responses: A Systematic Review of Risk of Bias and Measurement Property Quality According to the COSMIN Guidelines. *International Journal of Sports Physiology and Performance* 2020;**15**:1203–15; <https://doi.org/10.1123/ijsp.2020-0386>.
142. McLaren S, Coutts A, Impellizzeri FM. Perception of Effort and Subjective Monitoring. *NSCA's Essentials of Sport Science*. First. Human Kinetics, Inc, 2022, 231–54.
143. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 1982;**14**:377–81; <https://doi.org/10.1249/00005768-198205000-00012>.
144. Chen MJ, Fan X, Moe ST. Criterion-related validity of the Borg ratings of perceived exertion scale in healthy individuals: a meta-analysis. *J Sports Sci* 2002;**20**:873–99; <https://doi.org/10.1080/026404102320761787>.

145. Lea JWD, O'Driscoll JM, Coleman DA *et al.* Validity and reliability of the 'Isometric Exercise Scale' (IES) for measuring ratings of perceived exertion during continuous isometric exercise. *Sci Rep* 2021;**11**:5334; <https://doi.org/10.1038/s41598-021-84803-8>.
146. Pageaux B. Perception of effort in Exercise Science: Definition, measurement and perspectives. *Eur J Sport Sci* 2016;**16**:885–94; <https://doi.org/10.1080/17461391.2016.1188992>.
147. Halperin I, Emanuel A. Rating of Perceived Effort: Methodological Concerns and Future Directions. *Sports Med* 2020;**50**:679–87; <https://doi.org/10.1007/s40279-019-01229-z>.
148. Sangan HF, Hopker JG, Davison G *et al.* The Self-Paced Submaximal Run Test: Associations With the Graded Exercise Test and Reliability. *Int J Sports Physiol Perform* 2021:1–9; <https://doi.org/10.1123/ijsp.2020-0904>.
149. Lovell R, Halley S, Siegler J *et al.* Use of Numerically Blinded Ratings of Perceived Exertion in Soccer: Assessing Concurrent and Construct Validity. *Int J Sports Physiol Perform* 2020;**15**:1430–6; <https://doi.org/10.1123/ijsp.2019-0740>.
150. Micklewright D, St Clair Gibson A, Gladwell V *et al.* Development and Validity of the Rating-of-Fatigue Scale. *Sports Med* 2017;**47**:2375–93; <https://doi.org/10.1007/s40279-017-0711-5>.
151. McLaren SJ, Taylor JM, Macpherson TW *et al.* Systematic Reductions in Differential Ratings of Perceived Exertion Across a 2-Week Repeated-Sprint-Training Intervention That Improved Soccer Players' High-Speed-Running Abilities. *Int J Sports Physiol Perform* 2020;**15**:1414–21; <https://doi.org/10.1123/ijsp.2019-0568>.
152. Winter EM, Abt G, Brookes FBC *et al.* Misuse of "Power" and Other Mechanical Terms in Sport and Exercise Science Research. *J Strength Cond Res* 2016;**30**:292–300. <https://doi.org/10.1519/jsc.0000000000001101>.
153. Bourdon PC, Cardinale M, Murray A *et al.* Monitoring Athlete Training Loads: Consensus Statement. *Int J Sports Physiol Perform* 2017;**12**:S2-161-S2-170; <https://doi.org/10.1123/ijsp.2017-0208>.
154. Buchheit M, Simpson BM. Player-Tracking Technology: Half-Full or Half-Empty Glass? *Int J Sports Physiol Perform* 2017;**12**:S2-35-S2-41; <https://doi.org/10.1123/ijsp.2016-0499>.
155. Nikolaidis PT, Busko K, Afonso J *et al.* The effect of maturity on heart rate responses during training and testing in postpubescent female volleyball players. *Hum Physiol* 2015;**41**:636–43. <https://doi.org/10.7868/s0131164615060053>.
156. Younesi S, Rabbani A, Clemente F *et al.* Session-to-session variations in external load measures during small-sided games in professional soccer players. *Biol Sport* 2021;**38**:185–93; <https://doi.org/10.5114/biolSport.2020.98449>.
157. Clemente FM, Rabbani A, Kargarfard M *et al.* Session-To-Session Variations of External Load Measures of Youth Soccer Players in Medium-Sided Games. *Int J Environ Res Public Health* 2019;**16**, DOI: 10.3390/ijerph16193612; <https://doi.org/10.3390/ijerph16193612>.
158. Malone JJ, Lovell R, Varley MC *et al.* Unpacking the Black Box: Applications and Considerations for Using GPS Devices in Sport. *Int J Sports Physiol Perform* 2017;**12**:S2-18-S2-26. <https://doi.org/10.1123/ijsp.2016-0236>.

159. Verheul J, Nedergaard NJ, Vanrenterghem J *et al.* Measuring biomechanical loads in team sports – from lab to field. *Science and Medicine in Football* 2020;**4**:246–52; <https://doi.org/10.1080/24733938.2019.1709654>.
160. Barrett S, Midgley AW, Towlson C *et al.* Within-Match PlayerLoad™ Patterns During a Simulated Soccer Match: Potential Implications for Unit Positioning and Fatigue Management. *Int J Sports Physiol Perform* 2016;**11**:135–40; <https://doi.org/10.1123/ijsp.2014-0582>.
161. Buchheit M, Gray A, Morin J-B. Assessing Stride Variables and Vertical Stiffness with GPS-Embedded Accelerometers: Preliminary Insights for the Monitoring of Neuromuscular Fatigue on the Field. 2015;**14**:698–701.
162. Cormack SJ, Mooney MG, Morgan W *et al.* Influence of Neuromuscular Fatigue on Accelerometer Load in Elite Australian Football Players. *Int J Sports Physiol Perform* 2013;**8**:373–8; <https://doi.org/10.1123/ijsp.8.4.373>.
163. Hobara H, Inoue K, Gomi K *et al.* Continuous change in spring-mass characteristics during a 400m sprint. *J of Sci Med Sport* 2010;**13**:256–61; <https://doi.org/10.1016/j.jsams.2009.02.002>.
164. Brughelli M, Cronin J. A review of research on the mechanical stiffness in running and jumping: methodology and implications: Mechanical stiffness. *Scand J Med Sci Sports* 2008;**18**:417–26; <https://doi.org/10.1111/j.1600-0838.2008.00769.x>.
165. Rowell AE, Aughey RJ, Hopkins WG *et al.* Identification of Sensitive Measures of Recovery After External Load From Football Match Play. *Int J Sports Physiol Perform* 2017;**12**:969–76; <https://doi.org/10.1123/ijsp.2016-0522>.
166. Silva JR, Ascensão A, Marques F *et al.* Neuromuscular function, hormonal and redox status and muscle damage of professional soccer players after a high-level competitive match. *Eur J Appl Physiol* 2013;**113**:2193–201; <https://doi.org/10.1007/s00421-013-2633-8>.
167. Fitzpatrick JF, Akenhead R, Russell M *et al.* Sensitivity and reproducibility of a fatigue response in elite youth football players. *Science and Medicine in Football* 2019;**3**:214–20; <https://doi.org/10.1080/24733938.2019.1571685>.
168. Garrett JM, Graham SR, Eston RG *et al.* Comparison of a Countermovement Jump Test and Submaximal Run Test to Quantify the Sensitivity for Detecting Practically Important Changes Within High-Performance Australian Rules Football. *Int J Sports Physiol Perform* 2020;**15**:68–72; <https://doi.org/10.1123/ijsp.2019-0150>.
169. Garrett J, Akyildiz Z, Leduc C *et al.* Peak running speed can be used to monitor neuromuscular fatigue from a standardized running test in team sport athletes. *Res Sports Med* 2021:1–12; <https://doi.org/10.1080/15438627.2021.1966012>.
170. Huygaerts S, Cos F, Cohen DD *et al.* Mechanisms of Hamstring Strain Injury: Interactions between Fatigue, Muscle Activation and Function. *Sports* 2020;**8**:65; <https://doi.org/10.3390/sports8050065>.
171. Cormack SJ, Newton RU, McGuigan MR *et al.* Reliability of Measures Obtained During Single and Repeated Countermovement Jumps. *Int J Sports Physiol Perform* 2008;**3**:131–44; <https://doi.org/10.1123/ijsp.3.2.131>.
172. Barrett S, Midgley A, Reeves M *et al.* The within-match patterns of locomotor efficiency during professional soccer match play: Implications for injury risk? *J Sci Med Sport* 2016;**19**:810–5; <https://doi.org/10.1016/j.jsams.2015.12.514>.

173. Kelly SJ, Murphy AJ, Watsford ML *et al.* Reliability and validity of sports accelerometers during static and dynamic testing. *Int J Sports Physiol Perform* 2015;**10**:106–11; <https://doi.org/10.1123/ijsp.2013-0408>.
174. Eggers TM, Massard TI, Clothier PJ *et al.* Measuring Vertical Stiffness in Sport With Accelerometers: Exercise Caution! *J Strength Cond Res* 2018;**32**:1919–22; <https://doi.org/10.1519/jsc.0000000000002318>.
175. Barrett S, Midgley A, Lovell R. PlayerLoad™: reliability, convergent validity, and influence of unit position during treadmill running. *Int J Sports Physiol Perform* 2014;**9**:945–52; <https://doi.org/10.1123/ijsp.2013-0418>.