Quantification of the physical demands of training and match-play in elite youth soccer players

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Abstract

A detailed understanding of the relationship between external and internal training load (dose-response) is crucial for the effective optimisation of athletic performance (Impellizzeri et al., 2019). To date, limited attention has focused on the validity of measurement tools frequently used to quantify the demands of training and match-play in soccer. The purpose of the thesis was to examine the validity of these measurement tools using elite youth soccer players.

Using elite youth soccer players' maximal sprinting speeds (MSS) collected from a criterion and non-criterion measure, the aim of the first study (Chapter 3) was to demonstrate how practitioner opinion can be used to determine measurement validity. Twelve elite youth soccer players performed two maximal 40 m sprints, measured by 10-Hz GPS units (non-criterion) and a 100-Hz Laser (criterion). Setting statistical equivalence bounds as practitioner opinion of the practically acceptable amount of measurement error for MSS, the agreement between GPS and Laser was assessed. MSS was 8.79 ± 0.33 m/s (Laser) and 8.75 ± 0.32 m/s (GPS), and the mean difference was 0.04 (90% confidence interval -0.03 to 0.11) m/s. Equivalence testing showed Laser and GPS as likely equivalent measures (probability 93.7%). Using an analytical method informed by expert opinion on the acceptable amount of measurement error for MSS, practitioners can rely on GPS for an accurate assessment of MSS.

The aim of the second study (Chapter 4) was to investigate whether players' MSS occurs during sprint testing or typical soccer training activities and competitive matches. The MSS of 12 full-time male youth soccer players was recorded during a 40-m sprint test and their routine activities (matches, sprints, and skill-based conditioning drills: small-sided games [SSG], medium-sided games [MSG], large-sided games [LSG]). All activities were monitored with 10-Hz GPS, with the highest speed attained during each activity retained as the instantaneous MSS. MSS was faster for the sprint test (8.76 ± 0.39 $m \cdot s^{-1}$) compared with matches (7.94 ± 0.49 $m \cdot s^{-1}$), LSG (6.94 ± 0.65 $m \cdot s^{-1}$), MSG (6.40 ± 0.75 $m \cdot s^{-1}$), and SSG (5.25 ± 0.92 $m \cdot s^{-1}$), but not sprints (8.50 ± 0.36 $m \cdot s^{-1}$). These findings highlight the importance of 40-m sprint testing to assess players' MSS and suggest that practitioners should incorporate specific sprint drills with adequate space (e.g., 40 meters) during purposeful sprint training to expose players to MSS stimuli.

The aim of the third study (Chapter 5) was to examine the moderating effect of familiarisation on the relationship between proxy measures of external load and ratings of perceived exertion (RPE) in elite youth soccer players. The final sample included familiarised (blackness test; n= 20) and non-familiarised players (n= 15) with the Borg centiMax scale; players were monitored over a 31-week period. Global RPE and dRPE for breathlessness (RPE-B) and leg-muscle exertion (RPE-L) were recorded 15 to 30 minutes following training sessions and match-play. Players improved their blackness test score from 39% to 78%. For explorations by number of accelerations, familiarisation effects were not practically relevant for the global RPE and RPE-B variables. The width and sign of the effects for the RPE-L variable at 30 efforts of 10 AU (95% CI, 4-16 AU) suggested that scores were lower for players who underwent familiarisation versus players who did not. Familiarisation effects were not practically relevant for any RPE variable irrespective of the number of deceleration efforts and high-speed running (HSR) covered. These data indicate that improved performance on the blackness test did not have a moderating effect on the relationship between proxy measures of external load and RPE.

The aim of the fourth and final study (chapter 6) was twofold. First, to assess the between-method agreement for the quantification of HSR distance by comparing absolute and relative speed threshold approaches. Secondly, to investigate the associations between internal and external load (dose-response relationship), using session type-specific differences in perceived exertion (RPE, dRPE) at pre-specified values of absolute and relative HSR distance in elite youth soccer players. The final sample consisted of thirteen elite youth soccer players who completed approximately five training sessions per week over a 31-week period. The use of relative HSR thresholds resulted in consistently lower median HSR distances compared to absolute thresholds across strength (176 m vs. 168 m), endurance (268 m vs. 247 m), and speed (173 m vs. 146 m) sessions.

For explorations with global RPE as response variable, visual inspection of the density strips surrounding the mean estimate suggested no effect clearly exceeded the predefined region of equivalence regardless of the HSR quantification method. The mean difference in global RPE for game versus endurance session type comparison was 11 au (95%CI, 3 to 18 au) at 500 m of absolute HSR. Game versus speed session type mean differences in global RPE by absolute and relative HSR at 500 m were 11 au (95%CI, 3 to 19 au) and 12 au (95%CI, 3 to 20 au), respectively. For explorations with RPE-B as response variable, density strips suggested most of the estimated effects were broadly uncertain and not practically relevant. For explorations with RPE-L as response variable, density strips indicated some clear and practically relevant effects mostly at HSR distances of 500 m. For instance, at absolute HSR of 500 m, mean differences in RPE-L for game versus endurance and game versus speed session type comparisons were 15 au (95%CI, 4 to 27 au) and 14 au (95%CI, 4 to 24 au), respectively. The results presented demonstrated that global RPE in response to external load remained similar whether analysed using absolute or relative speed zones and did not change across the different type of training sessions. RPE-L exhibits greater sensitivity to variations across different training modes compared to RPE-B. However, both measures maintain a strong association with global RPE. Notably, this relationship persists regardless of whether external load is assessed using absolute or individualised speed thresholds.

The results of this thesis provide novel insights into the quantification of the physical demands of training and match-play in elite youth soccer players. The data demonstrate the validity of GPS-based speed measurements and highlight important contextual considerations for sprint performance assessment. Finally, information was presented on the associations between internal and external load (dose-response) in elite youth soccer players, suggesting that global RPE remains a valid and efficient tool for monitoring internal responses to external training loads. Practitioners can confidently implement global RPE in daily training environments without the need for additional differential RPE measures.

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List of Abbreviations

ASR	Anaerobic speed reserve
AU	Arbitrary units
B[La]	Blood lactate concentration(s)
CI	Confidence interval
cm	Centimetres
CP	Phosphocreatine
CMJ	Countermovement jump
CR10	Borg category-ratio 10 (deciMax®) scale
CR100	Borg category-ratio 100 (centiMax®) scale
dRPE	Differential ratings of perceived exertion
GPS	Global positioning systems
HIIT	High-intensity interval training
HR	Heart rate (beats per minute)
HSR	High speed running
IQR	Interquartile range
kg	Kilograms
Km/h	Kilometres per hour
LSG	Large sided games
m	Meters
m/s	Meters per second
MD	Match day
MAS	Maximal aerobic speed

MSG	Medium sided games
MSS	Maximal sprinting speed
PC	Phosphocreatine
Q	Question
RSA	Repeated sprint ability
RPE	Rating (s) of perceived exertion
RPE-B	Rating(s) of perceived breathlessness
RPE-L	Rating(s) of perceived leg muscle exertion
s	Seconds
sRPE	Session rating of perceived exertion
sRPE-TL	Sessions rating of perceived exertion training load
SD	Standard deviation
SSG	Small-sided games
TD	Total distance
TRIMP	Training impulse
VT	Ventilatory thresholds
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_2$ max	Maximal oxygen uptake

CHAPTER 1: INTRODUCTION

1. Introduction

Training to enhance physical performance is an adaptive process that involves progressive manipulation of the physical load (Manzi et al., 2010). As a result, changes in cardiometabolic, neuromuscular and musculoskeletal systems occur as a functional adaptive responses to that physical stress (Impellizzeri et al., 2019). Central to this process is the monitoring of training load, which allows coaches to manage the balance between physical exertion and recovery, ensuring optimal adaptation (Akubat et al., 2012; Akenhead & Nassis, 2016). Current practices and perceptions of monitoring in professional soccer demonstrate that elite clubs adopt a variety of methods and tools to monitor player load (Akenhead & Nassis, 2016; Weston, 2018).

Assessing the physical demands of training requires the measurement of both internal and external load. This is particularly important in team sports, where players exhibit heterogeneous physiological responses to identical external workloads (Manzi et al. 2010). External load refers to the total mechanical activity (accelerations/decelerations), locomotor activity (distance covered in different speeds) and the non-locomotor activity that are performed by a player (Vanrenterghem et al, 2017; Impellizzeri et al., 2019). In contrast, internal load reflects the physiological responses to external demands and serves to mediate the adaptive response to training (Viru & Viru, 2000; Impellizzeri et al., 2019). A combined approach to monitoring both internal and external loads is considered optimal for evaluating players' performance, fatigue, and readiness to train or compete, as it provides a more complete understanding of the dose-response relationship between training stimuli and physiological adaptation. (Akubat et al., 2012; Malone et al., 2015; Bourdon et al., 2017).

While overall distance covered provides a general overview of soccer match-play demands, a more detailed analysis of the high-speed elements of the game, namely accelerations/decelerations, sprints, jumps, tackles and turns, is needed in order to better understand the physical demands of the game (Carling et al., 2016). During a 90-min game, players can achieve very high sprinting speeds (i.e, ~85-94% of maximal sprinting speed [MSS]) regardless of age or playing position (Mendez-Villanueva et al., 2011). The practical significance of sprinting is evident in findings that straight-line sprints often precede a high proportion of goals (Faude et al., 2012), and that successful teams tend to cover greater sprint distances during matches compared to less successful ones (Yang et al., 2018). Fully automatic timing systems, laser devices and high-speed video analysis are widely regarded as the gold standard for measuring MSS (Haugen & Buchheit, 2016). However, these methods are often costly and time-consuming, making them less practical for regular use by practitioners in applied settings.

In contrast, global positioning systems (GPS) now serve as a convenient tool through which to measure external load in the field, particularly movement distance across various locomotor categories (i.e., from walking to sprinting), (Akenhead & Nassis, 2016; Malone et al., 2017; Weston, 2018). Validity studies are fundamental in the development of alternate measures, such as GPS which are non-criterion measures (Roe et al., 2017; Beato et al., 2018). However, these studies, reflecting a commonly used approach to validity assessment have typically interpreted between-system differences using standardised thresholds, which are inherently influenced by sample heterogeneity (Hopkins, 2018; Lakens et al., 2018; Pek & Flora, 2018). Importantly, researchers and practitioners in team sports should not rely exclusively on standardised effect sizes to determine practical relevance, as defining meaningful differences based solely on such metrics should be considered a measure of last resort (Lakens, 2013; Cook et al., 2018). Effect (e.g., difference) magnitude should be evaluated according to its practical relevance and a standardised scale may not be relevant to the research question (Pek and Flora 2018). An alternative to standardisation involves eliciting expert opinion to establish the smallest important difference, thereby incorporating practitioner insight as a valuable contributor to external validity (Thorpe et al., 2017; Esculier et al., 2018). Despite its potential, this practitioner-informed approach remains largely unexplored within the context of sports performance research.

The use of arbitrary speed thresholds to quantify external load has been criticised for failing to account for the individual "capacity" of players (Abt and Lovell, 2009). To address these limitations, an increasing number of studies advocate expressing external load relative to each player's physiological capabilities (Harley et al., 2010; Cahill et al., 2013; Mendez-Villanueva et al., 2013; Gabbett et al., 2015; Hunter et al., 2014; Reardon et al., 2015; Abbott et al., 2018). This shift has led to the growing adoption of individualised speed thresholds in applied settings, where adjusting speed zones to a player's specific capacity enables more precise evaluation of the energetic demands and recovery requirements of training and match-play (Mendez-Villanueva et al., 2013; Hunter et al., 2014; Gabbett et al., 2015; Zurutuza et al., 2017). Whether used in isolation or in combination with maximal aerobic speed, MSS remains a key metric for informing external load individualisation in the field (Scott and Lovell, 2018). Accurate measurement of MSS is therefore essential, rather than relying on assumed or historical peak values. Using underestimated MSS to set individualised thresholds would overestimate high-speed running metrics (Reardon et al., 2015). In team sports, individualised speed zones have often been anchored to the highest velocity recorded during any session throughout a season (Reardon et al., 2015; Casamichana et al., 2018) or during competitive matches (Cahill et al., 2015). However, in soccer, MSS is typically derived from controlled sprint testing (Harley et al., 2010;

Mendez-Villanueva et al., 2013; Hunter et al., 2014; Gabbett, 2015). Despite these practices, there remains uncertainty in the literature regarding which context; testing, training, or match play, most reliably captures a player's true MSS.

The use of ratings of perceived exertion (RPE) to assess internal load, has gained prominence for its simplicity and validity in reflecting the combination of aerobic and anaerobic effort during exercise (Foster et al., 2001; Coyne et al., 2018). While RPE provides a broad assessment of intensity, it may lack the specificity needed to capture the nuances of exertion across different physiological systems, especially in team sports with variable demands like soccer (Weston, 2013). Recent studies have focused on differential ratings of perceived exertion (dRPE), which separates RPE into distinct categories, such as breathlessness (RPE-B) and leg fatigue (RPE-L), to provide a more comprehensive view of internal load (Weston et al., 2015; McLaren et al., 2017; Wright et al., 2020; Maughan et al., 2020; Houtmeyers et al., 2022). This approach has the potential to enhance understanding of the physiological, musculoskeletal, and cognitive demands placed on players during training and match-play, with implications for optimising performance and reducing injury risk (Jaspers et al., 2017; Jones et al., 2017). In team sports, athletes provide different dRPE ratings after resistance exercise (e.g. higher RPE-L) and running-based aerobic endurance (e.g. higher RPE-B) (McLaren et al, 2017; Wright et al., 2020). Contrary to such observations, during team-sport training and match-play, contrasting evidence exists regarding players ability to provide different ratings (Gil-Rey et al., 2015; Los Arcos et al., 2016; Leceaga et al., 2017; Maughan et al., 2020; Houtmeyers et al., 2022). In situations where distinct dRPE scores would be expected due to varied loading patterns, a lack of clear differentiation may instead reflect inconsistent background knowledge and insufficient familiarisation with the scale (Saw et al., 2017; Macpherson et al., 2019). Despite previous research demonstrating that familiarisation with RPE improved individuals' ability to estimate intensity using the blackness test in semi-professional soccer (Macpherson et al., 2019), no study has investigated how familiarisation with subjective measures of perceived exertion influences its subsequent relationship with measures of external load.

In the absence of any 'gold standard' criterion measure of internal load (Vanrenterghem et al., 2017), examining the associations between internal and external load can provide evidence for construct validity and sensitivity of a chosen training load measure (Castillo et al., 2017). Optimising training outcomes in soccer requires a clear understanding of the relationship between internal and external load, as this interplay informs decisions around training prescription, periodisation, and player management (Malone et al., 2015; McLaren et al., 2018). This relationship, often described as the dose-response, is shaped not only by the mode of training but also by individual differences in physiological capacity (McLaren et al., 2018). Although the concept of using individualised external load thresholds is to better understand the individual players' dose-response and energetic demands of training and match-play (Hunter et al., 2014), their impact on the subsequent relationship with RPE remains under-researched. Scott and Lovell, (2018) found similar relationships between external load and RPE when using both absolute and individualised speed zones, suggesting that individualised thresholds may not enhance relationship between external load and RPE (dose-response relationship) in soccer. Further work is needed to better understand how individualised external loads influence the subsequent relationship with the internal load response when accounting specific modes of training.

Furthermore, the effectiveness of dRPE in strengthening the internal-external load relationship in soccer remains uncertain when external load is assessed using absolute thresholds (Maughan et al., 2020; Houtmeyers et al., 2022). Findings are inconsistent regarding the relationship between external load and dRPE measures when accounting for the mode of training (McLaren et al., 2017; Houtmeyers et al., 2022). For instance, McLaren et al. (2017) reported positive associations between sRPE and sRPE-L during high-intensity intervals (r = 0.67; 90% confidence limits ±0.22), and sRPE-B during repeated high-intensity efforts (r = 0.89; ±0.08). In contrast, Houtmeyers et al. (2022) found that players provided different ratings for sRPE-B and sRPE-L in only 22% of sessions, with no consistent pattern in the direction of differentiation. Given the critical role of both external and internal load metrics in training monitoring, performance optimisation, and injury risk mitigation, there is a clear need to further investigate their interaction, particularly when individualised external load and perceived exertion measures (global RPE, dRPE) are applied across different training modalities.

1.1 Background to Research Studies

Effective decision-making in applied sport settings depends on the use of performance assessment tools that are both practically accessible and scientifically validated, particularly when those tools are non-criterion measures (Roe et al., 2017; Beato et al., 2018). Validity research plays a critical role in supporting the adoption of alternative technologies such as GPS, which provide a cost-effective and practical solution for collecting field-based data (Dixon et al., 2018). Although previous studies have evaluated the validity of such technologies, their conclusions often rely on standardised statistical thresholds that may not adequately capture the nuanced requirements of applied sport science contexts (Pek & Flora, 2018). Incorporating practitioner perspectives into the statistical evaluation process may offer more practically meaningful interpretations of measurement differences. Recently, equivalence testing has been suggested to have potential for advancing measurement research in exercise science (Dixon et al., 2018). What may be of more relevance to practitioners and researchers in sports performance research is setting equivalence thresholds based on the smallest meaningful difference, expressed in raw units, as defined by expert consensus. Therefore, the initial study will assess the validity of 10-Hz GPS for measuring MSS against a criterion reference (100-Hz laser device), employing equivalence testing with practitioner-informed thresholds of practical significance.

MSS is a fundamental parameter for individualising external training loads in soccer Scott and Lovell, 2018. As such, obtaining an accurate measure of this metric is critical for performance monitoring and training prescription. Practitioners have commonly derived individualised high-speed running thresholds based on the highest sprinting speeds recorded across various contexts, including throughout an entire season (Reardon et al., 2015; Casamichana et al., 2018), during competitive match-play (Cahill et al., 2015), or through controlled sprint testing protocols (Harley et al., 2010; Mendez-Villanueva et al., 2013; Hunter et al., 2014; Gabbett, 2015). However, it remains unclear which of these contexts consistently elicits an athlete’s true maximal sprinting capacity. Therefore, the second aim of this thesis is to investigate the occurrence of MSS across different soccer-specific settings; comparing values attained from structured sprint tests, match-play, and a broader spectrum of training activities, to determine the most reliable and valid source for informing individualised load prescriptions.

Perceived exertion scales (global RPE, dRPE) are widely recognised as valid and practical tools for quantifying internal load in soccer, applicable across both training and competitive contexts (Weston, 2013). However, variability in findings concerning the effectiveness of the scales may partly stem from inconsistencies in participant education and familiarisation with these tools (Coyne et al., 2018; Macpherson et al., 2019). To date, no study has systematically investigated how familiarisation with exertional rating scales influences the relationship between perceived exertion measures (global RPE, dRPE) and external load metrics during field-based activities. Therefore, the third aim of this thesis is to explore the moderating effect of familiarisation with the CR100 scale on players' perceived exertion ratings, evaluated in relation to proxy measures of external load during training and match-play in elite youth soccer players.

Findings remain inconsistent regarding the associations between perceived exertion scales (global RPE, dRPE) and external load when accounting for mode of training (McLaren et al., 2017; Wright et al., 2020; Houtmeyers et al., 2022) and players' physiological characteristics (Scott and Lovell, 2018). The final aim of this thesis is twofold. First, it aims to examine how external load measurements vary when calculated using absolute versus individualised speed thresholds, with particular attention to differences across various session types. Second, it seeks to investigate the dose-response relationship; specifically, assessing session type-specific differences in perceived exertion (global RPE, dRPE) at pre-specified values of absolute and relative high-speed running distance. This will represent the first study to explore the dose-response relationship using individualised speed zones and perceived exertion measures across a diverse range of field-based training modalities in elite youth soccer players.

1.2 Aims and Objectives

To study the associations between internal and external load (dose-response relationship) of training and match-play in elite youth soccer players.

Objectives

1. To assess the validity of GPS by comparing maximal sprinting speed data collected from a criterion measure (100-Hz laser) and a non-criterion measure (10-Hz GPS), using equivalence testing with practitioner-informed thresholds of practical significance.

2. To test the hypothesis of whether maximal sprinting speed occurs during sprint testing or during typical soccer training modalities and competitive match-play.

3. To study the moderating effect of familiarisation with the CR100 scale on RPE anchored against proxy measures of external load during training and match-play.

4. To examine the associations between internal and external load (dose-response relationship), by assessing session type-specific differences in perceived exertion (RPE, dRPE) at predefined absolute and relative high-speed running distances in elite youth soccer players.

CHAPTER 2: REVIEW OF LITERATURE

2. Review of Literature

The aim of this review of literature is to provide the reader with information regarding the quantification of the physical demands of training and match-play in elite youth soccer players. The initial section of the review outlines the physical and physiological demands of soccer followed by an examination of the training periodisation to physically prepare the players for competition. Subsequent sections review the training load monitoring and the associations between internal and external load in elite youth soccer players.

2.1 Physical demands of soccer

2.1.1 Match activity profile

Soccer is an invasion-style sport involving two opposing teams competing to outscore one another. A standard match lasts 90 minutes, divided into two 45-minute halves separated by a 15-minute interval. Match play is typically divided into two main phases: (a) open play, which encompasses the four tactical moments of the game - offensive organisation, defensive organisation, defensive transition, and offensive transition; and (b) set plays, including kick-offs, free kicks, corners, throw-ins, and penalties. The ball is generally in open play for approximately 55–60 minutes (Bloomfield et al., 2007), with the remaining time comprising stoppages for throw-ins, set pieces, injuries, goal kicks, and other periods when the ball is out of play (Carling & Dupont, 2010).

The activity profile of soccer match-play is characterised by its intermittent nature, consisting of prolonged periods of low-intensity running interspersed with brief, high-intensity efforts across the 90-minute duration (Rampinini et al., 2008). Total distance covered during a match offers valuable insight into the overall energy demands of the game (Andrzejewski et al., 2016). On average, players cover between 9 and 13 km per match, with the majority of this distance attributed to low-intensity running, and approximately 10% comprising high-speed running (Bradley et al., 2009; Di Salvo et al., 2009; Andrzejewski et al., 2016). Several contextual factors, including quality of opposition, match outcome, playing position, and tactical strategies, significantly influence the total distance covered, contributing to high match-to-match variability (Gregson et al., 2010; Bradley et al., 2013; Barnes et al., 2014; Andrzejewski et al., 2016). Regarding positional demands, central and wide midfielders consistently cover the greatest total distances, averaging 11,450 ± 608 m and 11,535 ± 933 m, respectively (Bradley et al., 2009).

While overall distance covered provides a general overview of the soccer match-play demands, a more detailed analysis of the high-speed elements of the game, namely accelerations/decelerations, sprints, jumps, tackles and turns, is needed in order to better understand the physical demands of the game (Carling et al., 2016). During match-play, players typically perform 1000-1525 discrete bouts of activity (Mohr et al., 2003), 3-40 sprints (>23 km/h) (Di Salvo et al., 2007), 30-40 jumps and tackles (Bangsbo et al., 2006) and 600-800 turns (Bloomfield et al., 2007). In terms of positional demands, wide defenders usually perform more maximal accelerations and high-speed running with central defenders and midfielders performing less sprints compared to all other positions (Bradley et al., 2009; Varley and Aughey, 2012; Ingebrigtsen et al., 2015). During a 90-min game, players can achieve very high sprinting speeds (i.e, ~85–94% of maximal sprinting speed) regardless of age or playing position with faster players reaching greater absolute speed during the games than their slower teammates (Mendez-Villanueva et al., 2011).

Physical activity profiling in elite soccer has evolved significantly since the early investigations employing video-based match analysis systems (Reilly & Thomas, 1979; Bangsbo et al., 1991). Building on these foundational studies, the introduction of high-speed camera technology enabled more sophisticated analyses, incorporating both physical and tactical aspects of match-play (Di Salvo et al., 2006; Di Salvo et al., 2009). This advancement has facilitated a growing body of research exploring detailed components of the game, such as team tactics and their impact on physical demands (Castellano et al., 2014; Yang et al., 2018; Bradley & Ade, 2018). Notably, Bradley and Ade (2018) proposed an integrated framework for analysing match demands, which emphasises high-speed running contextualised by key tactical actions specific to each playing position (e.g., overlapping runs, pressing, or creating space). A multitude of contextual factors can also influence team performance during a match, including match location (Courneya & Carron, 1991), tactical formation (Bradley et al., 2011), level of competition or country (Dellal et al., 2011; Bradley et al., 2013), quality of opposition (Rampinini et al., 2009), player fatigue (Carling & Dupont, 2011), and individual fitness capacity (Ingebrigtsen et al., 2012). For instance, in relation to competition level, match performance data from the top three tiers of English soccer indicate that players across all positions in the second (Championship) and third (League One) divisions covered greater high-speed running distances than those in the top tier (Premier League) (Figure 2-1) (Bradley et al., 2013). Playing style and tactical formation also exert a substantial influence on players' physical performance (Bradley et al., 2013; Barnes et al., 2014). In the Premier League, for instance, teams typically adopt possession-based tactics, in contrast to the more direct, long-ball strategies often employed in lower-tier leagues (Bradley et al., 2013). Furthermore, Barnes et al. (2014) demonstrated that the physical demands of the English Premier League have evolved in recent years, with notable increases in high-intensity running (~30%) and sprinting (~35%), while total distance covered has remained relatively stable (~2%).

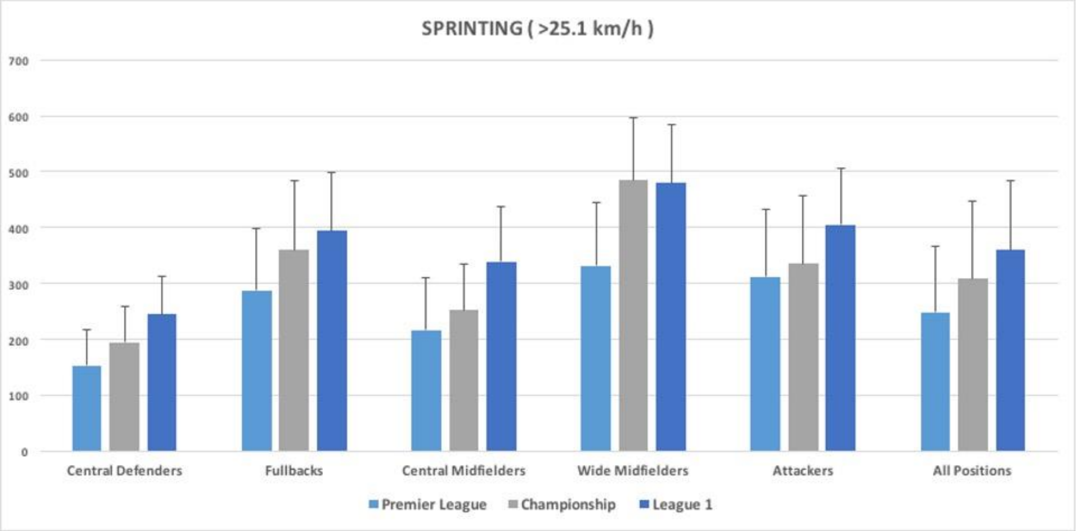

Figure 2-1: Sprinting performance during matches (>25.1 km/h) among players in the top three tiers of English professional soccer (Bradley et al., 2013)

2.1.2 Aerobic energy demands

Soccer match-play is characterised as an intermittent sprint sport, where the overall exercise intensity across the 90-minute duration is predominantly aerobic in nature (Di Salvo et al., 2007; Castagna et al., 2011). Energy expenditure in a soccer match-play is about 90% aerobic (Hoff et al., 2002) with average and peak heart rates around 85% and 98% of maximal values, respectively (Reilly & Thomas, 1979; Bangsbo, 1994). In addition, soccer match-play has a corresponding respiration of 70–75% maximum oxygen uptake and blood lactate concentrations of 4-6 mmol/L (Mohr et al., 2005; Bangsbo et al, 2006). The literature lacks a precise profile of players' oxygen uptake ($\dot{V}O_2$) during soccer match-play, largely due to the challenges associated with field-based $\dot{V}O_2$ measurement. However, portable gas analysers have been employed to examine $\dot{V}O_2$ kinetics during various soccer-specific activity patterns (Esposito et al., 2004). In one such study, amateur players performed moderate- to high-intensity soccer-specific drills, and the researchers observed a strong linear relationship between heart rate (HR) and $\dot{V}O_2$. These findings suggest that the physiological demands of soccer activities can be reliably estimated through field-based heart rate monitoring (Esposito et al., 2004; Castagna et al., 2005; Bangsbo et al., 2006).

Although anaerobic actions, such as sprinting, accelerations, and rapid changes of direction, are often regarded as “match decisive” in soccer, an increasing body of research supports a positive association between players' maximal aerobic capacity and various indicators of match performance and team success (Helgerud et al., 2001; Hoff et al., 2002). Higher levels of aerobic fitness have been linked to greater total distance covered, more frequent high-intensity efforts, and improved ability to sustain work rate throughout a match. However, the sensitivity of maximal aerobic capacity, typically measured as VO_2max, as a singular predictor of soccer performance has been questioned, given the sport's highly intermittent and multifaceted nature (Edwards et al., 2003; Bangsbo et al., 2006). Soccer is characterised by a repeated high-intensity activity profile, where players perform numerous short bursts of high-speed running interspersed with lower-intensity recovery periods. In this context, average oxygen uptake across a match may underestimate the physiological strain experienced during these intense episodes (Krustrup et al., 2004). As such, evaluating match-play intensity solely through average values may fail to accurately reflect the true demands of competition (Glaister, 2005). A more meaningful perspective considers the role of aerobic metabolism in facilitating recovery between high-intensity bouts. The aerobic energy system is essential for the resynthesis of phosphocreatine (PCr), the clearance of metabolic by-products (e.g., lactate and hydrogen ions), and the restoration of homeostasis during intermittent activity (Glaister, 2005). The ability to recover rapidly between repeated high-intensity efforts is critical for sustaining performance throughout the match, particularly in its latter stages when fatigue becomes a limiting factor. Therefore, while anaerobic attributes directly support explosive actions, aerobic fitness serves as the foundation for repeated high-intensity performance, underscoring its importance in elite soccer conditioning programs.

2.1.3 Anaerobic energy demands

While aerobic metabolism is the primary source of energy over the course of a soccer match, it is the anaerobic energy systems that fuel the most decisive and high-impact actions of the game (Stølen et al., 2005). Elite male players typically execute approximately 1,350 discrete actions per match, with activity changes occurring every 4 to 6 seconds (Mohr et al., 2003). Of these, around 150 to 250 are high-intensity efforts, such as sprints, accelerations, and explosive movements, highlighting the considerable demand placed on anaerobic energy pathways (Mohr et al., 2003; Zamparo et al., 2015). This intermittent and high-intensity profile of match-play demands a flexible and dynamic contribution from multiple energy systems. The immediate supply of energy for short, intense efforts is primarily derived from the rapid breakdown of PCr stores. PCr serves as a readily available substrate to fuel maximal efforts lasting only a few seconds. Notably, this energy pathway is heavily dependent on the subsequent resynthesis of PCr during lower-intensity phases or brief recovery periods within the match (Bangsbo, 1994). Evidence from post-match muscle biopsies demonstrates significant depletion of PCr stores, with levels observed to drop to approximately 70% of pre-match values (Krustrup et al., 2006). However, these measurements likely underestimate the true extent of PCr depletion during match-play, as muscle biopsies were taken 15-30 seconds post-exercise, by which time partial PCr resynthesis would have already occurred (Krustrup et al., 2006). Indeed, research suggests that PCr levels may transiently drop to as low as 30% during the most demanding phases of elite match-play (Bangsbo, 1994). The high frequency of anaerobic efforts, combined with limited recovery intervals, places substantial strain on the body's capacity to rapidly regenerate energy substrates. This underscores the critical importance of both anaerobic power and aerobic recovery mechanisms in sustaining performance, particularly during the latter stages of a match when fatigue can compromise decision-making and execution of key actions.

Blood and muscle lactate data observed during match-play further highlight the critical role of anaerobic energy production. Blood lactate concentrations exceeding 12 $mmol \cdot L^{-1}$ have been reported, with typical values ranging from 2 to 10 $mmol \cdot L^{-1}$ across various phases of match-play (Ekblom, 1986; Bangsbo, 1994; Krustrup et al., 2006). Interestingly, lactate accumulation occurs at a significantly higher rate in muscle tissue compared to blood, illustrating a notable disparity between local (muscular) and systemic (blood) metabolic responses (Bangsbo et al., 1994). However, direct measurements of muscle lactate during soccer match-play are scarce. In the only available study, Krustrup et al. (2006) found that muscle lactate concentrations increased to approximately 15 mmol/kg dry weight in non-professional players during a friendly match, only about 30% higher than resting levels, suggesting a moderate contribution from muscular glycolysis. Importantly, this study concluded that elevated blood lactate levels can occur despite relatively low muscle lactate, indicating that blood lactate is an unreliable surrogate marker for muscle lactate accumulation during match-play.

Soccer's intermittent activity profile characterised by extended periods of low-intensity running interspersed with fewer but decisive high-intensity bouts, places substantial demands on both aerobic and anaerobic energy systems. While the aerobic system is essential for sustaining prolonged activity and facilitating recovery, anaerobic pathways remain fundamental for executing high-impact actions such as sprints, tackles, and explosive movements that frequently influence match outcomes.

2.2 Training periodisation in soccer

2.2.1 Preparing soccer players for competition

The physiological demands of soccer are complex and multidimensional. The primary goal of soccer-specific training is to enhance a player's capacity to perform repeated high-intensity efforts with minimal recovery, a critical determinant of success in the sport (Reilly, 2005). Given the intermittent nature of soccer characterised by frequent sprints, rapid changes of direction, accelerations, and decelerations, players require well-developed aerobic and anaerobic energy systems (Bangsbo et al., 2006). To better understand adaptation processes, Vanrenterghem et al. (2017) proposed a framework that distinguishes between physiological load pathways, such as running distances and speed thresholds, and biomechanical load pathways, including whole-body loads, accelerations, and decelerations, providing a comprehensive approach to monitoring and managing load in team sports. Specifically, cardiometabolic (endurance) training activates molecular pathways that promote mitochondrial biogenesis in skeletal muscle, enhancing oxidative capacity. In contrast, neuromuscular and musculoskeletal (strength) training stimulates pathways involved in translational regulation and protein synthesis, facilitating muscle hypertrophy and improved force production (Coffey & Hawley, 2007; Hawley et al., 2014). Together, these adaptations contribute to shorter recovery times between high-intensity efforts and a greater capacity to sustain performance throughout a match. Additionally, repeated-sprint ability (RSA), a vital attribute for elite-level soccer, is closely linked to these physiological adaptations and can be markedly improved through targeted interventions such as high-intensity interval training (HIIT), small-sided games (SSG), and sprint-specific drills (Owen et al., 2004; Bangsbo et al., 2006).

An appropriate training stimuli is fundamental for achieving the desired physiological objectives, incorporating running protocols and soccer-specific activities that support the team's tactical strategy while simultaneously promoting the development of players' technical, tactical, physical, and mental capacities (Morgans et al., 2014). Structuring fitness training into targeted components aligned with specific performance goals (Figure 2.2) can effectively enhance a player's physical robustness and endurance (Bangsbo et al., 2006). These physical attributes are crucial for the successful execution of technical skills (e.g., passing, shooting) and tactical actions (e.g., formation, strategy), which ultimately influence match outcomes (Morgans et al., 2014). However, contextual factors during match-play, such as match status, quality of opposition, and game location, can significantly affect players' running performance and often prevent them from reaching their full physical potential (Paul et al., 2015). Soccer players do not necessarily need to be the fittest athletes overall but must maintain a high level of physical performance during competition while minimizing injury risk and executing tactical requirements effectively (Lacome et al., 2017). Therefore, well-designed soccer-specific training programs aim not only to replicate the demands of match-play but also to provide an optimal stimulus for enhancing a player's capacity to repeatedly perform high-intensity actions, which are frequently decisive in competitive situations.

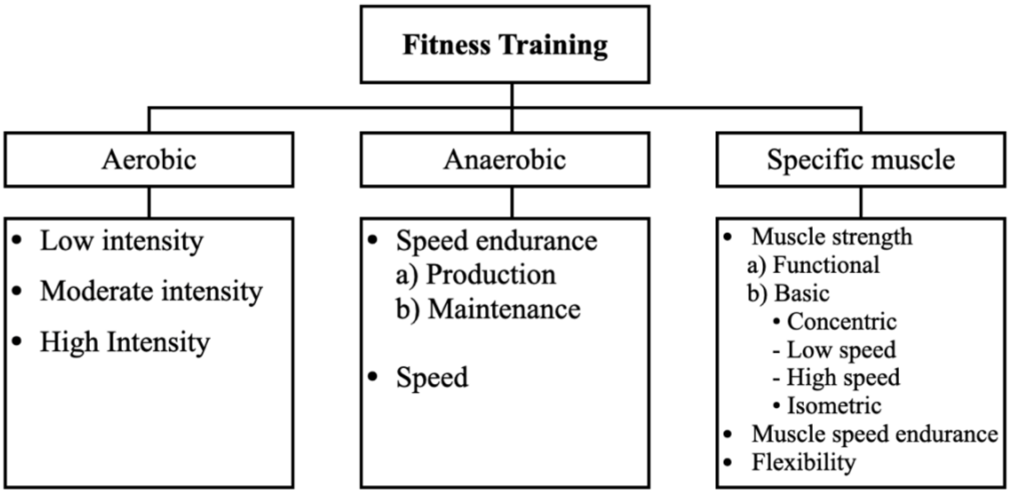

Figure 2-2: Components of soccer training (Bangsbo et al., 2006)

2.2.2 Training periodisation models

The primary responsibility of coaches at all levels is to design both short- and long-term training programs that elicit the desired physiological adaptations and maximize player performance throughout the competitive season (Issurin, 2010; Mujica et al., 2018). To achieve this, practitioners must strategically plan periods of loading, unloading (recovery), and tapering aligned with the most important competitions of the year (Morgans et al., 2014). In soccer, periodisation involves the deliberate alternation of training load and recovery to manage fatigue, the pre-planned focus on developing specific physical qualities (e.g., strength, speed, endurance), and the segmentation of the season into distinct phases (Delgado & Villanueva, 2018).

According to the literature, Matveyev (1964) was the first to define traditional training periodisation concepts by dividing the season into distinct training cycles: (a) the micro-cycle, which encompasses a series of training sessions over a short period, typically one week; (b) the meso-cycle, consisting of several micro-cycles focused on a specific training goal, usually lasting about a month; and (c) the macro-cycle, made up of multiple meso-cycles, generally spanning 6 to 12 months. However, Verchoshanskij (1999), a prominent contemporary researcher in training periodisation, challenged the rigidity of Matveyev's model. He advocated for a more flexible approach that emphasizes an athlete's adaptive readiness to training stimuli rather than strictly following predefined structures (Mujica et al., 2018).

Soccer training methodologies are increasingly shifting towards integrated physical training approaches, emphasising training with the ball in match-derived scenarios. This approach prioritises both the quality and density of players' specific actions and their on-field communication, rather than focusing solely on physical development (Lacome et al., 2017). Given that team sport athletes must consistently perform at a high level each week, coaches need to implement effective tapering strategies before games (Pyne et al., 2009), taking into account factors such as the time between matches, travel demands, opponent competitiveness, injury status, minutes played, and recovery needs (Mujica et al., 2018). At the elite level, a typical training micro-cycle consists of 4 to 6 training sessions plus one competitive match per week (Wrigley et al., 2012; Mujica et al., 2018). When planning training programs, practitioners must adhere to fundamental principles including frequency, intensity, time, type, specificity, progressive overload, and reversibility to optimize performance and reduce injury risk (Pyne et al., 2009).

Recently, tactical periodisation, a contemporary training method developed by Portuguese coach Vitor Frade, has gained prominence in soccer coaching (Delgado & Villanueva, 2018). This approach allows coaches to design soccer-specific training models where physical components such as strength, endurance, speed, and recovery define the session's objectives. The key principle of tactical periodisation is to align each day's training focus with the team's overall game model, while carefully managing load to avoid over-stressing any single physical component. According to tactical periodisation, every moment in the soccer game contains a decision (tactical dimension) and an action or motor skill (technical dimension) that requires a particular movement (physiological dimension) and is directed by volitional and emotional states (psychological dimension). In the end, coaches have to incorporate all these dimensions in their drills and training sessions. As the game is the most demanding session of the week, coaches need to plan lower training demands on training days immediately after and preceding games; in order to ensure players' preparedness for the upcoming game. Many practitioners have adopted this contemporary method in their training programming; however, coaches have to remember that this method still lacks evidence-based support (Mujica et al, 2018).

In senior soccer players, numerous studies have documented the training load over periods ranging from 4-10 weeks (Gaudino et al., 2013; Owen et al., 2017) to 3-7 months (Casamichana et al, 2013; Zurutuza et al., 2017) to an entire season (Gaudino et al., 2015; Malone et al., 2015; Kelly et al., 2015; Kelly et al., 2020). Particularly, studies have shown that training load (total distance, high speed running, sRPE) across a sum of micro-cycles (mesocycle periods) had limited variation (Malone et al., 2015; Owen et al., 2017; Kelly et al., 2020). Across the micro-cycle the highest load was on match day (MD) and the lowest on pre match day (MD-1) with a progressively declined training load over 3 days before a match (Los Acros et al., 2017; Owen et al., 2017; Kelly et al., 2020). Martin-Garcia et al (2018) obtained GPS training and match data from 24 professional players across a 42-training week (37- match) competition phase from a Spanish La Liga club. Typical tapering of the training load in the weekly plan was observed as the game approached. Total distance

(~1400-1500 m), and high-speed distance covered (~130-137 m) were reduced during the three-day period before a match. In a more recent study, Kelly and his colleagues (2020), in a 36-week competition phase period investigation of a Premier League team, found across the team's micro-cycles that total distance and very high-speed running (19,8-25,2 km/h) distance covered were gradually reduced over the last 3 days before the MD. Therefore, coaches need to use tapering strategies to overload stimulus within the micro-cycle maximising players performance in the match-play (Owen et al., 2017). It seems that the weekly training load in elite soccer teams is influenced by the distribution of competitive matches and philosophy of the head coach (Akenhead and Nassis, 2016; Weston, 2018).

In contrast, limited information is currently available regarding the training loads experienced by elite youth soccer players. Previous research investigating weekly periodisation and age-group differences in elite youth players has provided some insights (Wrigley et al., 2012; Coutinho et al., 2015). Wright et al. (2020) studied training load (heart rate and sRPE) across U14 to U18 players and identified age-related differences in both volume and intensity of weekly in-season training. However, this study was limited by its short duration (2 weeks) and the absence of external load data. Similarly, Coutinho et al. (2015) used GPS technology to monitor external load patterns during a weekly micro-cycle in U15 to U19 elite Portuguese youth players, finding consistent loading patterns relative to match day. Nonetheless, this study also had limitations, examining only 33 training sessions. Furthermore, a recent survey conducted with French academy teams examined typical weekly periodisation patterns, finding that the days immediately following matches (MD+1 and MD+2) were primarily dedicated to recovery, while the days before matches (MD-2 and MD-1) focused on tapering (Douchet et al., 2023). This periodisation closely resembles that of senior teams, which tend to prioritise match preparation over player development, highlighting a need for coaches to reconsider their approaches to youth soccer periodisation.

Future work is required to examine periodisation models currently adopted in elite youth training programmes. Such information in turn will be important in furthering our understanding of the influence of long turn loading on player performance and development (Gabbett et al., 2014).

2.3 Monitoring training load

2.3.1 Training process

Training to enhance physical performance is an adaptive process that involves progressive manipulation of the physical load (Manzi et al, 2010). As a result, changes in cardiometabolic, neuromuscular and musculoskeletal systems happen due to the functional adaptive responses to that physical stress (Impellizzeri et al., 2019). During the training process, soccer players are regularly exposed to systematic and repetitive exercise stimuli with the target of maximising performance, delaying the onset of fatigue and reducing the risk of injury. Monitoring training load is therefore essential in managing the training ‘’dose” to ensure the desired improvements in performance are attained (Akubat et al., 2012; Akenhead & Nassis, 2016). Current practices and perceptions of monitoring in professional football demonstrate that elite clubs adopt a variety of methods and tools to monitor player load (Akenhead & Nassis, 2016; Weston, 2018).

A theoretical model of the training process (Figure 2-3) has been proposed by Impellizzeri et al. (2019). The process begins with the training plan, in which coaches prescribe a specific training dose. Training load is commonly categorised into external and internal load, depending on whether it reflects the physical demands imposed on the athlete or the athlete’s physiological and psychological responses to those demands. External load pertains to the organisation, quality, and quantity of the exercises prescribed by coaches (Impellizzeri et al., 2019), encompassing external workload metrics such as total distance covered or the number of efforts performed at various speeds (Osgnach et al., 2010). The physiological strain resulting from the external training factors has been labelled the internal load (Viru & Viru, 2000; Impellizzeri et al., 2019). Thus, external training load is the training dose, and internal load is the players' physiological responses to that training dose. As such, internal load elicits adaption to training (Impellizzeri et al., 2005; Malone et al., 2015). Furthermore, internal load from a specific external stimulus may be different between or within players, depending on specific contextual factors such as training status, nutrition, health, psychological status, and genetics (Impellizzeri et al., 2019). A potential combination of internal-external load monitoring will therefore provide the most effective means through which to derive information regarding the players performance, fatigue and readiness to train or play (Acubat et al., 2012; Malone et al., 2015; Drew & Finch, 2016; Bourdon et al., 2017).

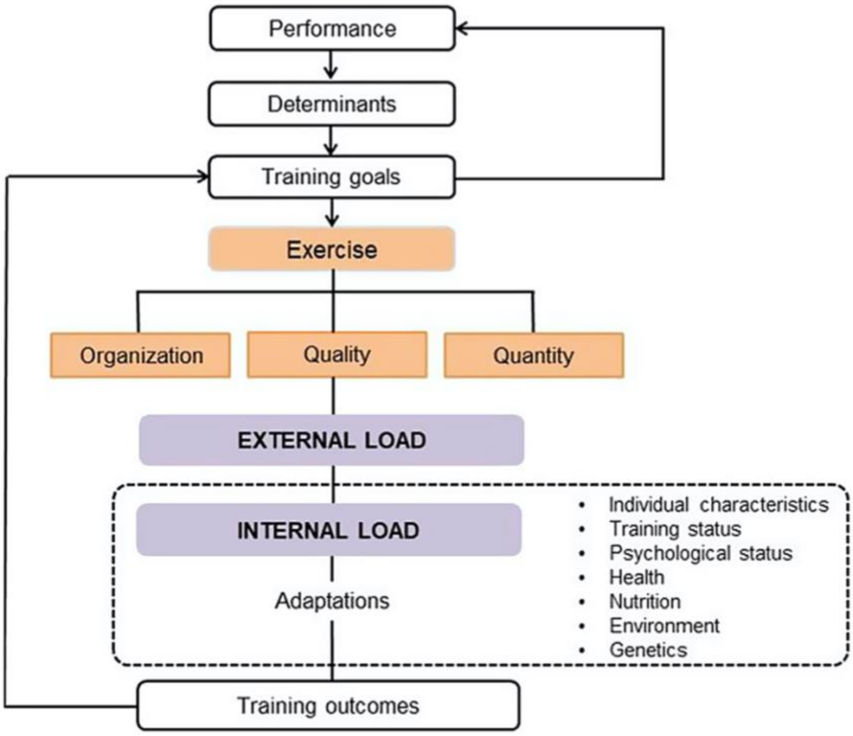

Figure 2-3: Training Process (Impellizzeri et al, 2019)

2.3.2 The dose-response relationship (Planning and adjusting the training)

Interactions between training load prescription and the subsequent training outcome (such as fitness, fatigue and performance), are the criteria of an effective training plan. Banister et al (1975), with a simple model attempted to explain that relationship, suggesting that performance at any given time point is determined by two main components: a fitness response and a fatigue response (Performance = Fitness – Fatigue). The fitness response involves the physiological adaptation to training, which is the long-term positive effect and will eventually result in an improvement in performance. Coaches and support staff widely recognise the importance of training load monitoring for reducing injury risk, evaluating the effectiveness of training programs, detecting fatigue, and prescribing appropriate recovery (Akenhead & Nassis, 2016; Weston, 2018). Within a soccer team, the responsibility for monitoring, analysing, and interpreting training load data typically falls to the support staff, including sport scientists, strength and conditioning coaches, and medical personnel (Weston, 2018). The major challenge for these practitioners is to derive meaningful insights from daily monitoring data that can effectively guide training prescriptions and translate into actionable strategies for all relevant stakeholders within the team (Gabbett et al., 2017).

The wide variety of practices employed by practitioners to monitor the training process, combined with the lack of consensus among team stakeholders, highlights the need for a clear and unified rationale for player monitoring (Gabbett et al., 2017). To address this, Gabbett et al. (2017) proposed a step-by-step strategy (Figure 2-4) to guide practitioners in interpreting player monitoring data. This approach begins with coaches introducing players to a single external training stimulus and progresses through subsequent exposures to different training stimuli, facilitating informed decision-making throughout the training process. This cycle involves four key components: (1) the workload performed by the players (i.e., external load), (2) the players' physiological and psychological response to that workload (i.e., internal load), (3) the athletes' capacity to cope with the imposed load (i.e., perceptual well-being), and (4) the assessment of their readiness for subsequent training or competition (i.e., readiness to train/compete). Consequently, the monitoring process used by coaches and support staff to guide daily training planning and prescription should be holistic and collaborative, involving input from multiple disciplines (Gabbett & Whiteley, 2016).

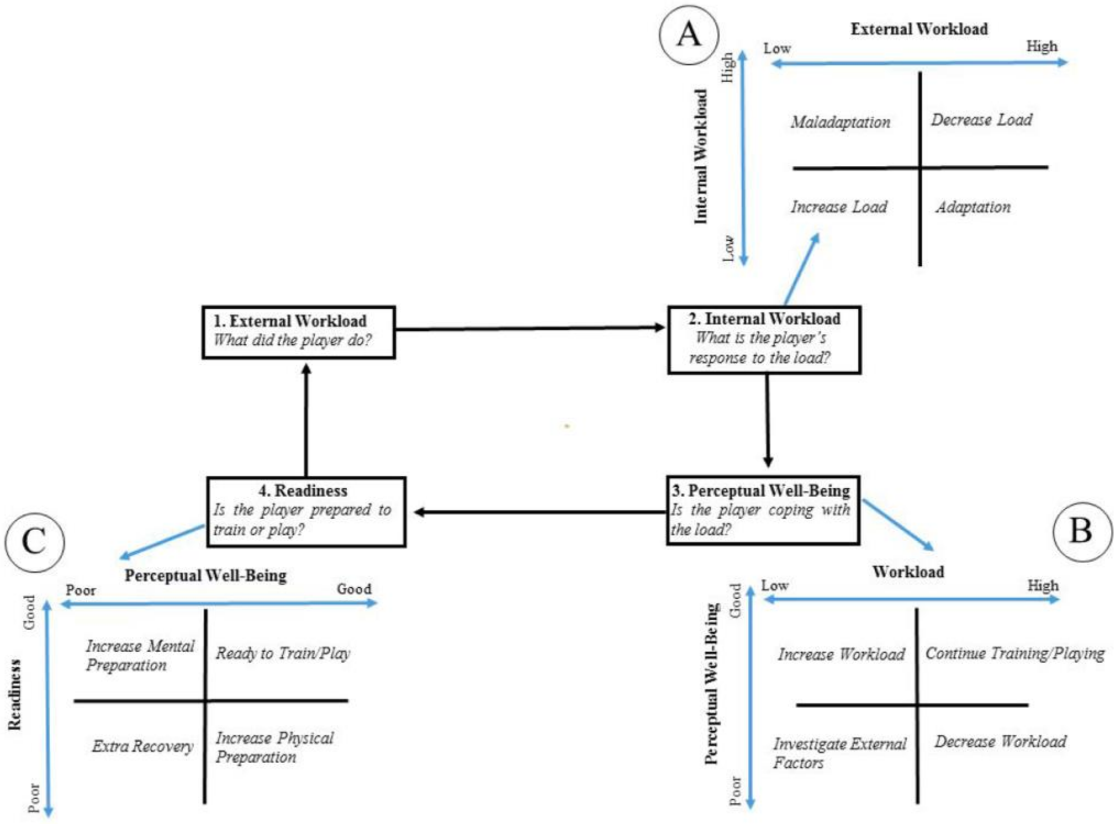

Figure 2-4: The athlete monitoring cycle (Gabbett et al, 2017)

2.3 External training load

2.3.1 Definition, measurement and soccer practices

External load encompasses the total mechanical activity performed by a player, including accelerations and decelerations, locomotor activity such as distance covered at various speeds, and non-locomotor actions (Vanrenterghem et al., 2017). The first attempt to quantify external load in soccer dates back to 1952, when Winterbottom used hand notation methods to estimate match demands based on distance covered. Later advancements included automated camera systems that measured distances and the speed breakdowns at which these distances were covered (Di Salvo et al., 2007; Gregson et al., 2010). More recently, Global Positioning Systems (GPS) have revolutionised external load measurement by providing detailed data on acceleration patterns and distance covered across different velocity zones. These GPS-derived variables are now the most commonly used metrics by practitioners for monitoring external load in soccer (Akenhead & Nassis, 2016; Drew & Finch, 2016; Malone et al., 2017; Bourdon et al., 2017; Weston, 2018).

The validity and reliability of GPS to assess instantaneous velocity, accelerations and decelerations (Varley et al., 2012, Johnston et al., 2014) has been established, allowing practitioners to continue using their equipment to monitor session training load. In order to better quantify external load and players loading, a further categorised of velocities into zones is required. However, the way to classify these velocity zones varies in the literature. In practice, most of the practitioners match the velocity zones thresholds to the semi-automated tracking systems used in soccer stadiums (i.e. Stats/Amisco) (Di Salvo et al., 2009).

Total distance (TD) and high-speed running (HSR) (>15 km/h) are some of the most commonly used variables as measures of external load (Akenhead and Nassis, 2016). In recent years, practitioners use HSR as a measure of exertion and performance when they design their weekly plans, however they must be careful when interpreting the match play data as the variability in HSR between match to match is high (Gregson et al., 2010). Several studies attempted to investigate the relationships between external load and changes in fitness. Particularly, no significant associations were found between exposure time variables and changes in aerobic fitness (Jaspers et al, 2017), whereas positive but also negative relationships were found for exposure time variables and sprint performance (Silva et al., 2011; Los Arcos et al., 2015). Moreover, no significant relationship was found between total exposure time and variation in body composition (Carling & Orhant, 2010), and results were inconsistent for countermovement jump (CMJ) testing (Jaspers et al., 2017).

In soccer practices, apart from external load of field training, practitioners must also evaluate resistance training mode perform in the gym. This can be prescribed with accuracy with the number of sets, repetitions, and percentage of one-repetition maximum which are usually integrated into a tonnage score (Scott et al., 2016). For instance, 4 sets of 8 reps back squat, lifting 80% of one-repetition maximum ([1RM], etc.). Moreover, practitioners have to bear in mind that when using these physical parameters to analyse their training sessions or matches, they only quantify the movement profile of the sessions or matches, and not the non-locomotor activities such as tackling, kicking, duels, jumping that could metabolically influence the player's performance.

2.3.2 Individualised external training load

Whether obtained through semi-automated video systems or GPS, external load data are typically analysed based on the time spent in various locomotor categories that capture the full spectrum of movement intensities, from walking to sprinting (Akenhead & Nassis, 2016). Traditionally, this data is expressed as distances covered within predefined, arbitrary, or player-independent running speed zones (Hunter et al., 2014). Afterwards, implementing player/team comparisons, practitioners can use this data to effectively plan their periodisation models. Such an approach, however, has been criticized for failing to account for the individual "capacity" of players (Abt and Lovell, 2009; Gabbett, 2015). As stated above, it is each players physiological responses (internal load) to an external stimuli that underpins the adaptations to a physical output (Impellizzeri et al., 2005; Malone et al., 2015). For instance, the amount of high-speed activity undertaken during match-play and training is often used as an indicator of physical performance. It is therefore important that the method used for measuring when a player is active in the high-speed "zone" be accurate. To date, the speed criteria used to define where high-speed running begins has largely been based on arbitrary, absolute speeds (Bradley et al., 2009, Lacome et al., 2017). Given the highly individualised nature of the exercise-intensity continuum, it would appear that there is potential for large errors in the measurement of the distance run at high-speeds based on absolute speed thresholds (Abts and Lovell, 2009). For instance, mean distance run at high-intensity based on the absolute and relative thresholds was 845 meters and 2258 meters, respectively [mean difference 1413 m; $P < 0.001$ (95% CI: 1037-1789 m) (Abts and Lovell, 2009). Therefore, for some players, the absolute speed at which they begin to exercise at high-speed will be either higher or lower than these speeds.

In an attempt to overcome such practical limitations of arbitrary speed thresholds, a growing body of research has expressed external load relative to individual players capacity (Harley et al., 2010; Cahill et al., 2013; Mendez-Villanueva et al., 2013; Hunter et al., 2014; Gabbett et al., 2015; Reardon et al., 2015; Abbott et al., 2018), the premise of which being to better understand the individual players' dose-response/recovery and energetic demands of training and match-play (Hunter et al., 2014; Zurutuza et al., 2017; Tomazoli et al., 2020). Unfortunately, though, the majority of research into this practice led process simply describes the impact of different approaches to speed zone classification (Drust, 2018) in that individualisation increases high-speed running of slower players, yet decreases high-speed running of faster players (Hunter, et al., 2014; Gabbett, 2015; Abbott et al., 2018).

Integral to individualising speed zones are the metrics used to represent a player's physical capacity. Abt and Lovell (2009) proposed that high-intensity speed thresholds should be personalised based on ventilatory thresholds (VT), following methods similar to those suggested by Lucia et al. (2003). They identified that the median high-intensity threshold, defined by the velocity at the second ventilatory threshold (VT2), was approximately 15 km/h (ranging between 14 and 16 km/h), which is notably lower than the default thresholds used by most GPS and camera tracking systems. This discrepancy led to a threefold increase in the measured distance covered at high-speed running (HSR) when using VT-based thresholds compared to the conventional arbitrary threshold set above 19.8 km/h. This finding underscores that using higher arbitrary thresholds may significantly underestimate actual HSR activity.

Furthermore, studies have anchored individualised speed zones to the players' maximal sprinting speed (MSS) (Harley et al., 2010; Gabbett, 2015; Cahill et al., 2015; Reardon et al., 2015). Anchoring zones on isolated MSS presents difficulty though in the anchoring of adjacent speed thresholds (Weston, 2013), and may also be error prone (Hunter et al., 2014). A more robust method for enhancing the validity of speed thresholds is using the athlete's functional limits of both endurance and sprint capacity (Abbott et al., 2018) with studies anchoring individualised speed zones on measures of maximal aerobic speed (MAS) and MSS (Mendez-Villanueva et al., 2013; Hunter et al., 2014; Scott and Lovell, 2017; Abbott et al., 2018). Subsequently, a valid indication of MAS and MSS is required.

2.3.3 Application of relative speed zones in soccer

Although, the method used by Abt and Lovell (2009) with individualised speed thresholds based on ventilatory thresholds was a useful addition to player monitoring, the fact that requires extensive laboratory testing which might not be feasible in an applied soccer environment, makes it not so practical. Hunter et al. (2014) compared a number of different methods for individualising speed thresholds (Table 2.1), including both laboratory and field-based measures. Whilst valid, laboratory assessments remain largely impractical for use in elite soccer due to time restraints and often difficulty in accessing the required equipment, a more practical approach may therefore incorporate a number of field tests which require limited equipment and are time efficient when testing large groups of players. Such assessments permit the determination of key physical parameters such as MSS and MAS (Mendez-Villanueva et al., 2013).

Studies anchoring individualised speed zones on measures of MAS and MSS (Mendez-Villanueva et al., 2013; Hunter et al., 2014; Scott & Lovell, 2017; Abbott et al., 2018). Mendez-Villanueva et al. (2013) used field-based testing data to estimate a players' MAS and MSS also involving players' anaerobic speed reserve (ASR) which it has been used to establish a players' transition (>30% ASR) into anaerobic workload (Bundle et al., 2003, Mendez-Villanueva et al, 2013). Mendez-Villanueva and his colleagues (2013) established five running intensity zones to describe each player's individual external load in the matches: speed zone 1 (S1): below 60% of MAS, speed zone 2 (S2): from 61% to 79% of MAS, speed zone 3 (S3): from 80% to 99% of MAS, speed zone 4 (S4): from 100% of MAS to 29% of Anaerobic Speed Reserve (ASR) and, speed zone 5 (S5): above 30 % of ASR.

Table 2.1: Description of methods used to categorise speed thresholds (Hunter et al., 2014).

	ARB	**IND**	**MAS**	**MSS**	**LOCO**
Low-Speed Running	<14.99	< RCT	79% MAS	< 49% MSS	< 79% MAS
High-Speed Running	15.00 - 17.99	RCT - sV˙O2max	80-99% MAS	50-59% MSS	80% -99% MAS
Very High-Speed Running	18.00 - 24.99	sV˙O2max - 29% ASR	100-139% MAS	60-79% MSS	100% MAS - 29% ASR
Sprinting	25.00 - 35.00	30% ASR – MSS	140% MAS - 35 km.h-1	80% - 100% MSS	30% ASR - MSS

RCT: speed corresponding to a players respiratory compensation threshold; sV˙O$_{2\text{max}}$: Speed corresponding to the players maximal oxygen uptake; ASR: anaerobic speed reserve; MAS: maximal aerobic speed; MSS: maximum sprint speed; ARB: arbitrary speed zones; IND: Individualised speed zones incorporating RCT, sV˙O$_{2\text{max}}$, and MSS; LOCO: locomotor speed zones incorporating MAS and MSS.

2.3.4 Measurement of MSS and MAS

An accurate assessment of MSS is essential, as it serves as a key physiological parameter for establishing individualised speed thresholds in players. Studies have anchored individualised speed zones to the players' MSS, as determined by either a sprint test (Harley et al., 2010; Gabbett, 2015), peak value during a match (Cahill et al., 2015), or the retrospectively obtained peak value from any training and playing data across a season (Reardon et al., 2015). For an accurate assessment of MSS, fully automatic timing systems represent the gold standard with dual-beamed photocells; laser guns and high-speed video timing representing cheaper, more practical tools with acceptable accuracy (Haugen and Buchheit, 2016). In contrast, GPS are more accessible and easier to use in daily practice; therefore, GPS are now frequently used in team sports to measure and monitor player running velocities during training and matches (Massard et al., 2018). However, it is important that practitioners have confidence in systems used to measure sprinting speeds, especially when systems are noncriterion measures (Roe et al., 2017), thus validity studies are fundamental in the development of alternative measures that save costs, facilitate analyses, and enable data field-based collection (Dixon et al., 2018).

The second key physical parameter for prescribing individualised speed thresholds, is MAS, which refers to the minimal running velocity at which maximal oxygen uptake (VO2 max) occurs. Studies employing MAS to individualise speed thresholds using field-based assessments have utilised various tests, including a modified version of the Montreal Track Test (Leger and Boucher, 1980), using the average speed during a time trial for any distance between 1200 and 2200 metres (Lorenzen et al., 2009, Bellenger et al., 2015) and the VAM-EVAL (Mendez-Villanueva et al, 2013; Hunter et al, 2014; Abbott et al, 2018). Another widely used alternative is the Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1), which provides an indirect estimation of MAS and is especially relevant in team sports contexts like soccer (Bansgsbo et al., 2008). Regardless of the protocol used, accurate determination of MAS is critical for setting relative speed thresholds.

Despite these advantages, the application of relative thresholds in soccer research remains limited, particularly in youth settings. Most existing studies continue to employ absolute thresholds, often derived from normative adult values or arbitrary speed bands, which may misrepresent the actual metabolic cost of activities in younger or less developed athletes. As such, there remains a notable gap in the literature regarding the implementation of relative thresholds and the quantification of training load in elite youth players.

2.4 Internal training load

In order to prescribe an effective training stimulus, coaches need to consider the players' internal responses to a given external training load (Gaudino et al., 2015). Internal load refers to players biochemical (physiological and psychological) and biomechanical, responses to external training loads (Impellizzeri et al., 2005). The measurement of internal load requires quantification of the intensity of the physiological stress imposed on the players and the duration of this stress (Impellizzeri et al., 2007). Foster et al (2021) refer to intensity, time and volume as the main factors influencing the outcome of a training session. Whilst the time (duration) of a training session or match-play is an easy task, intensity can be determined with several methods, such as heart rate (HR) and ratings of perceived exertion (RPE) (Impellizzeri et al., 2007; Akenhead and Nassis, 2016).

Numerous methods to quantify intensity using HR have been examined in individual and team sports. For instance, the training impulse (TRIMP) is an HR-based method, converting the HR data from a training session into an arbitrary unit (AU) that reflects the physical effort (Jaspers et al., 2017). The quantification of internal training load using TRIMP was originally proposed by Banister (1975 and revised in 1991). This method is based on HR and a modelled blood lactate response to increasing exercise intensity. Banisters TRIMP takes into consideration the intensity of exercise, which is calculated from the heart rate reserve method and the duration of exercise and models the dose-response relationship with fitness and fatigue (Banister, 1975). Following the original TRIMP method proposed by Banister (1975), several modifications to the method have been proposed. Edwards (1993) proposed a new method that gained popularity, which was a TRIMP method using five arbitrary HR zones with each zone weighted from one to five where the duration spent in each zone is multiplied by a weighting factor to provide a total

TRIMP score. Later, Lucia et al. (2003) proposed a three-zone based TRIMP method with zones around the first and second ventilatory thresholds: zone one is below the ventilatory threshold, zone two is between the ventilatory threshold and the respiratory compensation point and zone three above the respiratory compensation point. Afterwards, another proposal by Stagno et al (2007) was introduced, suggesting a modified Banister's TRIMP where players blood lactate profile was directly measured. Manzi et al. (2009) proposed the first method that the TRIMP weighting is based on individual HR and blood lactate responses to incremental exercise. This effort was step further to individualised TRIMP (iTRIMP) based by gender (Banister 1991) and by group (Stagno, 2007). Moreover, iTRIMP weighting is not expressed in arbitrary units as Edrward (1993) and Lucia (2003).

Although these methods are theoretically robust, their practical application presents significant challenges (Foster et al., 2021), while still there is not a coherent model for integrating the intensity-time-volume equation discussed above into a measurable expression of internal load (Foster et al., 2021). Moreover, relative HR measures and threshold-based models fail to quantity the metabolic stress during exercise (Foster et al, 2021). Whilst heart rate monitoring is a valid method for monitoring training intensity in endurance sports, its validity is reduced in sports where the anaerobic energy systems are required (Impellizzeri et al, 2005).

2.4.1 Rating of perceived exertion (RPE)

Having all these difficulties to quantify internal load, Foster et al (1995), first use in an experimental and control group of athletes, an innovative way to measure their athletes' responses to the load, which was using a RPE. The athletes simply had to answer to the question “How hard was the session” choosing a number from 1 to 10 (CR 10 Borg Scale), with the chosen number representing the perceived intensity of the training session. By multiplying this number by the duration of the session, a single value representing the overall training load was obtained, including warm-up, main session, and cool-down. This metric is referred to as the session rating of perceived exertion (sRPE). sRPE accounts for both the intensity and duration of a training session to estimate an athlete's training load. The value reported by the athlete reflects the perceived exertion of the “mean training intensity” across the entire session (Haddad et al., 2017). The sRPE method offers several advantages: it provides immediate feedback, is easy to administer, can be completed by an entire team in under 10 minutes, and is non-invasive. Furthermore, sRPE is a simple and valid tool for monitoring internal training load in activities involving both aerobic and anaerobic components (Foster et al., 2001; Foster et al., 2004).

Borg (1962) originally defined perceived exertion as “the sensation from the organs of circulation and respiration, from the muscles, the skin, the joints and force”. Since that time, lot of researchers attempted to use ratings of perceived exertion to monitor and prescribe training, however, there was always a disagreement in the use of the words: exertion and effort. Marcora (2010) with simply words defined the perceived exertion as “the conscious sensation of how hard, heavy, and strenuous a physical task is”. As previously mentioned, Foster et al. (1995) were the first to propose the use of sRPE, initially validating it as a marker of internal training load in endurance sports (Foster et al., 2001). Subsequent studies extended the application of sRPE to soccer, demonstrating its validity through comparisons with heart rate- and blood lactate-based methods (Impellizzeri et al., 2004; Coutts et al., 2009). Specifically, Impellizzeri et al. (2004) evaluated sRPE against established models of internal load quantification, including those proposed by Banister (1991), Edwards (1993), and Lucia et al. (2003), and confirmed its validity for use in soccer contexts.

RPE can be delivered with two techniques (McLaren, 2018). Firstly, with an absolute magnitude estimation when the player makes a direct numerical assessment of effort, based on a pre-defined or self-selected range, (e.g. 1–10) (Stevens, 1957; Stevens, 1975). Secondly, with a category-ratio scale where a player makes a direct numerical assessment of effort from verbal anchors located on a numeric ratio scale, displaying the whole range of possible sensations (Borg, 1998; G. Borg & Borg, 2002). Foster et al. (2001) have revised the verbal anchors used in the CR-10 scale (Borg, 1962) to reflect the American idiomatic English (e.g., light becomes easy; strong or severe becomes hard). According to Foster et al. (2001), ratings of 6, 8, and 9 are not typically used on the CR10 scale. Therefore, players should be properly familiarised with the scale following standardised procedures before data collection begins. A single arbitrary unit (A.U.) representing the total training load for each session is then calculated by multiplying the reported training intensity (RPE) by the session duration in minutes (Haddad et al., 2017). For example, a 60-minute training session with an RPE of 4 ("quite hard") would result in a training load of 240 A.U. (i.e., 60 × 4 = 240).

The Borg Category-Ratio 10 scale (deciMax; CR10) is widely regarded as the most commonly used tool among practitioners for measuring perceived exertion. An enhanced version of this scale, the Category-Ratio 100 scale (centiMax; CR100), was later introduced to improve sensitivity in detecting smaller changes in perceived effort (Borg, 2007). Fanchini et al. (2016), in a study with professional soccer players, demonstrated the benefits of using the CR100 scale over the traditional CR10 scale. They found that player responses on the CR100 were less clustered around verbal anchors, providing a more precise and nuanced measure of training intensity. This increased precision has led to greater adoption of the CR100 scale in recent soccer research (Barrett et al., 2018; Macpherson et al., 2019; McLaren et al., 2020), highlighting its practical advantages and improved interpretability. A key benefit of the CR100 is its alignment with percentage-based thinking, which athletes often find more intuitive (Fanchini et al., 2016). Additionally, Fanchini et al. (2017) demonstrated that retrospective RPE remain feasible and reliable up to 48 hours post-match, an important consideration for practitioners when immediate data collection is not possible. Nonetheless, retrospective RPE assessments should be reserved for exceptional cases, such as when immediate data is lost.

2.4.2 Underpinning factors and application in soccer

When implementing RPE to monitor training load and intensity, practitioners must understand the various factors that influence perceived effort. The afferent mechanisms underlying effort perception offer insights into the physiological and biomechanical mediators of RPE, which are critical for understanding the load-response relationship in team sports (Vanrenterghem et al., 2017). These afferent contributions to RPE can be broadly categorised into two primary domains: central and peripheral factors (McLaren, 2018). Central or cardiopulmonary factors may include exertion from respiratory mechanisms, such as heart, ventilation and respiration rates, as well as $\dot{V}O2$ (Hampson et al., 2001). The available literature examining the relationships between sRPE and indicators of cardiopulmonary exertion, due to the constrained techniques of data collection within the daily practice, focused on the associations between sRPE and average session heart rate, or sRPE-TL and TRIMP (McLaren, 2018). Research in soccer have shown large relationships between sRPE and average session heart rate (Little & Williams, 2007;

Casamichana & Castellano, 2015) and between sRPE and TRIMP (Impellizzeri et al., 2004; Alexiou & Coutts, 2008; Akubat et al., 2012; Casamichana et al., 2013; Campos-Vazquez et al., 2015; Kelly et al, 2015). However, several limitations are associated with the use of sRPE in team sports (McLaren, 2018). Notably, among the studies referenced, only Kelly et al. (2015) employed appropriate statistical analyses, reporting correlation coefficients derived from pooled repeated measures within individuals. Furthermore, the observed associations between sRPE and training impulse (TRIMP) may be confounded, as both variables incorporate training duration. Additionally, research indicates that these relationships may be influenced by the specific training context within a session (Campos-Vázquez et al., 2015; Casamichana & Castellano, 2015).

Peripheral, or local, factors influencing RPE can be further divided into metabolic and biomechanical components (McLaren, 2018). From a metabolic perspective, blood lactate concentration (B[La]) serves as a useful marker of exercise intensity, and several studies have demonstrated a positive association between RPE and B[La] (Chen et al., 2002). However, research examining peripheral metabolic influences on RPE remains limited, largely due to the practical challenges of measuring B[La] in daily training environments. In amateur soccer players, a substantial correlation between sRPE and B[La] has been reported during 67 small-sided games (r = 0.63) (Coutts et al., 2009). Nevertheless, it remains unclear whether this relationship holds in elite youth soccer players. Notably, the physiological development of youth athletes may influence their responses to training stimuli. Aerobic training tends to promote adaptations in oxidative metabolism, while adaptations to anaerobic training may differ due to the incomplete development of anaerobic systems in youth. These adaptations may include improvements in muscle size, strength, and biochemical capacity, potentially affecting anaerobic performance (Gabbett et al., 2014)

Examining the relationship between sRPE and external load metrics may provide valuable insights into the biomechanical (locomotor) demands of training sessions. This approach aids in understanding session demands and informing training prescription. Gaudino et al. (2015), in a study involving elite senior soccer players, reported small to moderate within-athlete correlations ($r = 0.23$-0.30) between sRPE and several external load variables, including high-speed running distance (HSRD; >14.4 km/h) per minute, impacts (>2 g) per minute, and hard accelerations ($>3\ \text{m·s}^2$) per minute. Their findings suggest that a combination of multiple external load parameters predicts training load (as perceived through sRPE) more accurately than any single measure alone. However, these relationships may not generalise to youth athletes, particularly those who are not yet fully physically mature. Currently, no studies have examined how external training load markers influence internal load (sRPE) across different training modes in youth soccer players, highlighting a notable gap in the literature that warrants further investigation.

In addition to the physiological and biomechanical mediators of RPE, soccer practitioners must also consider non-physiological influences, such as psychological and social factors. Concerns have been raised regarding the objectivity and appropriateness of RPE, given that effort perception involves cognitive appraisal processes mediated by neural and biological activity in the brain (McLaren, 2018). These concerns are valid, as physical or mental fatigue can lead to under or overestimation of actual physiological stress. However, performance in team sports extends beyond purely physical or physiological factors (Smith et al., 2018). Mental fatigue, for instance, has been shown to impair soccer-specific physical abilities, technical skills, decision-making, and tactical performance (Smith et al., 2018). Consequently, RPE serves as a valuable marker of internal load, reflecting both the physiological and psychological states of players, thereby providing a comprehensive tool for quantifying training load and intensity.

Session-RPE is a simple and valid method for monitoring players' internal load. However, both its validity (Chen et al., 2002) and reliability (Scott et al., 2013) have been questioned within the literature. Notably, field-based testing has revealed low reliability, suggesting that sRPE may lack sensitivity to detect small changes in exercise intensity during brief, intermittent running bouts (Scott et al., 2013). Furthermore, between-match coefficients of variation (CV) for sRPE have been reported to range between approximately 5-10% (Weston et al., 2015; McLaren et al., 2016). In contrast, variability in external load measures such as high-speed running during soccer matches is substantially greater, with CVs ranging from approximately 15% to 70% (Gregson et al., 2010).

Although the practical simplicity of sRPE is advantageous, research indicates that this method does not consistently align with dose-response models of training adaptation (Foster et al., 1996; Brink et al., 2010), highlighting the need for more detailed information on physiological and biomechanical demands is often necessary (Coyne et al., 2018). The sRPE score reflects a global measure of intensity but is insufficient to capture the full spectrum of exertion signals experienced during exercise (Weston, 2013; Drew & Finch, 2016). Athletes often tend to train harder than intended during sessions prescribed as "easy" by coaches, while conversely, they may train less intensely than expected during sessions designated as "hard" (Foster, 2001). This tendency complicates practitioners' efforts to accurately differentiate between session intensities. For example, an RPE rating of "hard" (~5 on the Borg CR10) assigned to a strength-focused small-sided game (SSG) cannot be directly compared to a "hard" RPE (~5) reported for an endurance-oriented large-sided game (LSG), as the physiological and biomechanical demands differ substantially. Consequently, sRPE lacks the sensitivity required to accurately quantify the complex external loads, both locomotor and non-locomotor, encountered in soccer (Barrett et al., 2018). Additionally, since sRPE is directly influenced by session duration, and many sessions with varying objectives have similar lengths, session length often becomes the predominant factor driving the calculated training load (Brink et al., 2010).

2.4.3 Differential rating of perceived exertion (dRPE)

A global score (like RPE) possibly can't accurately reflect the entire range of both physiological and biomechanical exertion gestures during exercise (Hutchinsona and Tenenbaum, 2006). The precision of scaling exertion during exercise can be improved by differentiating perceptual reports according to their specific physiological mediators (Weston et al., 2015). Differential ratings of perceived exertion (dRPE) separate central and peripheral exertion, offering practitioners a valuable indirect method to assess players' physiological (e.g., cardiovascular) and biomechanical (e.g., musculoskeletal and neuromuscular) internal loads (Vanrenterghem et al., 2017). Specifically, dRPE breaks down exertion into breathlessness (RPE-B), leg effort (RPE-L) and technical effort (RPE-T), providing a more detailed overview of internal load compared to global sRPE scores (Weston et al., 2015; McLaren et al., 2017; Vanrenterghem et al., 2017; Barrett et al., 2018; Macpherson et al., 2019). Supporting this, McLaren et al. (2016) investigated the sensitivity of dRPE in response to training load with twenty-two male university soccer players completing maximal incremental exercise protocols on cycle and treadmill across separate days. Players reported dRPE (CR100 scale) for breathlessness and leg-muscle exertion immediately after exercise termination and 30 minutes post-exercise. The study concluded that dRPE offers enhanced sensitivity for measuring internal load compared to conventional sRPE.

The potential separation of physiological, musculoskeletal, and cognitive load can give a more detailed understanding of dose-response nature of training and matches, changes in fitness (Jaspers et al., 2017; McLaren et al., 2020), fatigue (Los Arcos et al., 2014; Gallo et al., 2016), and the risk of injury or illness (Jones et al., 2016). Specifically, high scores in RPE-B may reflect aerobic fitness needs, high scores in RPE-L may reflect on possible strength or power needs, high scores in RPE-T may reflect technical needs (Weston, 2015). McLaren et al (2017) reported that dRPE measures combined to justify 66-91% of the variance in sRPE in rugby players. They also demonstrated the relationships between sRPE-L with high intensity intervals ($r = 0.67$; 90% confidence limits ±0.22), sRPE-B for repeated high-intensity efforts (0.89; ±0.08) and skill-based conditioning (0.67; ±0.19), sRPE-T for Speed (0.63; ±0.17) and Skills (0.51; ±0.28). Moreover, from the dRPE measures, RPE-L scores are the highest confirming that peripheral stimulus perceived higher than the central (Borg et al., 2015; Weston, 2015). In addition, previous work on dRPE showed that RPE-T was the only measure that there was an agreement between coach observed and players' reported scores (Macpherson et al., 2019), highlighting the importance of dRPE use as consistent coach underestimation of players' load might lead to an injury or overreaching (Brink and Frencken, 2018).

Research and application of dRPE in soccer is increasing the last few years. Numerous studies have documented dRPE use in soccer from senior players (Los Arcos et al., 2013; Los Arcos et al., 2014; Los Arcos et al., 2016; Barret et al., 2018; Azcárate et al., 2018; Houtmeyers et al., 2022) to youth (Gil-Ray et al., 2015; Los Arcos et al., 2017; Wright et al., 2020; Maughan et al., 2021) and from match-play monitoring (Los Arcos et al., 2016; Barret et al., 2018) to training and periodisation (Los Arcos et al., 2013; Gil-Ray et al., 2015; Los Arcos et al., 2017; Azcárate et al., 2018). In youth, Gil-Ray et al (2015) demonstrated positive correlation ($r = 0.67$-0.71) of dRPE measures with changes in aerobic fitness. Wright et al (2020) in a retrospective study in elite youth soccer girls observed practically meaningful differences between sRPE-B and sRPE-L in different training modalities with a distinct physical goal (i.e. fitness and resistance), however, in matches sRPE-B was harder than sRPE-L by 5 AU (90% CI 312 ~1 to 9, effect size 0.34,) this difference was not practical meaningful.

Despite the conceptual appeal of dRPE as a mean to capture the multifaceted nature of exertion during training, several studies have questioned whether dRPE offers meaningful advantages over a single global RPE measure. The dRPE framework typically requires athletes to rate perceived exertion across distinct physiological domains, commonly muscular (RPE-L) and respiratory or cardiovascular (RPE-B). However, evidence indicates that these differentiated scores often correlate strongly with global RPE, raising concerns about redundancy (Maughan et al., 2021; Houtmeyers et al., 2022). In many instances, dRPE dimensions show minimal divergence from global RPE values, suggesting that athletes may not reliably distinguish between exertional sources, particularly in complex or mixed-modality training environments typical of team sports (Houtmeyers et al., 2022).

The inconsistency observed across studies regarding the ability of dRPE to distinguish between different session types may, in part, be attributed to variations in participants' education and familiarisation with the use of perceptual rating scales (Coyne et al., 2018; Macpherson et al., 2019). As with any subjective measure, the validity and reliability of dRPE are contingent on appropriate psychometric application, this includes using the scale as intended (e.g., employing clear verbal anchors to elicit numerical ratings) and integrating educational strategies to enhance comprehension (Saw et al., 2017). Macpherson et al. (2019) demonstrated improved accuracy and consistency in exertional ratings from both coaches and athletes following systematic familiarisation with the Borg CR scales, supported by the blackness test. This tool offers a visual analogy for verbal anchors used in the CR10 and centiMax (CR100) scales by presenting a gradient of blackness (0% = white; 100% = black), where lower percentages correspond to lower exertion (e.g., 5% blackness = very easy; 15% = easy), thus helping users better conceptualise subjective effort. Notably, no study has yet examined whether familiarisation with the CR100 scale moderates the relationship between RPE and objective external load metrics during training or match play in youth soccer.

2.4.4 Associations between external and internal load

Given the lack of a definitive ‘gold standard’ for assessing internal training load (Vanrenterghem et al., 2017), the relationship between internal and external load has become a valuable proxy for evaluating the construct validity and responsiveness of different load monitoring tools (Castillo et al., 2017). Therefore, getting a solid understanding of the relationship between internal and external training load can assist practitioners to better manage their athletes’ readiness, as the mode of training influences the external and internal load relationship (McLaren et al., 2018). As such, recognising how different training modalities affect this relationship enables practitioners to better tailor training stimuli to individual athlete needs and ensure optimal adaptation while minimizing the risk of maladaptation or injury.

Inconsistent findings emerge when examining dRPE measures, specifically RPE-B and RPE-L in relation to different training modes (McLaren et al., 2017; Wright et al., 2020; Houtmeyers et al., 2022). For instance, McLaren et al. (2017), in a study involving professional rugby players, found that distinct training typologies elicited differentiated dRPE responses. Their findings suggested that RPE-B and RPE-L may help isolate specific perceptual demands associated with various training stimuli when using absolute thresholds. Similarly, Wright et al. (2020) reported a range of effects, from possibly trivial to most likely extremely large, for RPE-L across comparisons of different session types, further supporting the discriminative potential of dRPE. Notably, during strength-based sessions, RPE-L was rated significantly higher than RPE-B by an average of 13 arbitrary units, reflecting the greater muscular demands characteristic of this training modality. In contrast, studies involving professional soccer players have presented opposing results. Research by Maughan et al. (2021) and Houtmeyers et al. (2022) concluded that dRPE did not provide meaningful differentiation between training modalities, nor did it demonstrate a consistent relationship with external load when using absolute thresholds. This variability raises questions about the reliability and sensitivity of dRPE in applied team sport environments. Therefore, further research is needed to examine the associations between internal load (using global RPE, dRPE) and external load markers in elite youth soccer players.

2.5 Summary

In summary, this section describes the physiological demands of the daily training and match-play loads elicited in elite youth players. The use of valid and reliable measures by which to quantify both the external and internal load has been discussed, focusing specifically on the methodologies employed. Global RPE, RPE-B, RPE-L and GPS, are identified as the methods used in the current thesis to determine and quantify the training and match load periodisation strategies employed in elite youth soccer team. The importance of quantifying the validity of the measurement tools used in the current thesis will be investigated to ensure the accurate analysis of data. The initial investigation in the current thesis therefore assesses the validity of a non-criterion measure (10-Hz GPS) to measure maximal sprinting speed. The quantification of training and match-play load in the current thesis focus on the associations between internal and external load (dose-response relationship) in elite youth soccer players, utilising session type-specific differences in perceived exertion (global RPE, dRPE) alongside external load analysed through absolute and relative thresholds.

CHAPTER 3: A NOVEL APPROACH TO ASSESSING VALIDITY IN SPORTS PERFORMANCE RESEARCH: INTEGRATING EXPERT OPINION INTO THE STATISTICAL ANALYSIS

This study was presented as an oral communication at the 28th Isokinetic Medical Group Conference, London, England 2019 and also published as a full manuscript in the Science and Medicine in Football journal (Appendix, Chapter 10)

3. A novel approach to assessing validity in sports performance research: integrating expert practitioner opinion into the statistical analysis

3.1 Introduction

In soccer, maximal sprinting represents the most infrequent match activity recorded by elite male youth soccer players (Harley et al. 2010; Varley et al., 2017a). Despite this, the practical importance of sprinting speed is shown via straight-line sprints preceding a high percentage of goals scored (Faude et al. 2012) and match sprint distance being greater for successful compared to unsuccessful teams (Yang et al. 2018). Fully automatic timing systems, laser guns and high-speed video are considered to be gold standards for measuring sprinting speed (Haugen and Buchheit, 2016), yet Global Positioning Systems (GPS) are frequently used in team sports to measure and monitor player running velocities during training and matches (Massard et al., 2018). However, it is important that practitioners have confidence in systems used to measure maximal sprinting speed (MSS), especially when systems are non-criterion measures (Roe et al., 2017). Validity studies are therefore fundamental in the development of alternate measures, such as GPS, that save costs and enable field-based data collection (Dixon et al., 2018).

Validity studies compare a new or more practically feasible measure against a gold standard (criterion), and if the difference in measures is sufficiently small, validity is assumed. For example, the difference in 40 m MSS measured via 10-Hz GPS and a radar gun was trivial (−0.8%; 90% confidence interval −1.1 to −0.4%) and so GPS was concluded to provide a valid measure of MSS (Roe et al., 2017). This study and others (Beato et al., 2018) represent a common approach to validity assessment; however, between-system differences were interpreted against standardised thresholds which are influenced by heterogeneity (Hopkins 2018; Lakens et al., 2018; Pek and Flora, 2018). Furthermore, effect (e.g., difference) magnitude should be evaluated according to its practical relevance and a standardised scale may not be relevant to the research question (Pek and Flora, 2018). Indeed, team sport researchers and practitioners should not be constrained by interpreting practical relevance via standardised thresholds as specifying a meaningful/target difference - a difference that is considered realistic or important - based solely on a standardised effect size approach should be considered a last resort (Lakens 2013; Cook et al., 2018).

The seeking of expert opinion via panels, survey or interviews represents a valid approach to inform on the choice of a target difference (Cook et al., 2018). As such, an alternate approach to standardisation could be the gathering of information on what constitutes the smallest important difference through gauging expert/end-user opinion (Thorpe et al., 2017) as practitioner insight can represent a catalyst for external validity (Esculier et al., 2018). While opinion seeking is proposed as a method of determining a realistic or important difference in the biomedical literature, this approach is unexplored in sports performance research.

Recently, equivalence testing has been suggested to have potential for advancing measurement research in exercise science (Dixon et al., 2018). This approach assesses whether two measurement systems are statistically equivalent by comparing the differences against a pre-determined “area of equivalence”. The concept of statistical equivalence is, however, heavily influenced by the choice of the equivalence region (Dixon et al., 2018) and as previously stated, the use of standardised thresholds is considered a last resort (Lakens 2013; Cook et al., 2018). What may be of more relevance to practitioners and researchers in sports performance research is setting equivalence thresholds around the smallest numerical value, in raw units, that experts perceive practically relevant.

Using MSS data collected from a criterion (100-Hz Laser) and non-criterion measure (10-Hz GPS) to illustrate a novel methodological approach to the assessment of validity; this chapter's aim was twofold. Firstly, briefly survey experts on the measurement of MSS in elite soccer, and, secondly, demonstrate how equivalence testing informed by expert opinion can assess for measurement validity.

3.2 Methods

3.2.1 Maximal sprinting speed survey

To obtain information on issues related to MSS measurement, we conducted a short cross-sectional survey. Here, practitioners (sport scientists, strength and conditioning coaches, and fitness coaches) currently working in elite soccer were asked about perception and practices of their teams' measurement of MSS. This short survey was developed in-house by the author team who represent a broad range of relevant expertise and experience in the area, both practically and scientifically. The survey was purposively distributed privately to known contacts with subsequent snowball sampling, and the data were collected using an online survey platform (Online Surveys, formerly Bristol Online Surveys [BOS]). The survey consisted of 10 questions, covering 2 main areas: 1) introduction/informed consent and background information (Questions [Q] 1–5), and 2) issues related to the measurement of MSS (Q6– 10), of which all were multiple choice questions.

3.3 Participants

Twelve full-time male youth soccer players (age 16.3 ± 0.8 years, body mass 54.5 ± 1.2 kg, height 173.9 ± 6.2 cm) were recruited from an elite youth soccer academy. All players were participating in ~8 training sessions per week, combining soccer, strength and conditioning training, and competitive play. This observational study conformed to the Declaration of Helsinki and received ethics approval from the Aspire Zone Research Committee and the Anti-Doping Laboratory Institutional Review Board, Qatar (approval number E20140000012).

3.4 Experimental Design

Participants performed two maximal 40-m sprints (Trial 1, Trial 2) with three minutes rest between efforts. Testing was undertaken on an outdoor natural grass pitch in good environmental conditions (calm, dry and 24 degrees Celsius) and all players wore their regular soccer boots. Typical errors for the between-trial differences were 0.13 (90% confidence interval 0.10 to 0.20) m/s for Laser and 0.07 (0.06 to 0.11) m/s for GPS, and intraclass correlation coefficients were 0.85 (0.64 to 0.95) and 0.95 (0.88 to 0.98), respectively. MSS was assessed simultaneously via 10-Hz GPS (Catapult Optimeye S5, version 7.32) and Laser (Laveg LDM 300C, Jenoptik, Germany). Each sprint was recorded using a hand-held digital video recorder (SONY AX53 4K) to allow precise time alignment between GPS and Laser. Each GPS unit was inserted into the manufacturer provided vest that was fitted tightly to the players, holding the receiver between the scapulae. All devices were activated 15 min before data collection to allow acquisition of satellite signals in accordance with the manufacturer’s instructions (Duffield et al., 2010). The average horizontal dilution was 0.68 ± 0.04 and the average number of satellites per unit was 12.0 ± 0.0. Laser was calibrated with zero showing the start of the 40 m measured sprint and was centred on the middle of the running lane. Laser height was 1.2 m, and all measurements were taken from the centre of the lens which was 3.1 m behind the starting line. The laser beam was directed at the lower part of the players back. After recording, GPS data were downloaded to a computer and analysed using the manufacturer's software (Catapult Openfield Software, version 1.21.1) (Roe et al., 2017). The raw GPS velocity data were calculated using the Doppler-shift method (Varley et al., 2017b). Laser data were processed using the software associated with the device (das3e). Displacement-time data were captured at 100-Hz and analysed with a 51-point moving average, and from this, an instantaneous velocity trace was derived. The velocity trace was used to establish the MSS that occurred within the 40 m measured sprint.

3.5 Statistical analysis

All survey data are presented as response frequency (expressed as a percentage) or where appropriate, the median and interquartile range (IQR). The peak value attained from either Trial 1 or Trial 2 was used as the MSS recorded by the two different measurement systems. Using the TOSTER package (Lakens et al., 2018), we assessed for statistical equivalence between our two measurement systems using two one-sided tests (TOST), as per the guidelines for assessing agreement between a surrogate measure (GPS) with a known criterion measure (Laser) (Dixon et al., 2018). For equivalence testing, users need to define the targeted region (Dixon et al., 2018). Therefore, the median value experts perceived as the acceptable amount of measurement error for MSS was used (Q10) to define the equivalence region. As the responses to this question encompassed a range of measurement error (e.g., 0.15–0.20 m/s), the median value was represented by the upper end of the response category. With a median acceptable amount of measurement error of 0.20 m/s, our lower and upper equivalence bounds were set to −0.10 m/s and +0.10 m/s, respectively. Results of equivalence tests can be obtained by mere visual inspection of the confidence interval (Lakens et al., 2018), with statistical equivalence between the two measures concluded when the 90% confidence interval around the mean difference excludes the lower and upper equivalence bounds (Lakens et al., 2018). However, to avoid test interpretation via the dichotomy of null hypothesis significance testing (Greenland et al., 2016; Rothman 2016), we assessed equivalence on a continuous scale. This was done via conversion of the t statistics from both one-sided tests to a probability (via the t-distribution), with subsequent equivalence probability interpreted using a one-sided calibrated Bayes (Little 2006, 2018; Hopkins and Batterham .2018). Here, probabilities were interpreted using the following scale: 75–95%, likely; 95–99.5%, very likely; >99.5%, most likely (Batterham and Hopkins, 2006), and equivalence was indicated by the lower probability (Dixon et al., 2018; Lakens et al., 2018). Analyses were performed in R (version 3.4.1, R Foundation for Statistical Computing, Vienna, Austria). Uncertainty in all estimates is presented as 90% confidence intervals.

3.6 Results

Median time (min:sec) to complete the survey was 02:57 (02:08,4:27) and of 50 respondents, 60% were sports scientists, 32% fitness coaches, and 8% strength and conditioning coaches (Q2). Respondents had a median of 8 (5,12) years' experience working in elite soccer (Q3) and worked either exclusively with senior players (58%), a combination of senior and younger players (22%), or exclusively with younger players (20%) (Q4). The majority of respondents worked at high standard European soccer clubs (76%) (Q5) with the following breakdown of leagues that respondents clubs played in: English Championship (n = 13), English Premier League (n = 9), National Associations (n = 4), Greek Super League (n = 3), US Major Soccer League (n = 3), Cyprus First Division (n = 3), English League One (n = 2), Australia A-League (n = 2), Serie A (n = 2), Bundesliga (n = 2), Qatar Stars League (n = 2), Belgian First Division (n = 1), Scottish Premier League (n = 1), La Liga Juveniles (n = 1), Arabian Gulf League (n = 1), and Chinese Super League (n = 1).

The responses to Q6–9 are presented in Table 3-1. Where respondents selected a combination of methods for deriving MSS (Q9), the majority of responses were for the combination of match and training (55%). The median value for the practically acceptable amount of measurement error for MSS (Q10) was 0.20 (0.10,0.25) m/ s. For this question, two respondents chose 'Other' and provided exact values of 5% and 0.6 km/h, respectively; the latter of these values was included in the appropriate answer category giving a total of 49 answers for this question (Figure 3-1). The mean of the players' fastest sprint from either Trial was 8.79 ± 0.33 m/s (Laser) and 8.75 ± 0.32 m/s (GPS) with a mean difference of 0.04 (90% confidence interval −0.03 to 0.11) m/s. Equivalence of MSS measured by Laser and GPS was likely (probability 93.7%) (Figure 3-2).

Table 3-1: The most three frequent answers to the MSS survey (Questions 4, 6-9)

4. What is the age category of the players you work with?	*Senior* **58%**	*Senior, PDP, YDP* **10%**	*PDP* **6%**
6. What system do you consider the “gold standard” to measure maximal sprinting speed?	*Laser and Radar Guns* **34%**	*Fully Automatic Timing System* **28%**	*Timing Gates* **22%**
7. What system (s) do you use to measure maximal sprinting speed?	*GPS* **34%**	*Timing Gates, GPS* **26%**	*Timing Gates* **16%**
8. Have you ever undertaken a validity check for your system used?	*Never* **40%**	*Between 1 and 2 years* **28%**	*Once every 5 years* **14%**
9. What method do you use to derive maximal sprinting speed?	*Fitness Test* **44%**	*Combination of Two Methods* **30%**	*Training* **14%**

GPS, Global Positioning Systems; PDP, Professional Development Phase (Under 18 to 23 years); YDP, Youth Development Phase (Under 13 to 16 years)

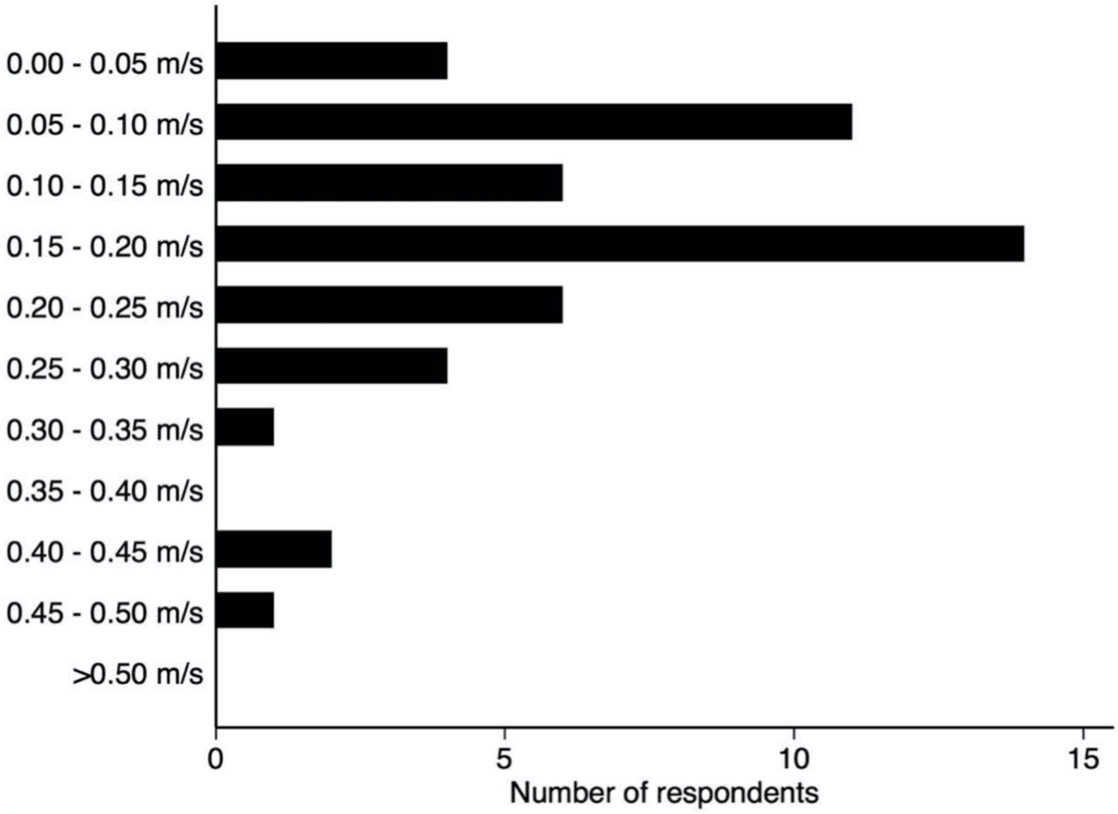

Figure 3-1: Responses (n = 49) for the practically acceptable amount of measurement error for MSS (Q10)

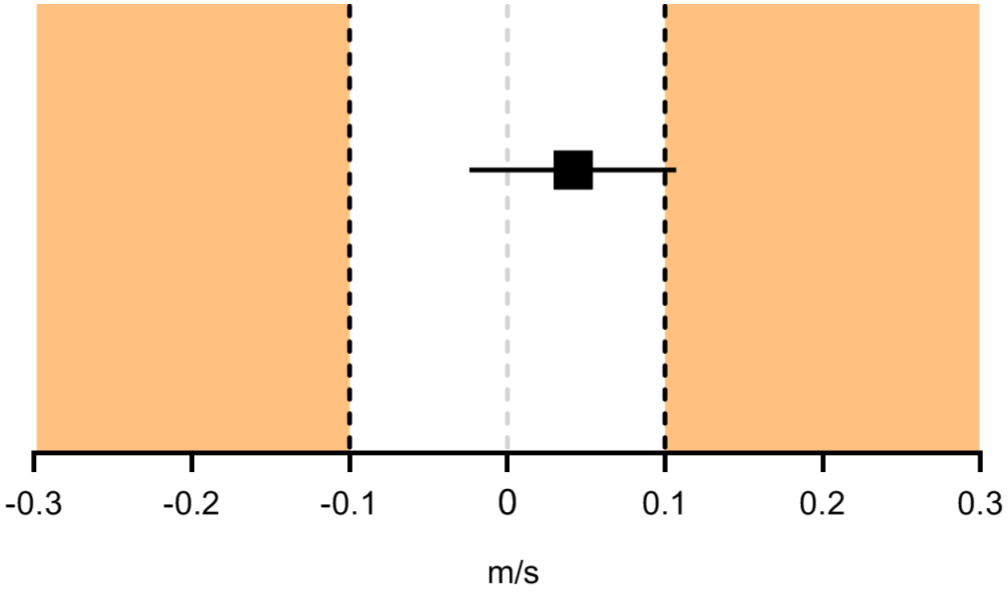

Figure 3-2: Mean difference (m/s) and uncertainty for the difference (90% confidence interval) in MSS measured by Laser and GPS. The black vertical dashed lines represent the expert-informed statistical equivalence region of 0.2 m/s (−0.1 m/s to +0.1 m/s)

3.7 Discussion

In this chapter, a novel approach for assessing validity was employed. Maximal sprinting speeds (MSS) collected by a criterion (100-Hz Laser) and non-criterion measure (10-Hz GPS) were used to showcase a newly proposed method for validity assessment involving equivalence testing informed by expert practitioner opinion. This is the first attempt to integrate expert opinion into the statistical framework for determining validity for a measure of sports performance. This chapter's findings indicated that GPS-measured MSS was likely equivalent to the criterion measure and, therefore, practitioners should continue to have confidence in GPS as a measure MSS. Additionally, the survey results provide valuable insights into current practices surrounding the measurement of MSS in elite soccer.

While previous work has shown validity of 10-Hz GPS for measuring MSS (Roe et al., 2017), criterion comparison was made via standardisation. Standardised scales, however, lack practical context and may therefore not be relevant to the research question (Pek and Flora, 2018). This is by no means a criticism as establishing externally valid minimum important differences represents a huge challenge to sport and exercise science as changes in one variable need to be assessed against subsequent changes in a relevant anchor such as performance (Thorpe et al., 2017). Use of expert opinion, therefore, represents a credible approach to informing the definition of practically important differences (Cook et al., 2018) or, in the context of our study, an acceptable amount of measurement error for measures relevant to sports performance (Lassere et al., 2001).

Generally, reliability studies in sports performance entail the indiscriminate calculation of Pearson's correlation coefficients (Atkinson and Nevill, 1998), or the definition of the typical error of the estimate expressed in percentage points whose magnitude assessment may be irrelevant for both the researcher and practitioner (Atkinson, 2003). Notwithstanding the deceptive simplicity and specious practicality of calculating these common statistics, failure to express the actual amount of measurement error adopting a meaningful metric may limit practitioner definition of what represents a true population increase in the response of interest deemed substantially greater than a predefined practically important difference (Lassere et al., 2001). Furthermore, tests of mean difference are common in agreement research but may not necessarily represent the best statistical approach (Dixon et al., 2018). Equivalence testing has been proposed as a more appropriate method for evaluating agreement among measures than mean difference tests; however, choosing and justifying equivalence regions is a difficult aspect of this approach (Dixon et al., 2018). Indeed, previous studies using equivalence testing have reported, yet not justified the smallest effect size of interest for the equivalence bounds (Lakens et al., 2018). Therefore, in this chapter, these methodological concerns were overcome by setting the equivalence bounds on what a relatively large sample of experienced practitioners perceived to be an acceptable amount of measurement error when measuring MSS. This novel and rigorous approach enabled us to conclude that GPS-measured MSS is likely equivalent to the speed recorded by a gold standard measure (100-Hz Laser).

While standardisation reflects a common approach to determining important differences/smallest worthwhile effects in sports performance research, the use of standardised effect sizes to derive meaningful and realistic differences has recently been questioned (Cook et al., 2018; Pek and Flora, 2018). With standardisation used in the present chapter, we would have had an unrealistic value for interpreting a meaningful difference between our criterion and non-criterion measure. To illustrate this point, the pooled standard deviation of MSS recorded by GPS and Laser was 0.32 m/s. Taking 0.2

standard deviations as the smallest effect size gives a value of 0.06 m/s and a subsequent equivalence region of −0.03 m/s to +0.03 m/s. In this study, these values clearly lack practical context as only 15/49 of experts surveyed reported an acceptable amount of measurement error at 0.10 m/s or less (Figure 4-1).

For an accurate assessment of MSS, fully automatic timing systems represent the gold standard with dual-beamed photocells, laser guns and high-speed video timing representing cheaper, more practical tools with acceptable accuracy (Haugen and Buchheit, 2016). The results presented in this study lend the first empirical support of this observation given that 84% of the survey respondents perceived either laser/radar guns, fully automatic timing systems and timing gates as gold standard measures. Only 16% of the respondents regarded GPS as gold standard despite these systems being the most frequent system (49%) used to measure MSS. Chapter's 3 findings help to address this apparent disconnect as practitioners can be assured of the validity of MSS recorded by 10-Hz GPS. The infrequent nature of system validity checks observed in our study possibly reflects a lack of available time given that practitioners are indeed cognizant of the need for validity assessments (Akenhead and Nassis, 2016).

The most common single method to derive MSS in our survey was fitness tests. The need for sprint testing was recently questioned though as peak speeds recorded during matches were faster than when recorded during a 40-m maximal running test, albeit in semi-professional senior players (Massard et al., 2018). These findings contrast with previous work whereby highly trained youth footballers' maximal match speeds were ~90% of the speed attained on a 40-m sprint test (Mendez- Villanueva et al., 2011; Al Haddad et al., 2015). In light of these equivocal findings, it is encouraging that survey respondents derived MSS from a variety of scenarios (e.g., tests, training, matches). Such an approach will help to ensure an ongoing calibration of maximal speeds, which is of vital importance if speeds recorded during training and matches are interpreted against a player's individual capacity.

Sports performance researchers and practitioners are encouraged to consider more externally valid methods of establishing practically important differences. Using an analytical method informed by expert opinion on the acceptable amount of measurement error for MSS, practitioners can rely on GPS for an accurate assessment of MSS in elite youth soccer players.

CHAPTER 4: TO MEASURE MAXIMAL SPRINTING SPEED IN SOCCER, LET THE PLAYERS SPRINT

This study was published as a short research report in the Journal of Strength and Conditioning Research (Appendix, Chapter 10)

4. To measure maximal sprinting speed in soccer, let the players sprint

4.1 Introduction

The measurement of external loads in soccer in now commonplace (Weston, 2018). Whether collected via semi-automated video systems or via global positioning systems (GPS) (chapter 3), these data are most commonly analysed via time spent in several locomotor categories designed to encompass the broad range of movement intensity (i.e., from walking to sprinting) (Akenhead and Nassis, 2016). Such an approach, however, has been criticized for failing to account for the individual “capacity” of players (Abt and Lovell, 2009). In an attempt to overcome such practical limitations of arbitrary speed thresholds, a growing body of research has expressed external load relative to individual players capacity (Harley et al., 2010; Cahill et al., 2013; Mendez-Villanueva et al., 2013; Hunter et al., 2014; Gabbett et al., 2015; Reardon et al., 2015; Abbott et al., 2018), the premise of which being to better understand the individual players’ dose-response and energetic demands of training and match-play (Hunter et al., 2014). Unfortunately, though, the majority of research into this practice-led process simply describes the impact of different approaches to speed zone classification (Drust, 2018) in that individualisation increases high-speed running of slower players, yet decreases high-speed running of faster players (Hunter, et al., 2014; Gabbett, 2015; Abbott et al., 2018).

Three recent studies have, however, gone beyond a descriptive account of individualisation and attempted to assess the added value of this practice. While associations between internal and external load measures were largely consistent between arbitrary and individualised external loads (Scott and Lovell, 2018), there were differences in injury likelihood in acute very high-speed distance for slower players when data were expressed using a relative threshold (Murray et al., 2018) and the only clear associations between external load and changes in fitness were reported for individualised external load metrics (Fitzpatrick et al., 2018). Despite limited evidence for the added value of external load individualisation, the conceptual merits for this practice are clear - to better quantify the individual players' energetic demands leading to a potentially more accurate evaluation and prescription of load (Scott and Lovell, 2018).

Integral to speed zone individualisation are the metrics used to represent a players' physical capacity. Studies have anchored individualised speed zones to the players' maximal sprinting speed (MSS) (Harley et al., 2010; Cahill et al., 2015; Gabbett, 2015; Reardon et al., 2015), yet anchoring zones on peak velocities alone presents difficulty in the subsequent classification, description, and justification of the different speed zones (Weston, 2013), and may also be error prone (Hunter et al., 2014). A more robust method for enhancing the validity of speed thresholds is using the athlete's functional limits of both endurance and sprint capacity (Abbott et al., 2018) with studies anchoring individualised speed zones on measures of maximal aerobic speed (MAS) and MSS (Mendez-Villanueva et al., 2013; Hunter et al., 2015; Scott and Lovell, 2017; Abbott et al., 2018).

Whether used in isolation or in combination with MAS, MSS remains a key metric for informing external load individualisation. An accurate measure of MSS is therefore needed - not merely an assumed "peak" value - as basing high-speed thresholds on a percentage of a MSS less than the true value would overreport high-speed running metrics (Reardon et al., 2015). Team sports have anchored individualised zones to MSS obtained from any session across a season (Reardon et al., 2015; Casamichana et al., 2018) or during matches (Cahill et al., 2015), yet MSS in soccer is generally the value measured during sprint testing (Harley et al., 2010; Mendez-Villanueva et al., 2013; Hunter et al., 2014; Gabbett, 2015).

For an accurate assessment of MSS, practitioners can also rely on GPS as a more practical tool (chapter 3). Of concern here is that in semi-professional soccer players, MSS recorded during 40-m sprint testing were slower than speeds during matches; sprint testing did not therefore represent MSS (Massard et al., 2019). However, using only 2 activities and not the broad range of training activities typically performed by soccer players (e.g., skill-based conditioning) may have failed to capture the player's MSS.

As such, the main aim of this chapter is to see whether the aforementioned finding of Massard et al. replicates in a group of elite youth soccer players across a broader range of soccer activities. This study develops the practice of individualised training prescription and match evaluation; key roles for the strength and conditioning practitioner, by informing on the methodologies required for determining MSS.

4.2 Methods

4.3 Participants

Twelve full-time male youth soccer players (mean ± SD: age 16.3 ± 0.8 years, body mass 54.5 ± 1.2 kg, height 173.9 ± 6.2 cm) were recruited from an elite academy. Four players were excluded from the study because they did not meet our inclusion criteria of a minimum of 3 matches, ensuring sufficient representation of this activity category (Weston et al., 2015). All players were participating in ~ 8 training sessions per week, combining soccer, strength and conditioning training, and competitive match-play. Players were classified into five playing positions: Central Defender (n=2), Wide Defender (n=2), Central Midfielder (n=2), Wide Midfielder (n=1) and Striker (n=1). Given the age of our subjects, we obtained parental consent and subject consent through institutionally approved informed consent documents that detailed the purposes and procedures of our investigation. Our study conformed to the Declaration of Helsinki, and the Aspire Zone Research Committee and the Anti-Doping Laboratory Institutional Review Board, Qatar (E20140000012) provided ethics approval.

4.4 Experimental Design

In this chapter, MSS was recorded during a 40-m sprint test with a range of activities routinely performed by the players. Because the reference for all comparisons was the 40-m sprint test, it was important to control for the potential influence of time on MSS (e.g., change of fitness, growth etc.). This study, was therefore conducted across 4 consecutive months in the middle of the competitive season, using the 2 months immediately before and after the 40-m sprint test. Skill-based conditioning sessions were categorized by the academy's technical director into small-sided games (SSG), medium-sided games (MSG), and large- sided games (LSG), respectively.

All activity (Table 4-1) was monitored with 10-Hz global positioning systems (GPS; Catapult Optimeye S5, version 7.32), and these activities were all performed outdoors on natural grass, with players wearing their regular soccer boots. To eliminate interunit variability, each player wore their own unit, which was inserted into the manufacturer provided vest that holds the receiver tightly between the scapulae. All devices were activated 15 minutes before data collection to allow for acquisition of satellite signals in accordance with the manufacturer's instructions. The average horizontal dilution was 0.69 ± 0.01 and the average number of satellites per unit was 11.9 ± 0.1. After recording, GPS data were downloaded to a computer and analysed using the manufacturer’s software (Catapult Openfield Software, version 1.22.0). The raw GPS velocity data were calculated using the Doppler-shift method (Varley et al., 2017), with the highest speed attained during each activity, including the 40-m sprint test, retained as the instantaneous MSS.

4.5 Statistical Analyses

Descriptive data are presented as mean ± SD. MSS residuals for all activities followed a normal distribution, so analysis was performed on the raw untransformed data. A mixed linear model examined the effect of soccer activity on MSS. Fixed effects in the model were activity (40-m sprint test, matches, sprints, LSG, MSG, and SSG), with the 40-m sprint test used as the reference category for the fixed effect estimates. We included a random effect and intercept for the player to account for the dependency arising from repeated measures and also to determine the within- player variability in MSS for all activities. Uncertainty in our estimates is presented as 95% confidence intervals. Effects are calculated and presented as simple effect sizes (e.g., mean differences), with standardized effect sizes (i.e., mean difference divided by the pooled SD) also presented but not interpreted. The benefits of simple effect sizes over standardized effect sizes are that they are independent of variance, easier to compute, and scaled in the original units of analysis (Baguley, 2011), which maximizes the practical context of findings (chapter 3). Furthermore, as a player’s running velocity is likely constrained by either planned aims (e.g., training) or fulfilling tactical roles (e.g., matches), there is no implication of benefit/ positive or harmful/negative here, so a descriptive presentation of faster or slower is congruent with our research aim. Our interpretation of between-activity differences in MSS was therefore based on the width of the respective 95% confidence intervals for the mean difference (in raw units), with nonoverlap of the confidence intervals constituting a clear difference in velocity. Analyses were performed using the SPSS software (v.25, Armonk, NY: IBM Corp).

4.6 Results

Mean ± SD MSS attained during the soccer activities, along with MSS during the 40-m sprint test, are displayed in Table 4-1. Within-player variability was 0.89 (95% confidence interval 0.81–0.97) $m \cdot s^{-1}$ for SSG, 0.75 (0.69–0.82) $m \cdot s^{-1}$ for MSG, 0.65 (0.57–0.73) $m \cdot s^{-1}$ for LSG, 0.36 (0.29–0.46) $m \cdot s^{-1}$ for sprints, and 0.47 (0.39–0.57) $m \cdot s^{-1}$ for matches. MSS was clearly faster on the 40-m sprint test when compared with all activities other than sprints (Figure 4-1). MSS was also clearly faster during sprints when compared with SSG, MSG, and LSG and clearly slower during SSG when compared with MSG and LSG. Compared with the 40-m sprint test, standardized effect sizes were as follows: 3.9; 95% confidence interval 3.0 to 4.7 (SSG), 3.2; 2.4 to 3.9 (MSG), 2.9; 2.0 to 3.7 (LSG), 0.7; -0.1 to 1.5 (sprints), and 1.7; 0.8 to 2.5 (matches). Percentage differences when compared with the sprint test were as follows: -41% (SSG), -27% (MSG), -21% (LSG), -3% (sprints), and -9% (matches).

Table 4-1: Descriptive statistics (number, mean ± SD) and qualitative details for the six types of soccer activities

Activity	Mean ± SD max speed (m/s)	Details (Total number; mean ± SD per player)
40-m Sprint Test	8.76 ± 0.39	Two maximal 40-m sprints interspersed with 3 minutes rest (8; 1 ± 0)
Sprints	8.50 ± 0.36	Sprint training with the players performing a series of straight-line sprints (5-40 m) with a work:rest ratio of ~1:20. (35; 4.4 ± 0.4)
Match	7.94 ± 0.49	Competitive International tournaments of 70 min or 90 min. All players played the full match. (65; 7.9 ± 3.9)
LSG	6.94 ± 0.65	Density per player 197-347 m^2 (120; 15.0 ± 2.7)
MSG	6.40 ± 0.75	Density per player 96-186 m^2 (270; 33.8 ± 4.3)
SSG	5.25 ± 0.92	Density per player 11-94 m^2 (266; 33.3 ± 5.5)

SD, standard deviation; SSG, small-sided games; MSG, medium-sided games; LSG, large-sided games

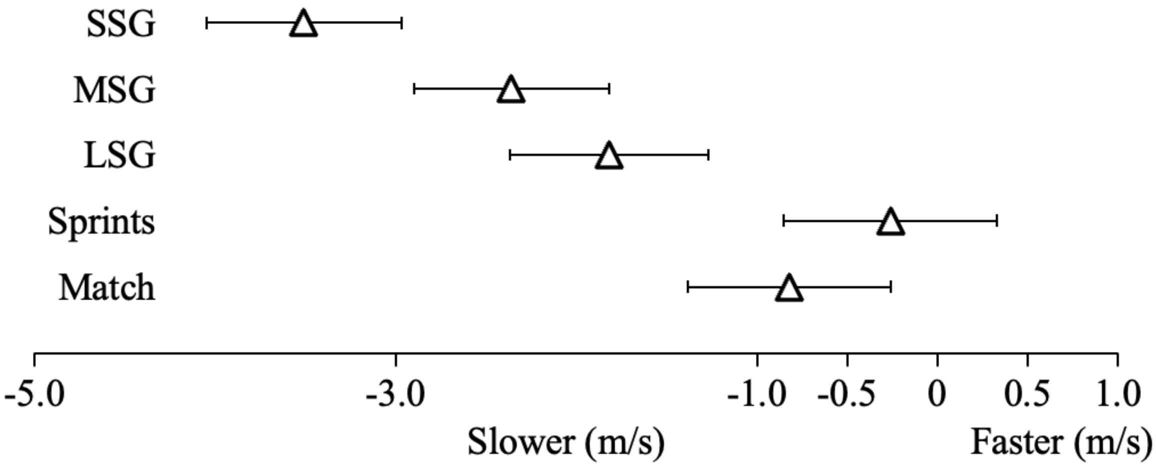

Figure 4-1: Effect statistics (mean differences and 95% confidence intervals) for the comparison of MSS attained during SSG, MSG and LSG, sprints, and match versus MSS recorded during a 40-m sprint test. Zero difference (0) on the x axis represents no difference between an activity and the 40-m sprint test

4.7 Discussion

The main findings of this chapter did not provide empirical support to the findings of Massard et al., as GPS-recorded MSS on a 40 m sprint test was faster than MSS on competitive matches. Chapter 4 findings are consistent with that of previous work, whereby elite youth players only attained ~90% of their MSS during matches (Mendez Villanueva et al., 2011; Al Haddad et al., 2015). While contrary to Massard and colleagues, this finding is hardly surprising given that most sprints during soccer matches are performed over short distances (Di Salvo, 2009). Match-play did not, therefore, provide the players the opportunity to sprint maximally over a long enough distance, no doubt a consequence of the tactical constraints of match-play (Mendez Villanueva et al., 2011).

The practical context for chapter 4 main finding focuses on developing the practice of individualised training prescription and match evaluation. Given the highly individualised nature of the exercise-intensity continuum, there is potential for substantial errors in the measurement and interpretation of high-speed running distance when using absolute speed thresholds. Expressing speeds zones relative to player's physical capacities may limit these errors and provide a better understanding of dose-response (Hunter, 2014). Of these physical capacities, MSS is a key metric. If our findings extend to other populations and sports, then previous work using either all session data and/ or sprint test data would likely have led to accurate individualisation of high-speed zones; whereas work relying only on match data would most likely have led to an inaccurate interpretation of players individualised running performances. Reassuringly, the survey conducted in chapter 3, showed the practice deriving MSS from either a sprint test (44%), a combination of methods (30%), or physical training (14%) was more common than using the value obtained during soccer matches (8%) or skill-based conditioning (4%).

Skill-based conditioning drills are commonplace in soccer as they enable the simultaneous technical, tactical and physical training by replicating the movement demands, physiological intensity and technical requirements of competitive match play (Hill Haas et al., 2011; Lacome et al., 2018). Alongside chapter's 3 main finding, it is also demonstrated that MSS attained in the Sprint sessions was clearly faster than velocities attained during soccer activities integrating physical training with ball training (e.g., SSG, MSG, LSG). Furthermore, Match MSS was also faster SSG and MSG's. These findings are consistent with previous reports (Djaoui et al., 2017; Olthof et al., 2018) suggesting that SSG, MSG, and to a lesser extent LSG employed by the coaches in the present study could be insufficient to improve and maintain MSS in this group of elite youth soccer players. Coaches are therefore advised to include additional specific speed drills to prepare players for matches with a suitable stimulus of MSS (Djaoui et al., 2017).

It is acknowledged that the low match sample represents a potential limitation of this chapter, especially given the high match-to-match variability in sprinting (Gregson et al., 2010). The match-to-match variation in MSS was however, only 5.6%, which is consistent previous work (Al Haddad et al., 2018) and therefore substantially lower than the variability for match sprinting distance (30.8%) (Gregson et al., 2010). This match-to-match stability is further illustrated by the within-player variability and associated narrow confidence intervals for Match MSS. For example, when the within-subject variability for Match (0.47 m/s) is added to and subtracted from the mean of 7.94 m/s, the estimate for Match typically varies from 7.47 m/s to 8.41 m/s. Another potential limitation is that the low subject sample precluded a differentiation of findings by playing position (e.g. Djaoui et al., 2017; Mendez-Villanueva et al., 2011). Even with a low number of players, however, there is still sufficient precision of our estimates - fixed and random effects - to illustrate a clear effect of soccer activity on MSS. Lastly, while laser guns and high-speed video, not GPS, are considered the gold standards for measuring sprinting speed (Haugen et al., 2016), we measured MSS via 10-Hz GPS. Nonetheless, as chapter 3 demonstrated, utilising practitioner opinion on the acceptable amount of between-device measurement error showed GPS-measured MSS is equivalent to that recorded by a Radar Gun.

Accurate assessment of MSS requires players measuring during sprinting activities, namely a sprint test or, to a lesser extent, sprint training. This will provide practitioners with confidence in their recording of MSS and, in turn, the subsequently reported individualised running metrics if MSS is indeed one of the physical capacities used for individualisation. Finally, given the importance of sprinting in elite soccer (Faude et al., 2015), it is vital that players are exposed to high velocities in training, which is most likely achieved by providing sufficient space (e.g., ;40 m) during purposeful sprinting exercises.

CHAPTER 5: INCONSISTENT EFFECR OF PSYCHOMETRIC-SCALE FAMILIARISATION ON THE RELATIONSHIP BETWEEN RATINGS OF PERCEIVED EXERTION AND EXTERNAL LOAD MEASURES IN ELITE YOUTH SOCCER PLAYERS

This study was presented as an oral communication at the 30th Isokinetic Medical Group Conference, London, England 2023 and also published as a full manuscript International Journal of Sports Physiology and Performance (Appendix, Chapter 10)

5. Inconsistent Effect of Psychometric-Scale Familiarisation on the Relationship Between Ratings of Perceived Exertion and External Load Measures in Elite Youth Soccer Players

5.1 Introduction

Having established the validity of the methods used to derive external load metrics (Chapter 3) and analysed these metrics across various training modalities and match-play (Chapter 4), attention is shifted towards examining players' internal load responses to training. Internal load represents the physiological and psychological responses elicited by an external stimuli (Impellizzeri et al., 2005). While external load quantifies the work completed (e.g., total distance, high-speed running, accelerations), internal load reflects the player's individual response to that work, accounting for factors such as fitness, fatigue, and psychological state (Akenhead & Nassis, 2016). Evaluating internal load in response to known external workloads provides a deeper understanding of training stress and allows for the detection of maladaptive responses, thereby informing individualised load management strategies and optimizing performance adaptation.

Ratings of perceived exertion (RPE) represent a simple, non-invasive, and valid means to monitor exercise intensity (Foster et al, 2001; Foster et al 2004; Coyne et al 2018). While RPE provides a global measure of intensity, it may lack sensitivity to cover the range of different exertion signals that arise during exercise. (Weston, 2013; Drew & Finch, 2016). To address this potential measurement short-coming, recent investigations have centred on the use of differential RPE (dRPE), which distinguishes exertional scores between central respiratory and peripheral neuromuscular systems by providing separate ratings for breathlessness (RPE-B) and leg- muscle exertion (RPE-L) (Weston, et al., 2015; McLaren et al., 2017; Wright et al., 2020; Maughan et al., 2020; McLaren et al., 2020; Houtmeyers et al., 2022). Given that dRPE measures represent unique sensory inputs, this could facilitate a more comprehensive understanding of the internal response induced by training and competition (Wright et al., 2020).

To date, the majority of research examining the utility of dRPE for monitoring internal intensity and load has centred on team sports (Weston, 2015; McLaren et al, 2017; McLaren et al, 2018, Mcpherson et al, 2019). Players provide different dRPE ratings after resistance exercise (e.g. higher RPE-L) and running-based aerobic endurance (e.g. higher RPE-B) (McLaren et al, 2017; Wright et al., 2020). Contrary to such observations, during team-sport training and match-play, contrasting evidence exists regarding players ability to provide different ratings (Gil-Rey et al., 2015; Los Arcos et al., 2016; Leceaga et al., 2017; Maughan et al., 2020; Houtmeyers et al., 2022). Furthermore, no clear differentiation of dRPE ratings is observed when training session types are clustered into distinct external intensity and load profiles (Maughan et al., 2020; Houtmeyers et al., 2022). Collectively, the evidence to date supporting the utility of dRPE for monitoring internal intensity and load in team sports is inconclusive.

Discrepancy between studies regarding the ability of dRPE to discriminate between session typologies could reflect differences in education and familiarisation with the rating scales (Coyne et al., 2018; Macpherson et al., 2019). Subjective measurement tools require formal psychometric appraisal, applied as intended (e.g., verbal anchors to obtain a numerical rating) and combined with education tools (e.g., Borg blackness test) to obtain the best results for athletes and coaches (Saw et al., 2017). Such processes, however, are rarely ascertained in the sports science literature. It may be assumed that, when different scores could be expected during sessions with disparate loading patterns, the absence of substantial differentiation in different dRPE scores could reflect differences in background education and familiarisation with the rating scale (Saw et al., 2017; Macpherson et al., 2019). Comprehensive reporting of methodologies concerning RPE procedures including the degree of familiarisation may, therefore, improve the quality of perceived exertion data generally collected. For example, Macpherson et al (2019) illustrated improvements in accuracy and precision of intensity ratings in team-sport coaches and players following familiarization with exertional scoring using the blackness test. The blackness test serves as an educational instrument to enhance understanding of the CR101 and centiMax (CR100) (Borg & Kaijser, 2006) scales by providing participants with examples of a range of differing levels of blackness (0% = white; 100% = black), which are analogous to verbal anchors on the Borg CR intensity scales (i.e., 5% blackness corresponds with very easy; 15% blackness corresponds with easy). Notwithstanding this, clinical research investigating the effects of familiarisation with RPE and dRPE challenged the notion of undergoing a formal learning trial prior to rating with RPE (Hutchinson et al., 2020). At moderate (50% V̇O2peak) to vigorous (70%V̇O2peak) exercise intensities determined on a maximal arm-cranking test, Hutchinson and his colleagues (2020), showed a 16-week period familiarisation with dRPE did not influence RPE on the CR10 scale in adults with spinal cord injury compared with those who received no familiarisation. Nevertheless, no study to date explored the moderating effect of familiarisation with the CR100 scale on RPE anchored against proxy measures of external load during training and matches in youth soccer.

With this in mind, chapter 5 aim to explore whether familiarisation with subjective RPE moderates the relationship between proxy measures of external load and global RPE and dRPE over an extended period of training and match play in elite youth soccer players.

5.2 Methods

5.3 Participants

Thirty-five elite male youth soccer players (age 17.5 ± 1.1 years, body mass 68.8 ± 7.5 kg, height 1.77 ± 0.6 cm) from an elite youth academy completed ~5 training sessions per week over a period of 31 weeks during the end of 2019-20 season and during the pre-season and start of 2021-2021 season. Players were classified into five playing positions: Central Defender (n=6), Wide Defender (n=7), Central Midfielder (n=10), Wide Midfielder (n=7) and Striker (n=5). Usual appropriate ethics committee clearance was not required as data was collected as a condition of employment (Winter and Maughan, 2009) and all players had previously consented for their data to be used for research purposes. Nevertheless, all data were anonymised prior to analysis to ensure player confidentiality.

5.4 Experimental Design

Unavoidable study conduct modifications in response to the COVID-19 pandemic resulted in important design revisions (Orkin et al., 2021). By following and adapting a relevant sample of items from the CONSERVE (CONSORT and SPIRIT extension for randomized control trials revised in extenuating circumstances) guidelines, we sought to retain the quality, completeness, and transparency of reporting despite unforeseeable circumstances (Orkin et al., 2021). These modifications aimed to preserve the validity of the forethought research procedures and extended the original research purpose (Table 5-1). Accordingly, modifications to the original study design due to extenuating circumstances followed a readaptation of the CONSERVE guidelines (Orkin et al., 2021) that resulted in having 2 groups of players; these groups included players that did the familiarisation (n = 20) and players that did not undergo the familiarisation (n = 15).

In this context, using an observational research design, data were collected following on-field training sessions (121 sessions) and competitive matches (18 matches) over a 7-week preseason and 18-week in-season training period. Given the nature of our data collection process, we conducted sensitivity analyses to assess potential preseason versus in-season differences in training and match load with the trivial between-period differences suggesting pooling all measurements for our primary analyses. The team's typical weekly plan followed a periodisation model centred on overloading each of the three main fitness components (strength, endurance, and speed) on a specific day alongside one competitive match. In a typical training week (table 5-2), Monday served as a recovery day with low-intensity, low-volume drills. Tuesday involved strength training sessions incorporating gym-based lower-body strength exercises together with high-intensity, moderate-volume field- based drills (1v1–5v5). Endurance training via moderate-intensity, high-volume field-based drills (6v6–11v11) was typically scheduled on Wednesday, with speed training via maximal-intensity, low-volume drills (maximal sprinting speed drills and tactical games) on a Thursday. Moderate-intensity, low-volume reaction drills together with set pieces occurred on a Friday. Training and match data were only analysed for players completing the whole session, excluding rehabilitation or individual sessions.

5.4.1 Familiarisation With dRPE

Players had not used the CR10 or CR100 scales previously. We provided all players and coaches with a tutorial on the CR100 scale that explained each of the verbal anchors, the numbers, and the sensations each represented. Then, a group of players underwent a familiarisation process (n = 20) in December 2019. The blackness test was provided to the players as a learning tool for the CR100 scale (Borg, 1998; Mcpherson et al., 2019). Players completed the blackness test on 3 occasions with 3 and 7 days between test 1 and 2 and test 2 and 3, respectively. The blackness test (figure 6-2) consisted of 9 pictures with filled squares differing in blackness using the grey preset colors in Microsoft PowerPoint (5%–95% blackness). Each picture was presented twice in a randomised order for 10 seconds with blanks between each page. The task was to estimate how "strong" the player experienced the blackness of each filled square according to the CR100 scale (Borg, 1998). The levels of blackness were closely linked to the verbal anchors on the CR100 scale, so players were asked to estimate how strong they experienced blackness on each image according to the CR100 (e.g., the 50% blackness square would represent the "strong" verbal anchor on the CR100) (Mcpherson et al, 2019). Each answer was scored for accuracy (i.e., correct/incorrect) and level of precision (i.e., how many arbitrary units [AU] away from the correct verbal anchor) (Mcpherson et al, 2019).

5.4.2 Training Sessions

Player dRPE, along with a global rating for each session (RPE), was recorded 15 to 30 minutes post session via a touch-screen tablet application (Iconia One 7 B1-750, Acer Inc) using CR100 scale, which was numerically blinded, labelled with the idiomatic English verbal anchors. Ratings were collected independently and confidentially for each player who was asked to login into the application via his shirt number. Coaches encouraged players to provide ratings for overall session effort (RPE), breathlessness (RPE-B), and leg- muscle exertion (RPE-L). Once players had provided their ratings using the touch-screen tablets, the application software uploaded each score as a number value to a cloud-based spreadsheet. All training and match activity were monitored with a 10-Hz global positioning system (GPS; Catapult Optimeye S5, version 7.32) which we know from chapter 3 represents a reliable and valid tool for monitoring locomotor activity. To eliminate interunit variability, each player wore their own unit which was inserted into the manufacturer- provided vest that holds the receiver tightly between the scapulae. The GPS devices were activated 15 minutes before data collection to allow for acquisition of satellite signals in accordance with the manufacturer's instructions. The average horizontal dilution was 0.74 (0.08), and the average number of satellites per unit was 14.3 (1.9). After recording, GPS data were downloaded to a computer and analysed using the manufacturer's software (Catapult Openfield Software, version 1.22.0, Catapult) (chapter 3).

5.5 Statistical Analysis

Summary data for participants who completed familiarisation sessions were presented as median and interquartile range (IQR). Data from practices and opinions of practitioners from around the world informed the present study modelling framework, with number of accelerations, number of decelerations, and high-speed running distance selected as external load variables of interest (Gaudino et al., 2015; Akenhead and Nassis, 2016). Separate multivariable-adjusted random-effects generalized additive models with restricted maximum likelihood (Wood, 2017) quantified familiarisation versus no-familiarisation differences in perceived exertion at prespecified values for each external load variable, respectively (Gaudino et al., 2015). Models included the raw RPE score (in arbitrary units) as the response variable; familiarisation (0, no; 1, yes) as a categorical fixed effect; a smooth term for the external load variable set at 3, 5, 7, and 9 basis functions; and a familiarisation × external load variable interaction term plus subject-specific and session duration random effects penalized by a ridge penalty (Wood, 2017). An information-theoretic approach was adopted for optimal smooth model selection (Wood, 2017). Postestimation model diagnostic was conducted based on visual inspection of each model residuals using the mgcViz package (Fasiolo et al., 2020). Effects were summarized as estimated marginal means with 95% CI presented using density strips to illustrate the degree of uncertainty surrounding the point estimates (Bowman, 2019; Lenth et al., 2021). Familiarisation versus no-familiarisation effects in perceived exertion by external load were declared different if the location of the 95% CI for the mean estimate exceeded the predefined region of equivalence ranging from −4 AU to + 4 AU (i.e., target value = 8 AU) for all RPE scores (Wright et al., 2020). Statistical analyses were conducted using R (version 3.6.3).

Table 5-1: Modifications to the original study design due to extenuating circumstances

Context	*Sample of adapted CONSERVE items*
The original aim of this study was to explore the blackness test familiarisation as a training tool to assess a player's ability and understanding of intensity estimation following a repeated measures design [13]	• *Extenuating circumstance*: pre-planned data collection procedures were terminated due to the COVID-19 pandemic • *Impacts*: non-random change in study participants from the original sample (January to March 2020) following resumption of training and data collection (July to November 2020) • *Mitigating strategies*: revised study design to mitigate threats to the original study validity and extend research purpose • These are important modifications that had implications for study conduct and procedures

Table 5-2: Training content prescribed on each training day type

Day	Day Type	Session Target	Volume	Intensity	Exercise Descriptor
Monday	MD+2	Recovery	Low	Low	Technical
Tuesday	MD+3	Strength	Moderate	High	1v1-5v5
Wednesday	MD-3	Endurance	High	Moderate	6v6-11v11
Thursday	MD-2	Speed	Low	High	Tactical
Friday	MD-1	Reaction	Low	Moderate	Tactical
Saturday	MD	Game			
Sunday	MD+1	Day Off			

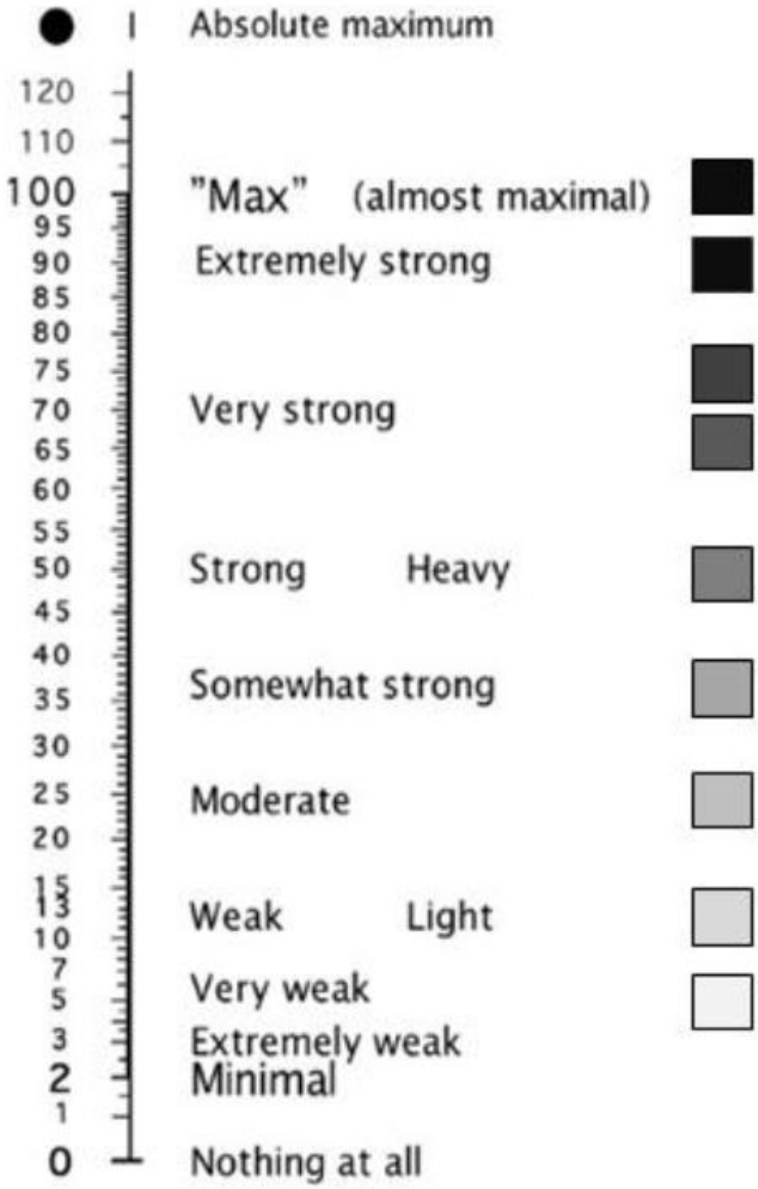

Figure 5-1: The levels of blackness corresponding to the levels of intensity on the CR100® RPE scale (as per Macpherson et al., 2019)

5.6 Results

5.6.1 RPE familiarisation

For players who completed the blackness test familiarisation session (n=20), players answered 39% questions correctly with a median (IQR) level precision of 9 (IQR, 7 to 11 AU) on the first session (Figure 5-3). In subsequent sessions, players answered 64% and 78% correctly with a median level of precision of 5 (IQR, 4 to 7 AU) and 3 (IQR, 2 to 4 AU) in sessions two and three, respectively.

5.6.2 RPE and External Load

Descriptive data for RPE and dRPE by number of accelerations, decelerations, and high-speed running are presented in Tables 5-2, 5-3, 5-4. For explorations by number of accelerations, familiarisation effects were not practically relevant for the RPE and RPE on breathlessness variables (Figure 5-3). The width and sign of the effects for the RPE-L variable at 30 acceleration efforts of 10 AU (95% CI, 4–16 AU) suggested scores were higher for players who did not undergo familiarisation versus players who completed the familiarisation (Figure 5-4). Familiarisation effects were not practically relevant for any RPE measurement irrespective of the number of deceleration efforts (Figure 5-5) and high-speed running distance (Figure 5-6) covered, respectively. Analysis of the random-effects variance components indicated the proportion of differences in RPE and dRPE scores accounted for by between-player variability was minimal regardless of the proxy measurement of external load considered in the model.

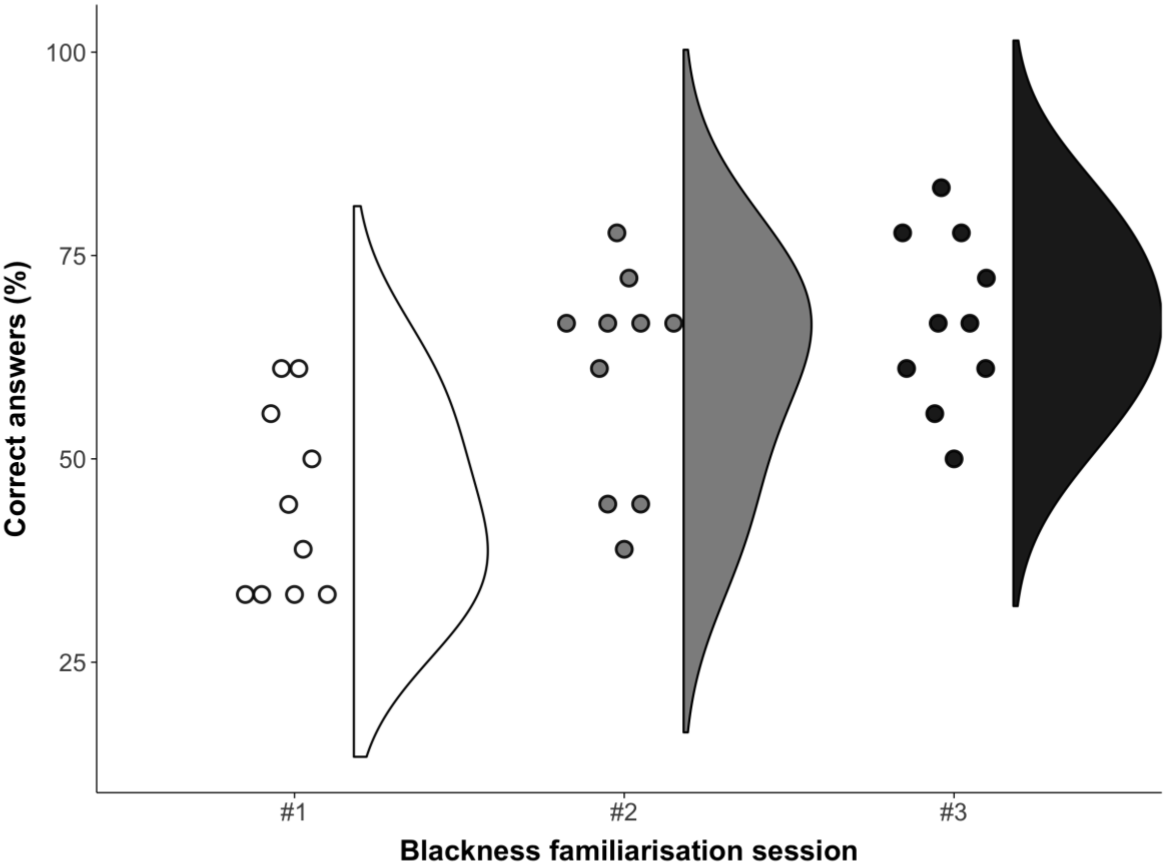

Figure 5-2: Level of correctness during blackness test

Table 5-3: Descriptive data for RPE, RPE-C, and RPE-L by number of accelerations

Effort (#)	Blackness familiarisation	RPE			RPE-B			RPE-L		
		mean	95% CI		mean	95% CI		mean	95% CI	
10	No	46	43	48	40	37	43	47	44	49
20		47	45	50	42	39	44	51	48	54
30		54	50	58	50	46	54	61	57	66
40		56	49	63	53	45	61	66	58	74
10	Yes	46	44	48	43	41	45	46	44	48
20		47	45	49	44	41	46	46	44	49
30		52	48	56	49	46	53	52	48	56
40		59	49	68	58	47	68	57	46	68

Table 5-4: Descriptive data for RPE, RPE-C, and RPE-L by number of decelerations

Effort (#)	Blackness familiarisation	RPE			RPE-B			RPE-L		
		mean	95% CI		mean	95% CI		mean	95% CI	
10	No	46	43	49	40	37	43	46	43	48
20		48	45	50	42	39	45	49	46	51
30		53	50	56	48	45	51	55	53	58
40		59	56	63	55	51	59	63	60	67
10	Yes	43	40	45	39	36	41	43	41	46
20		44	41	46	41	39	44	44	42	46
30		52	49	54	49	46	52	52	49	54
40		59	55	63	56	52	61	61	57	65

Table 5-5: Descriptive data for RPE, RPE-C, and RPE-L by HSR (>20km/h) distance covered

Distance (m)	Blackness familiarisation	RPE			RPE-B			RPE-L		
		mean	95% CI		mean	95% CI		mean	95% CI	
500	No	47	45	49	41	39	43	49	47	51
1000		55	53	57	51	48	53	57	55	59
1500		63	60	66	59	56	63	65	62	68
2000		71	67	75	67	63	72	72	68	77
2500		79	74	84	75	69	81	79	73	85
500	Yes	42	40	44	39	36	41	44	42	45
1000		57	54	59	55	52	58	56	53	58
1500		66	62	69	65	61	69	66	63	70
2000		68	62	73	68	62	73	74	69	79
2500		74	66	81	74	67	82	81	73	88

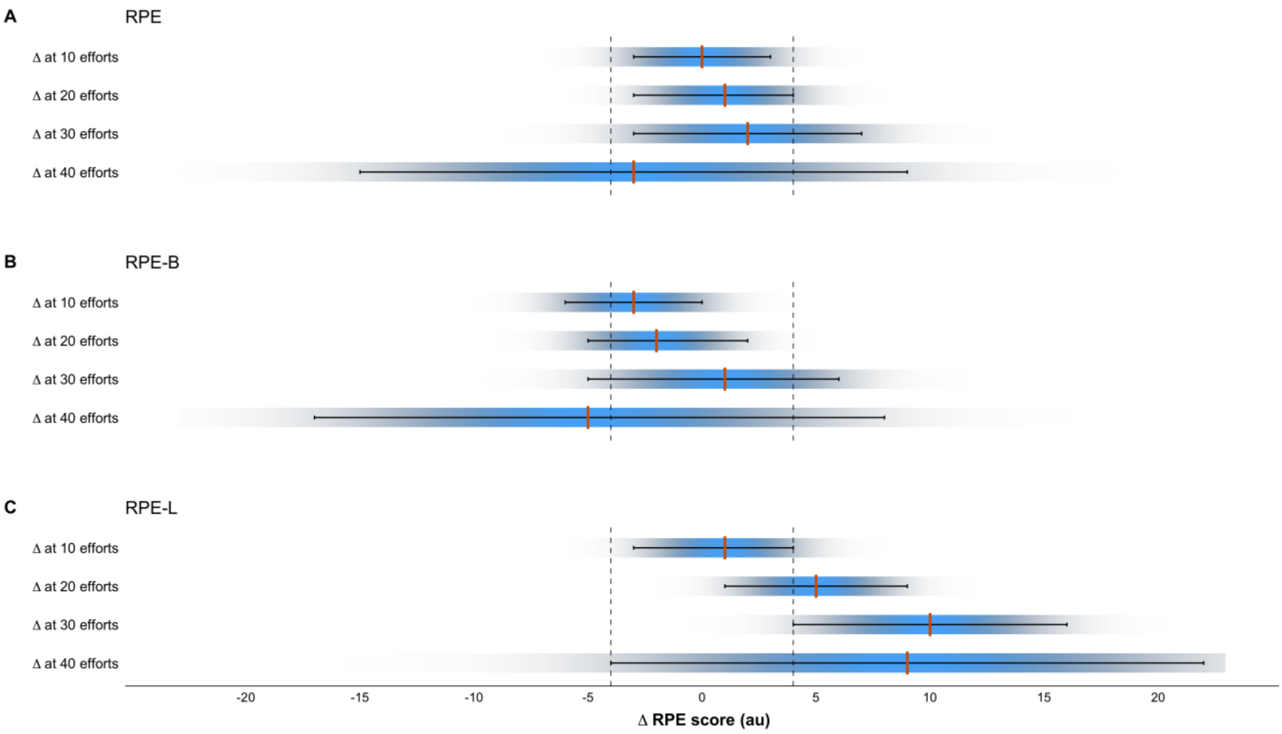

Figure 5-3: Explorations by number of accelerations for familiarisation versus no-familiarisation effects in perceived exertion

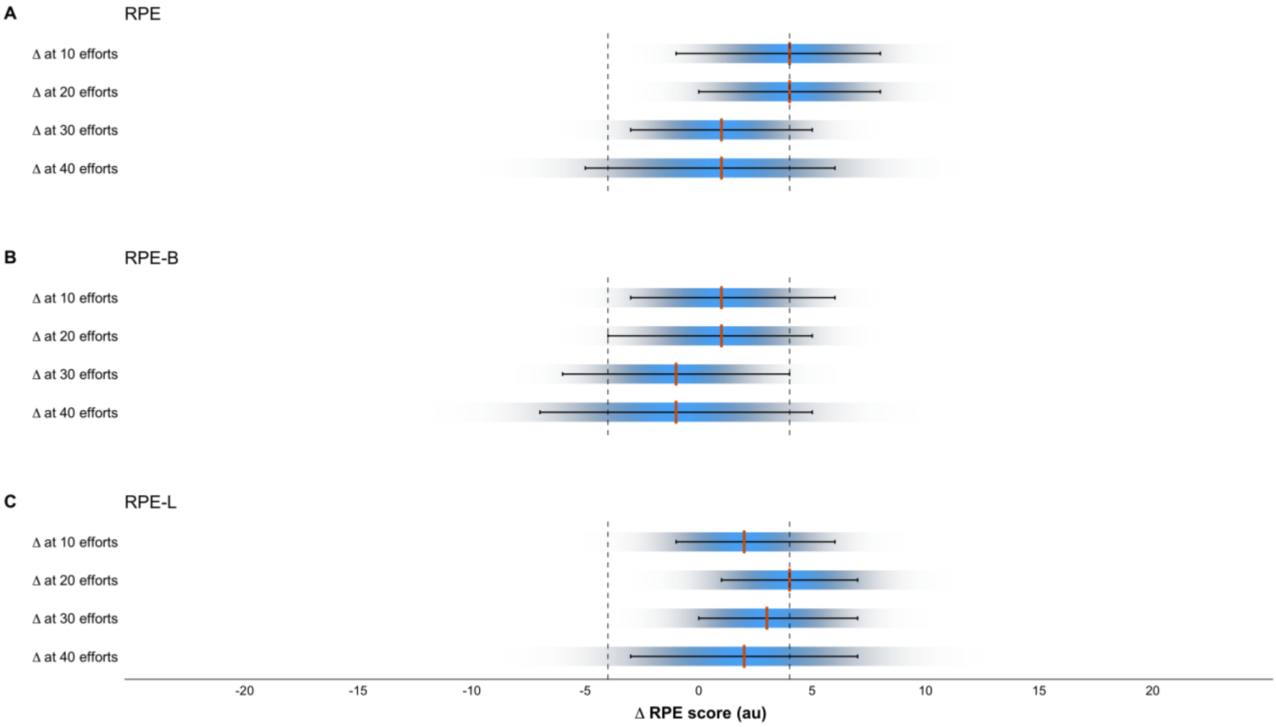

Figure 5-4: Explorations by number of decelerations for familiarisation versus no-familiarisation effects in perceived exertion

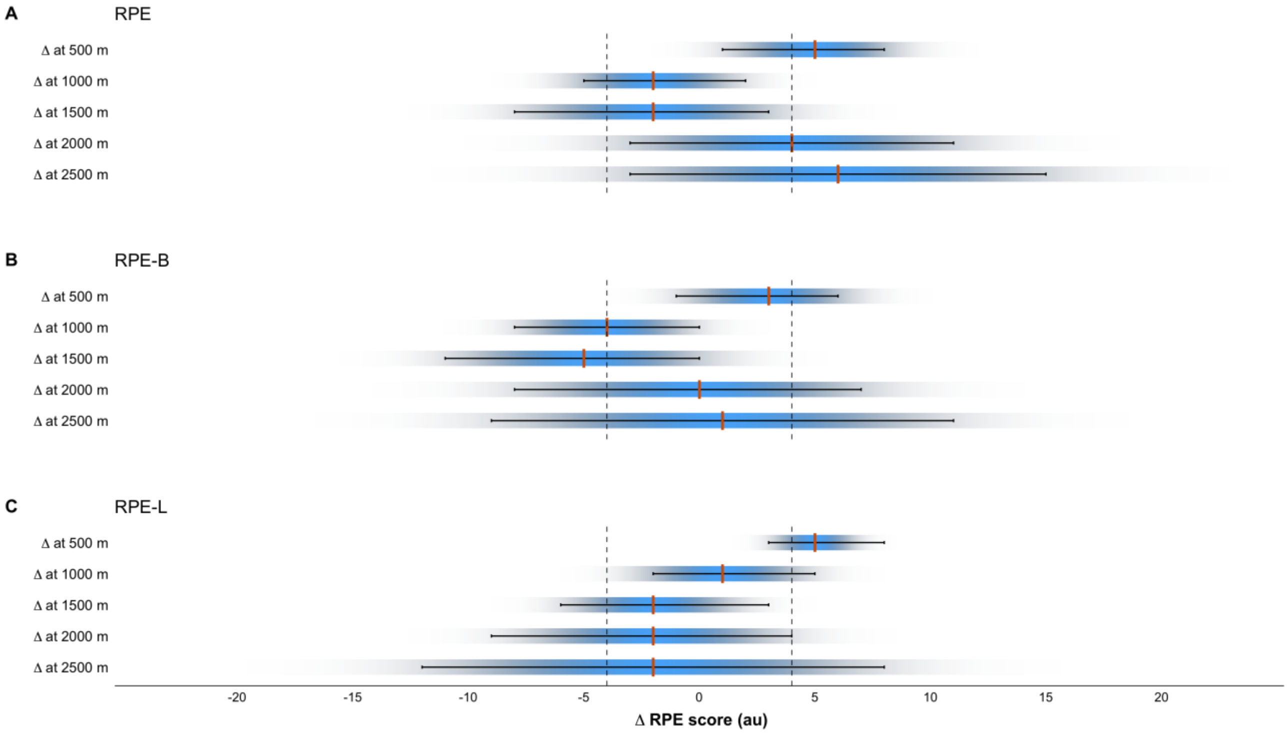

Figure 5-5: Explorations by HSR distances covered for familiarisation versus no-familiarisation effects in perceived exertion

5.7 Discussion

In team sports, the use of perceived exertion scales has now become an established approach to gather proxy measurements of internal load during training and match play (McLaren et al., 2017; Macpherson et al., 2019; Wright et al., 2020; Maughan et al., 2020). Despite its widespread application, data collection procedures relevant to RPE assessment remained underexplored. Chapter 5 provides novel information regarding the value of familiarisation on the relationship between proxy measures of external and internal load during training and match play in youth academy soccer players. Not-withstanding improved ratings on the blackness tests in this sample of players following familiarisation, chapter's 5 findings suggest the moderating effect of familiarisation on the internal-external load relationship was not meaningful.

With the objective to address current practices in youth soccer and the existing knowledge base, chapter 5 is the first to investigate how familiarisation with subjective measurement instruments of perceived exertion moderates the relationship between proxy measures of external and internal load over an extended period of training and match play. Exertion scale data-collection procedures may suffer from methodological limitations before (i.e., familiarisation) and/or during (i.e., non-validated scales) the period of data collection itself, which may hinder the validity of such data (Pageaux, 2009). In this context, modern psychophysiological theory suggests that specific strategies (e.g., standardised practices, education, and validated scales) are necessary to preserve the integrity of exertion data collection (Borg & Borg, 22001; Saw et al., 2017). However, in the clinical realm, Hutchinson et al (2020) challenged the notion of completing a formal learning trial prior to collecting valid RPE scores. Despite the different study sampling characteristics and use of the CR10 scale, our findings are consistent with this line of evidence. Conceptually, RPE principally reflects the central motor command and is deemed independent of afferent feedback (Marcora, 2009; Pageaux, 2016). Therefore, inability of familiarisation to alter the central motor command could provide a logical explanation for the lack of meaningful differences in dRPE between players who did and did not complete a prior learning trial in the present and previous studies (Hutchinson et al., 2020). In sport, Macpherson et al (2019) first explored whether preliminary familiarisation with RPE enhanced an individual's ability to understand intensity estimation via the blackness test in semi-professional soccer. Participants improved the percentage of correct answers (39%, 78%, and 83%) and precision of ratings (~7 AU, ~8 AU, and ~1 AU) over the course of 3 familiarisation sessions, respectively (Mcpherson et al., 2019). In the present study, the players had previously used unconventional, non-validated RPE scales. In line with Macpherson et al (2019) and following the same methodological procedures, players from our study sample improved the percentage of correct answers (39%, 64%, and 78%) and the precision of ratings (9 AU, 5 AU, and 3 AU) throughout the familiarisation process. Collectively, our study investigation showed familiarisation procedures can enhance players' ratings with exertional scales, although confirming the lack of an influence when compared with players who were not familiarised.

Considering the general use of RPE among practitioners in the field (Akenhead and Nassis, 2016; Saw et al., 2017), we deemed it important to explore whether the lack of familiarisation hinders the integrity of perceived exertion data. While players' education remains an important element of fundamental element of team sports monitoring strategies (Macpherson et al., 2019), the present findings suggest that coaches and practitioners may be better served by allocating time to other aspects of their monitoring strategies rather than use their time to familiarize players with the exertional measurement procedures. It is important to note that the width and sign of the effects for the RPE-L variable at 30 efforts of 10 AU (95% CI, 4–16 AU) suggested that scores were higher for subjects who did not undergo familiarisation versus subjects who completed the familiarisation process. The reasons for these differences are difficult to ascertain from the current study. Likewise, irrespective of differences in external load, the general consistency between dRPE scores (Tables 5-2, 5-3, 5-4) is another aspect of our findings suggesting the collection of RPE, as opposed to dRPE scores, remains the most plausible measurement in soccer and deserves consideration. In soccer practices, RPE-L may better measure the peripheral load imposed on players during sessions with small- sided games due to high number of accelerations and decelerations (Hampson et al., 2001; Vanrenterghem et al., 2017). The more precise nature of acceleration movements in small spaces may possibly be more difficult to gauge for the less familiarised players. Further work, however, is required to elucidate this using training scenarios which enable closer examination of the role of familiarisation processes on dRPE responses.

From a general standpoint, a key limitation of chapter 5 stems from the description of familiarisation effects on dRPE scores without accounting for session type (Maughan et al., 2020; Houtmeyers et al., 2022). Training periodisation in soccer during the competition phase is typically centred around structuring the weekly micro-cycle to facilitate recovery while developing/maintaining the key physical components of strength, speed, and endurance. Future work examining the association between these session types and dRPE offers a way to further examine the utility of dRPE for monitoring internal intensity and load in football. Likewise, the interpretation of the differences we estimated against a predefined range of equivalence from -4 AU to +4 AU requires consideration since illustrated and generalized, for the first time, in a study involving youth female soccer players (Wright et al., 2020). Also, the conceptual definition and elaboration of dRPE measurement scores in our investigation are another aspect deserving attention. While in keeping with existing literature in this field (De Vet et al., 2011), formal and distinct assessment of dRPE measurements rests on assuming perceived exertion as a multidimensional construct that, by definition, can be measured using scale instruments on a reflective model framework basis (De Vet et al., 2011). In that context, the items are generally summed up (De Vet et al., 2011). Conversely, in a formative model, each item contributes a part of the construct, and together the items form the whole construct with different procedures available to derive sum scores or overall scores (De Vet et al., 2011). Considering this chapter design and procedures, exploratory investigation lends support to considering perceived exertion as a formative construct that, in samples of soccer players, can be assessed using conventional measurement approaches previously illustrated in the exercise physiology literature (Borg, 1982).

Despite general recommendations concerning the implementation of education tools like the Borg blackness test to enhance awareness of athletes and coaches when using exertional scoring, our findings question the worthwhileness of this practice in elite youth academy soccer players. While players improved their ratings on the blackness test, this improvement did not translate to the practical environment as the internal-external load relationship was largely consistent for all RPE scores irrespective of familiarisation or no familiarisation. Therefore, we maintain that practitioners can focus on other tasks that would potentially help them enhance their training-load-monitoring strategies rather than investing time and resources to familiarise their players with the exertional measurement procedures.

CHAPTER 6: ASSOCIATIONS BETWEEN INDICATORS OF INTERNAL AND EXTERNAL LOAD (DOSE-RESPONSE RELATIONSHIP) IN YOUTH SOCCER PLAYERS

This study was presented as an oral communication at the 31st Isokinetic Medical Group Conference, Madrid, Spain 2024

6. Associations between indicators of internal and external load (dose-response relationship) in youth soccer players

6.1 Introduction

In the high-performance environment of modern soccer, monitoring training load has become a fundamental aspect of athlete management and performance optimisation (Akenhead & Nassis, 2016; Impellizzeri et al., 2019). Given the multifaceted physical and physiological demands of the sport, effective load monitoring enables practitioners to balance training intensity, manage fatigue, reduce injury risk, and support long-term athletic development (Malone et al., 2017). External load refers to the objective quantification of work performed by the athlete, such as total distance covered and sprint count (Impellizzeri et al., 2019). In contrast, internal load reflects the individual's physiological and perceptual responses to these external demands, assessed through markers such as ratings of perceived exertion (RPE) (Viru & Viru, 2000; Impellizzeri et al., 2019).

Despite the widespread recommendations for formal psychometric evaluation of subjective measurement tools, Chapter 5 questions the value of this practice when applied to elite youth soccer players, suggesting that practitioners can focus on other tasks that would potentially help them enhance their training load monitoring strategies. In the absence of any 'gold standard' criterion measure of internal load (Vanrenterghem et al., 2017), examining the internal-external load relationship can provide evidence for construct validity and sensitivity of a chosen training load measure (Castillo et al., 2017). Understanding the associations between internal and external training loads can support training prescription, periodisation, and player management, particularly since the mode of training influences the dose-response relationship (McLaren et al., 2018).

In soccer, in-season training is typically planned around match days, with higher volume and intensity intermittent exercise training occurring mid-week, while lower volume, lower-intensity sessions are performed toward the end of the week (Malone et al., 2015; Walker & Hawkins, 2017; Martin Garcia et al., 2018). This structure necessitates significant adjustments in the work-rest ratio to achieve the desired training adaptations (Zanetti et al., 2022; Dios-Alvarez et al., 2024). Consequently, the effectiveness of any load measure under such conditions is largely determined by its ability to account for diverse load-adaptation pathways (Vanrenterghem et al., 2017).

Alongside the mode of training, individual differences in physiological capacity may also influence the internal-external load relationship (McLaren et al, 2018). External load in soccer is frequently analysed as time spent in arbitrary speed zones, however, this approach fails to account for differences in the individual capacity of players (Abt and Lovell, 2009; Hunter et al, 2014; Freeman et al., 2023). To address these limitations, external load is often expressed relative to an individual player's physical capacities (Abt and Lovell, 2009; Villanueva et al., 2013; Abbot et al., 2018; Scott & Lovell, 2018). Scott and Lovell (2018) reported similar relationships between external load measures and internal load (heart rate metrics and RPE) for both absolute speed zones and zones anchored to players' maximum sprinting speed (MSS), concluding that individualised speed thresholds do not enhance the dose-response relationship in soccer. Nonetheless, the study's short duration (3 weeks, pre-season) and lack of session-type analysis highlight the need for further research. To date, no study has examined the associations between internal-external load (dose-response relationship) when using individualised external loads in elite soccer players.

As outlined in Chapter 3, session rating of perceived exertion (sRPE) is a widely adopted method for monitoring internal load in team sports. However, its utility is constrained by a lack of sensitivity needed to capture the full spectrum of exertional signals during team sports (Weston, 2013). This limitation has led to the development and increased use of differential ratings of perceived exertion (dRPE), which address the need for a more detailed assessment by separating perceived exertion into distinct categories: breathlessness (RPE-B) and leg fatigue (RPE-L) (Weston et al., 2015; Wright et al., 2020; Maughan et al., 2020; Houtmeyers et al., 2022). Despite the increased use of dRPE, its efficacy in enhancing the dose-response relationship in soccer remains questionable, especially when assessing external load using absolute thresholds (chapter 5; Maughan et al., 2020; Houtmeyers et al., 2022). In the same line, Chapter 5 demonstrated that although players improved their scores on the Blackness Test, these enhancements did not translate meaningfully into applied settings. Specifically, the relationship between internal and external load using absolute thresholds remained largely stable across all RPE scores (global RPE, RPE-B, RPE-L), regardless of whether participants had undergone familiarisation. Inconsistent findings are also evident when examining the relationship between external load and dRPE when accounting for mode of training (McLaren et al, 2017; Houtmeyers et al., 2022). McLaren and colleagues (2017) found positive associations between sRPE and sRPE-L for high-intensity intervals ($r = 0.67$; 90% confidence limits ±0.22) and sRPE-B for repeated high-intensity efforts (0.89; ±0.08). On the contrary, Houtmeyers et al., (2022) reported that players rated sRPE-B and sRPE-L differently in just 22% of the sessions with no pattern in the direction of differentiation. To date, no study has investigated the associations between internal and external load across various field-based training modalities in elite youth soccer players, using absolute and relative external load measures alongside indicators of internal load (global RPE, dRPE).

The aims of chapter 6 were:

a) Assess the agreement between absolute and relative speed threshold methods for quantifying HSR distance across different session types in elite youth soccer players.

b) Examine the associations between internal and external load (dose-response relationship), by assessing session type-specific differences in perceived exertion (RPE, dRPE) at predefined absolute and relative high-speed running distances in elite youth soccer players.

6.2 Methods

6.3 Participants

Participants utilised in Chapter 5 were also used for the purpose of this Chapter. As part of this exploratory study, a practical approach was adopted to refine the dataset. Only players who participated in a minimum of five training sessions per session type (strength, endurance, speed, reaction, game) were included. The final sample consisted of thirteen elite male youth soccer players (age: 17.1 ± 0.9 years, body mass: 69.2 ± 5.3 kg, height: 1.78 ± 0.5 m). These players completed approximately five training sessions per week over a 31-week period, covering the latter part of the 2019-20 season, pre-season, and the start of the 2020-21 season. The sample included central defenders (n=2), wide defenders (n=2), central midfielders (n=4), wide midfielders (n=3) and strikers (n=2). Data was exclusively derived from team field-based training sessions, with individual rehabilitation or fitness sessions excluded from the analysis. For ethics information refer to chapter 5 section 3.

6.4 Experimental Design

The research design used in Chapter 5 was adopted for the purpose of this Chapter. Please refer to chapter 5 section 4.

6.4.1 Physical testing battery

As data were collected during two phases, the day prior to start soccer training, each athlete completed a maximal sprinting speed (MSS) and maximal aerobic speed (MAS) protocols to determine peak speed and estimate vVO2max, respectively. The MSS and MAS protocols were previously utilised by other studies that investigated the usefulness of relative thresholds on elite soccer players (Mendez-Villanueva et al., 2013; Hunter et al., 2015; Abbiot et al., 2018). MSS was defined as the fastest speed over two maximal 40-m linear sprints, with full rest in between. Speeds were recorded by 10-Hz GPS which was previously proved to be equivalent to a gold standard measure (laser gun) (Chapter 3). Players' MAS was estimated using a modified version of the Montreal Track test (VAM-EVAL). Players ran around a 200 m track on a grass field, commencing at 8 km·h−1, with 0.5 km·h−1 speed increments applied every minute thereafter. Running pace was determined with an audio MP4, with compliance to the pace determined at 20 m intervals. Players ran until either exhaustion, or three consecutive cones were missed. MAS was estimated as the speed of final 1-min stage completed by the athlete. Testing protocols were completed on the same grass surface and footwear used throughout the investigation and the reliability of these protocols, as applied within our research setting, has been previously established (chapter 3, Kyprianou et al., 2019, Lolli et al., 2022).

6.4.2 Relative bands calculation

Using MSS and MAS scores, each athlete's theoretical ASR was calculated. ASR was defined as the difference between the MSS and MAS score. As relative bands, we used five running intensity zones (Villanueva et al., 2013) to describe each player's individual external load in the training and matches: speed zone 1 (S1): below 60% of MAS, speed zone 2 (S2): from 61% to 80% of MAS, speed zone 3 (S3): from 81% to 100% of MAS, speed zone 4 (S4): from 101% of MAS to 30% of Anaerobic Speed Reserve (ASR) and, speed zone 5 (S5): above 31 % of ASR.

6.4.3 Training Sessions

All training & match activity were monitored as described in chapter 5, section 4.2.

6.5 Statistical analysis

The analysis framework of this study involved a two-step approach. First, we assessed between-method agreement for the quantification of HSR distance determined using absolute and relative speed thresholds approaches (Bland & Altman, 2007). With analyses conducted by game, strength, endurance, and speed session types, the Bland-Altman method for the analysis of repeated pairs of HSR distance measurements on the same youth player estimated the mean bias, standard deviation (SD), and the limits of agreement describing the expected range of differences between absolute versus relative high-speed running distance for 95% of pairs of future similar training sessions (Bland & Altman, 2007). Analyses were designed on the assumption the true difference value for measurements pairs on different sessions may vary (Bland & Altman, 2007; Zou, 2013), with the uncertainty surrounding the point estimate for each limit of agreement described as 95% confidence interval (CI) using the method of variance estimates recovery (Zou, 2013). Summary data for HSR distance covered by session type and determination method were presented as median and interquartile range (IQR).

Second, distinct random-effects generalized additive models with restricted maximum likelihood assessed session type-specific differences in perceived exertion at pre-specified values of absolute and relative HSR, respectively (Wood, 2017). Existing literature in this field informed considerations of high-speed running distance to justify its inclusion in the model as primary proxy variable of external load relevant to soccer performance (Gaudino et al., 2015; Akenhead & Nassis, 2016). Separate models included the raw RPE score (au) as the response variable, session type as a categorical fixed effect, a smooth term for the absolute or relative high-speed running distance variable set at 5 basis functions, a session type × absolute or relative high-speed running distance interaction term plus session duration and participant-specific random effects penalized by a ridge penalty. Following visual inspection of each model residuals as postestimation diagnostics (Fasiolo et al., 2020), effects were summarised as estimated marginal means with density strips illustrating the degree of uncertainty surrounding the point estimates and reported as 95% confidence interval (CI) (Bowman, 2019; Fasiolo et al., 2020). Session type-specific differences in perceived exertion by absolute or relative HSR distance were declared practically relevant if the location of the 95%CI for the mean estimate exceeded the predefined region of equivalence ranging from -4 au to +4 au (i.e., target value = 8 au) for all RPE scores (Wright et al., 2020). Statistical analyses were conducted using SAS OnDemand for Academics (SAS Institute, Inc., Cary, NC, 2011) and R (version 3.6.3, R Foundation for Statistical Computing).

6.6 Results

6.6.1 Absolute versus relative high-speed running determination

Table 6-1 illustrates summary information for HSR distance covered by session type. The lower and upper limits of agreement (Figure 6-1) relevant to the session type-specific mean absolute versus relative HSR bias of 437 m (95%CI, 321 to 552 m), 176 m (95%CI, 129 to 223 m), 268 m (95%CI, 186 to 350 m), 173 m (95%CI, 125 to 221 m) ranged from -99 m (95%CI, -356 to 47 m) to 972 m (95% CI, 826 to 1229 m) for game (Figure 6-1A), from -36 m (95%CI, -143 to 22 m) to 389 m (95% CI, 330 to 495 m) for strength (Figure 6-1B), from -63 m (95%CI, -260 to 47 m) to 599 m (95% CI, 489 to 796 m) for endurance (Figure

6-1C), and from -84 m (95%CI, -186 to -24 m) to 431 m (95% CI, 371 to 533 m) for speed (Figure 6-1D) session types, respectively.

The limits of agreement method SD for game-, strength-, endurance-, and speed-specific session types was ±273 m, ±109 m, ±169 m, and ±131 m, respectively (Figure 6-1). Regardless of the session type-specific between-method comparison of interest, visual inspection of each plot would indicate the presence of a clear proportional bias. Specifically, paired between-method measurement differences were more precisely positive in sign and heterogeneous as a function of the mean absolute and relative high-speed running distance (x-axis). The absolute widths for the limits of agreement ranged from ~214 m to ~536 m (Figure 6-1).

6.6.2 Differential perceived exertion by session type

Estimated marginal means for RPE, RPE-B, and RPE-L by HSR (>20 km·h−1) distance determined by absolute and relative speed thresholds are illustrated in Table 6-2 and Table 6-3. For session type-specific comparisons, effects were consistently more uncertain for generally higher absolute (Figure 6-2) and relative (Figure 6-3) HSR distances due to data sparsity.

For explorations with global RPE as response variable, visual inspection of the density strips surrounding the mean estimate suggested no effect clearly exceeded the predefined region of equivalence regardless of the HSR quantification method (Figures 6-2, 6-3). The mean difference in global RPE for game versus endurance session type comparison was 11 au (95%CI, 3 to 18 au) at 500 m of absolute HSR (Figure 6-2). Game versus speed session type mean differences in global RPE by absolute (Figure 6-2) and relative (Figure 6-3) HSR at 500 m were 11 au (95%CI, 3 to 19 au) and 12 au (95%CI, 3 to 20 au), respectively.

For explorations with RPE-B as response variable, density strips suggested most of the estimated effects were broadly uncertain and not practically relevant (Figure 6-2, 6-3). With relative HSR distance as predictor variable in the model, mean differences in perceived breathlessness for game versus endurance and game versus speed session type comparisons at 500 m were 12 au (95%CI, 3 to 20 au) and 10 au (95%CI, 2 to 19 au), respectively (Figure 6-2).

For explorations with RPE-L as response variable, density strips indicated some clear and practically relevant effects mostly at HSR distances of 500 m (Figure 6-2, 6-3). At absolute HSR of 500 m, mean differences in perceived leg-muscle exertion for game versus endurance and game versus speed session type comparisons were 15 au (95%CI, 4 to 27 au) and 14 au (95%CI, 4 to 24 au), respectively (Figure 6-2). The strength versus endurance session type comparison at 500 m of absolute high-speed running distance (Figure 6-2) revealed a mean difference in perceived leg-muscle exertion of 9 au (95%CI, 3 to 16 au). At relative HSR distances of 500 m, mean differences in perceived leg-muscle exertion for game versus endurance and game versus speed session type comparisons were 16 au (95%CI, 8 to 25 au) and 13 au (95%CI, 4 to 22 au), respectively (Figure 6-3). The mean difference in perceived leg-muscle exertion for game versus endurance at 1000 m of relative HSR (Figure 6-3) was 15 au (95%CI, 4 to 26 au).

Table 6-1: Summary information for high-speed running distance covered by session type

Session Type	High-speed running distance (m) [a]			High-speed running distance (m) [b]		
	Median	Interquartile range		Median	Interquartile range	
Game	1202	906	1517	771	511	1007
Strength	367	278	510	199	120	283
Endurance	657	547	876	410	282	554
Speed	456	328	659	310	213	448

Interquartile range denotes 25th and 75th percentiles, respectively.

[a], denotes distances covered in predefined absolute speed zones; b, denotes distances covered in relative speed zones as per individual-participant maximal sprinting speed test score.

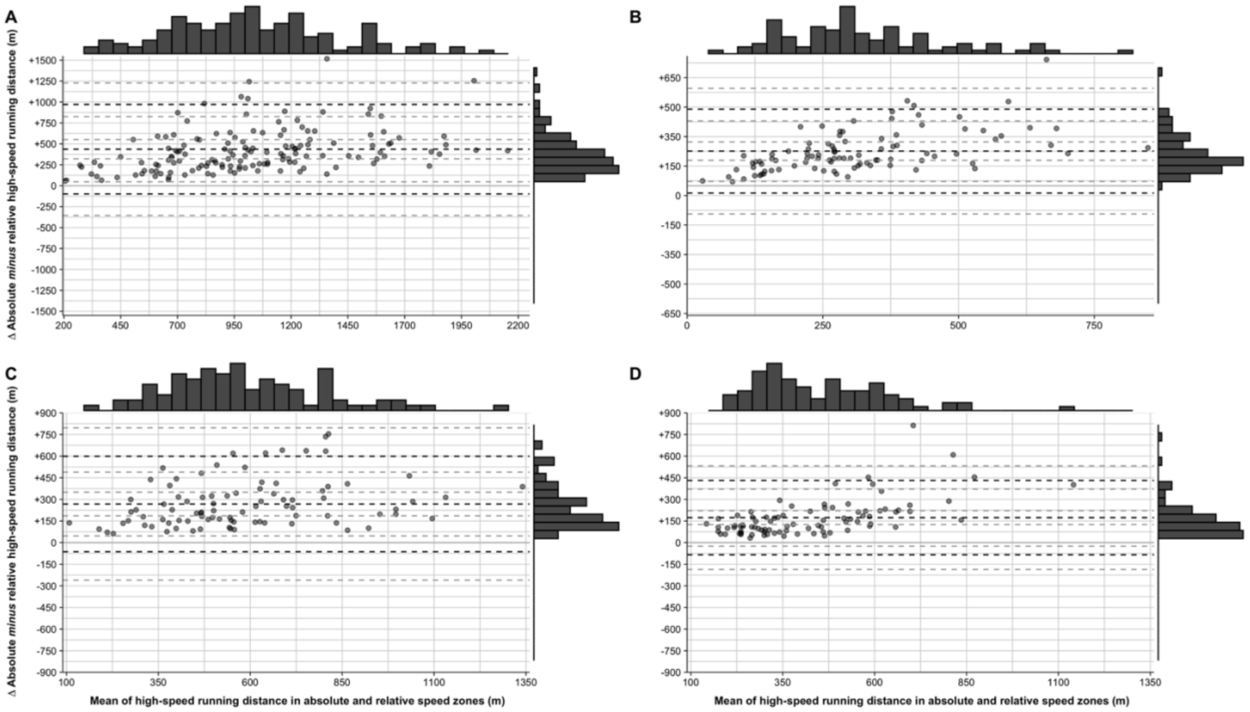

Figure 6-1: Bland-Altman method for the analysis of repeated pairs of HSR distance. The limits of agreement method SD for game-, strength-, endurance-, and speed-specific session types was ±273 m, ±109 m, ±169 m, and ±131 m, respectively

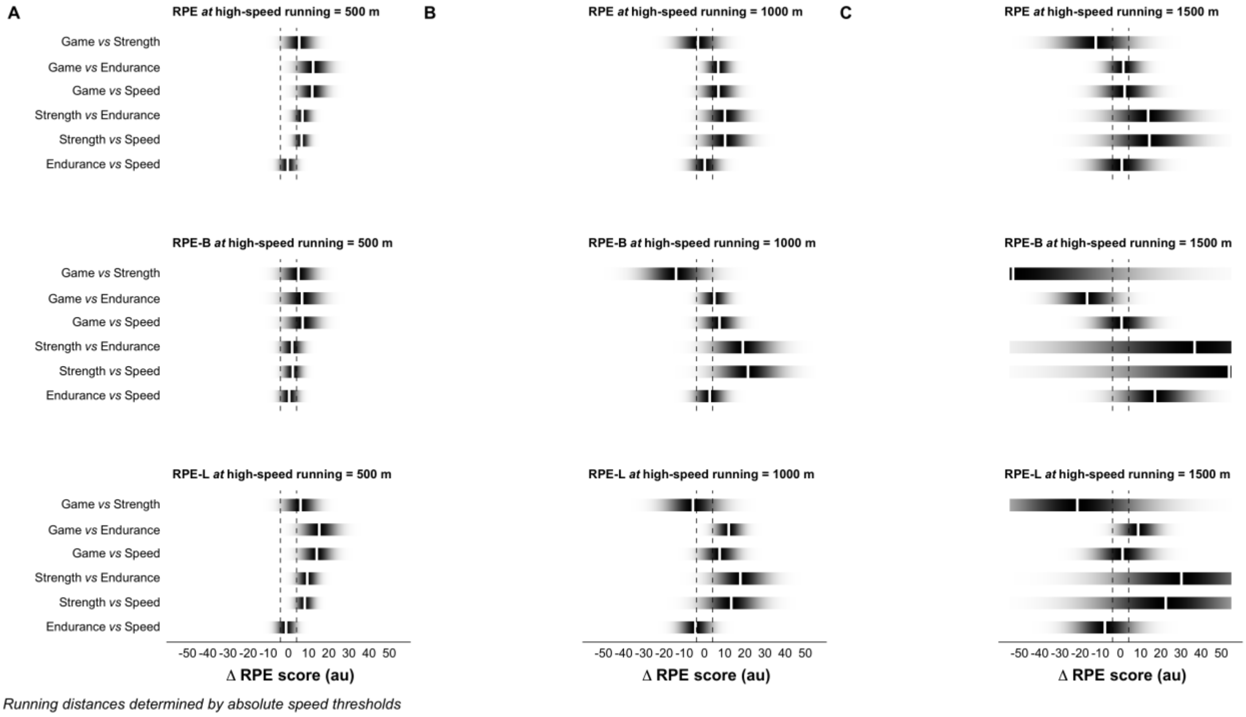

Figure 6-2: Session type-specific differences in perceived exertion by absolute HSR distance and uncertainty for the difference (95% confidence interval). The black vertical dashed lines represent the predefined region of equivalence ranging from -4 au to +4 au (i.e., target value = 8 au) for all RPE scores (Wright et al., 2020)

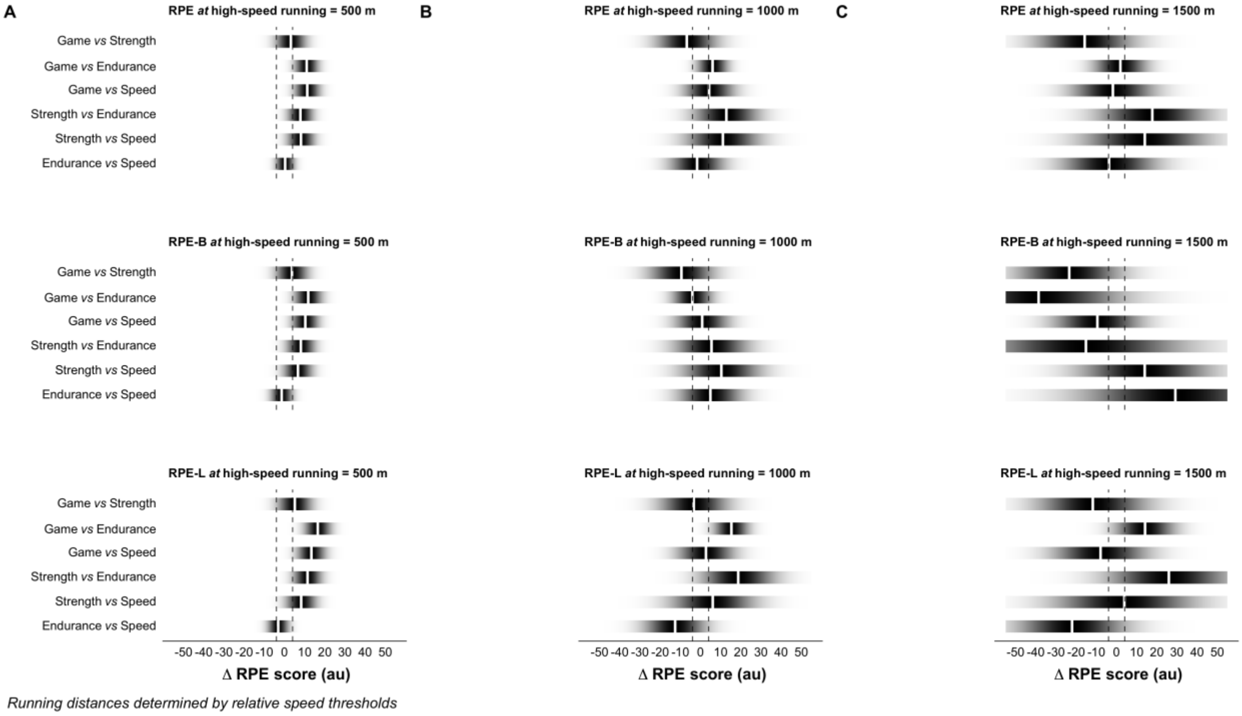

Figure 6-3: Session type-specific differences in perceived exertion by relative HSR distance and uncertainty for the difference (95% confidence interval). The black vertical dashed lines represent the predefined region of equivalence ranging from -4 au to +4 au (i.e., target value = 8 au) for all RPE scores (Wright et al., 2020)

Table 6-2: Estimated marginal means for RPE, RPE-B, and RPE-L by HSR (>20 km·h^{-1}) distance determined by absolute speed thresholds

Distance	Session Type	RPE (au)			RPE-B (au)			RPE-L (au)		
		mean	95%CI		mean	95%CI		mean	95%CI	
500	Game	58	50	66	48	39	58	61	53	70
	Strength	53	49	56	43	39	48	55	51	60
	Endurance	46	41	50	42	37	47	46	41	51
	Speed	46	43	50	41	38	45	47	44	51
1000	Game	62	58	66	58	54	63	64	59	69
	Strength	65	54	76	72	54	91	70	54	86
	Endurance	55	50	60	54	48	59	52	46	58
	Speed	55	47	63	51	42	60	57	47	66
1500	Game	66	63	69	61	57	65	67	63	70
	Strength	78	55	101	*	*	*	*	*	*
	Endurance	64	54	75	78	60	96	58	46	70
	Speed	64	48	79	61	44	77	66	48	83

Abbreviations: RPE, session ratings of perceived exertion score; RPE-B, session ratings of perceived exertion on breathlessness score; RPE-L, session ratings of perceived exertion on legs score. *denotes value could not be estimated due to data sparsity.

Table 6-3: Estimated marginal means for RPE, RPE-B, and RPE-L by high-speed running (>20 km·h^{-1}) distance determined by relative speed thresholds

Distance	Session Type	RPE (au)			RPE-B (au)			RPE-L (au)		
		mean	95%CI		mean	95%CI		mean	95%CI	
500	Game	61	56	66	56	51	62	65	59	71
	Strength	58	51	65	53	45	60	60	51	68
	Endurance	50	46	54	45	39	50	48	44	53
	Speed	50	45	55	46	41	51	52	46	57
1000	Game	66	62	69	61	58	65	67	63	70
	Strength	72	54	91	71	51	91	70	49	91
	Endurance	60	50	69	65	53	77	52	41	62
	Speed	61	46	77	60	44	77	64	47	82
1500	Game	71	64	78	65	58	72	69	62	76
	Strength	87	56	118	*	*	*	81	46	115
	Endurance	69	53	85	*	*	*	55	37	73
	Speed	73	46	99	75	47	103	77	47	107

Abbreviations: RPE, session rating of perceived exertion; RPE-B, ratings of perceived exertion on breathlessness; RPE-L, ratings of perceived exertion on legs. * denotes value could not be estimated due to data sparsity.

6.7 Discussion

In team sports, understanding the associations between internal and external training loads (dose-response relationship) can assist practitioners in better managing their athletes' readiness (McLaren et al., 2018). However, factors such as individual differences in physiological capacity (e.g., maximal sprinting speed) and training mode (e.g., session type) can influence the associations between internal and external load (Chapter 5; McLaren et al., 2018). This chapter is the first to examine the dose-response relationship using individualised speed thresholds and measures of internal load (global RPE, dRPE) across a range of field-based training modalities in soccer players. We observed that RPE-L is more sensitive to different modes of training than RPE-B, but it provides information consistent with global RPE, independent of whether absolute or individualised speed thresholds are used to measure external load.

Expressing external load relative to players' individual physical capacity has been undertaken to overcome the limitations of using absolute speed zones (Villanueva et al., 2013; Abt & Lovell, 2014; Abbot et al., 2018; Abt & Lovell, 2019). The present findings confirm previous observations that higher HSR distances are recorded when using absolute speed zones compared to relative zones, irrespective of session type (Scott & Lovell, 2018). We observed session-type-specific mean absolute versus HSR bias of 437 m (95% CI, 321 to 552 m), 176 m (95% CI, 129 to 223 m), 268 m (95% CI, 186 to 350 m), and 173 m (95% CI, 125 to 221 m) for game, strength, endurance, and speed sessions, respectively. When expressed as relative HSR distance, substantially lower median HSR distances were observed during strength (168 m), endurance (247 m), and speed (146 m) sessions. Given that relative thresholds are likely more important for optimising physiological adaptation at the individual player level, as they account for inter-individual variability (Gualtieri et al., 2023), practitioners should consider the practical implications of these values when planning training sessions. In contrast, absolute thresholds remain prevalent in applied practice due to their simplicity, ease of implementation, and utility in standardising performance metrics across individuals and teams (Malone et al., 2017). A comprehensive training analysis should incorporate both absolute and relative thresholds, with practitioners possessing a clear understanding of their contextual application. Such insights support more precise training prescriptions and individualised recovery strategies (Gabbett et al., 2015; Malone et al., 2017).

The present study examined whether individualising HSR determination influenced the relationship with global RPE across a range of field-based training modalities. Chapter's 6 findings demonstrated that global RPE in response to external load remained similar whether analysed using absolute or relative speed zones. Additionally, global RPE did not differentiate between sessions with varying physiological emphases, indicating it lacks the sensitivity required to capture the full spectrum of exertion signals during games or specific types of training sessions. These findings are consistent with previous observations which suggest while global RPE provides a global measure of intensity, it may lack sensitivity to cover the range of different exertion signals that arise during exercise (Hutchinsona & Tenenbaum, 2006; Weston, 2015). For example, Scott and Lovell (2018) found that individualising speed thresholds did not significantly enhance the understanding of dose-response relationship in elite soccer female players during a 21-day training camp. Associations between the HSR and RPE and were generally large to very-large, irrespective of the individualisation approach (Scott & Lovell, 2018).

Differential RPE (dRPE), which separates ratings for perceived central and peripheral exertion, is proposed to provide practitioners with a valid measurement of players physiological (i.e. cardiovascular) and biomechanical (i.e. musculoskeletal and neuromuscular) internal loads (Weston et al., 2015; Wright et al., 2020; Maughan et al., 2020; Houtmeyers et al., 2022). In the present study, visual inspection of the density strips surrounding the mean estimate, with RPE-B as a response variable, suggested most of the estimated effects were broadly uncertain and not practically relevant (i.e., did not exceed the target value of 8 au). This indicates RPE-B is not sensitive to changes in physiological stress elicited by different types of training irrespective of whether absolute or relative speed bands are used. Our results are not consistent with the findings reported in a previous study on professional rugby players, which showed that distinct training typologies elicit different dRPE, and the use of RPE-B may isolate the specific perceptual demands of training using absolute thresholds (McLaren et al., 2017). On the contrary, our findings are in line with previous studies on professional soccer players (Maughan et al, 2020; Houtmayers et al., 2022), which concluded RPE-B provides no evidence for the relationship between RPE-B and external load using absolute thresholds. This discrepancy may be attributed to the fact that exercise-induced hyperventilation, which is closely associated with the perception of breathlessness, arises from the body's efforts to compensate for lactic acidosis during anaerobic exercise. This condition likely influences perceptions of leg-muscle exertion. As a result, derived dRPE, specifically RPE-B, may struggle to differentiate between these overlapping exercise signals (Houtmeyers et al., 2022). Furthermore, factors such as the type of sport (rugby vs. soccer), target age group (youth vs. senior), study duration (few weeks vs. full season), and gender can all influence study outcomes (McLaren et al., 2017; Wright et al., 2020; Maughan et al, 2020; Houtmayers et al., 2022). This variability helps explain why some studies demonstrate that

RPE-B is sensitive, while others do not. Therefore, further research is necessary to better understand how these factors influence the sensitivity of RPE-B across different contexts.

In contrast to RPE-B, for explorations with RPE-L as response variable, density strips indicated some clear and practically relevant effects mostly at HSR distances of 500 m using both absolute and relative HSR classifications. At these distances, we observed differences in RPE-L for game versus endurance and speed sessions (15 au/14 au and 16 au/13au respectively), whereas the strength versus endurance at absolute HSR of 500m revealed a mean difference of 9 au (95%CI, 3 to 16 au). Our findings align with previous studies demonstrating the relationship between RPE-L and external load using absolute thresholds (McLaren et al., 2017; Wright et al., 2020). McLaren et al., (2017) investigating the relationship between sRPE-L and different training type sessions found strong associations between sRPE-L and high-intensity intervals (r = 0.67; 90% confidence limits ±0.22). They employed intermittent bouts of very-short sprints (<10 seconds) executed at high to maximal intensities, which closely resemble the training modalities utilised in our study. Furthermore, Wright and colleagues (2020), reported possibly trivial to most likely extremely large differences for between all different session type comparisons for RPE-L. In strength type sessions, RPE-L was rated significantly harder (-13 au) than RPE-B reflecting of the nature of this training typology and its biomechanical exertion gestures (Wright et al. 2020). Although global RPE in our study did not differentiate between session type, and mean estimate difference did not reach our pre-defined region of equivalence (target value = 8 au); the observed values were near this threshold. Specifically, the comparison of game versus endurance session type revealed a mean difference of 11 au (95% CI, 3 to 18 au) for 500 m of absolute HSR. In contrast, the comparison of game versus speed session type showed mean differences in global RPE of 11 au (95% CI, 3 to 19 au) for absolute HSR and 12 au (95% CI, 3 to 20 au) for relative HSR over the same distance.

This suggests that global RPE and RPE-L are largely consistent with each other. This finding aligns with previous research (Maughan et al., 2020; Houtmeyers et al., 2022), which indicates that derived dRPE do not offer distinct information beyond that provided by global RPE. As RPE-L specifically targets peripheral exertion, typically associated with muscular fatigue and neuromuscular stress, it has the potential to provide a more nuanced view of localised load, especially in sessions that emphasise strength, sprinting, or eccentric loading (Weston et al., 2015; Houtmeyers et al., 2022). Therefore, further research is required to investigate the use of RPE-L and examine its relationships with both objective neuromuscular load indicators and subjective perceptions of muscular fatigue.

The findings presented in this chapter provide a novel and practical approach to evaluate session type-specific variations in perceived exertion, grounded in predetermined thresholds of absolute and relative high-speed running distances. This technique provides practitioners with valuable insights into the associations between internal and external loads. In our study, we observed greater high-speed running distances when utilising absolute speed zones compared to relative ones, regardless of session type. Additionally, derived dRPE measures do not provide additional insights beyond those offered by global RPE, irrespective of the use of absolute or relative thresholds. Consequently, practitioners can confidently employ global RPE as an effective tool for monitoring players' internal responses to external training loads in their daily practices.

CHAPTER 7: SYNTHESIS OF FINDINGS

7. Synthesis of Findings

The aim of this chapter is to interpret and synthesise the findings presented within the current thesis. The possible applications and limitations of the studies outlined will be discussed. The realisation of aims will be confirmed before a review of the original hypotheses will be focussed upon. The following general discussion and conclusion sections will provide interpretations of the individual studies in relation to the quantification of the physical demands of training and match-play in elite youth soccer players.

7.1 Realisation of aims

The experimental sections of this thesis have fulfilled all the aims stated in Chapter 1. A novel methodological approach to the assessment of validity of MSS data collected from a criterion (100-Hz Laser) and non-criterion measurement tool (10-Hz GPS) was initially determined (Aim 1). Equivalence testing, using the median acceptable amount of measurement error with bounds informed by surveyed experts on the measurement of MSS showed Laser and GPS as likely equivalent measures. The hypothesis of whether MSS occurs during sprint testing or during typical soccer training activities and competitive matches was then examined (Aim 2). Data showed the necessity for 40-m sprint testing to determine players MSS, as the sprint speed attained during testing was greater compared with matches and typical soccer training activities.

Having established the validity of methods used to derive external load metrics (Chapter 3) and analysed these metrics across various training modalities and match-play (Chapter

4), attention was shifted towards examining players' internal load responses to training. In Chapter 5, the moderating effect of familiarisation with the CR100 scale on RPE anchored against proxy measures of external load during training and matches was explored (Aim 3). These findings demonstrated that while players improved their ratings on the blackness test, this improvement did not translate to the practical environment as the internal-external load relationship was largely consistent for all RPE scores irrespective of familiarisation or no familiarisation. In Chapter 6, the associations between internal and external load (dose-response relationship) were analysed (Aim 4). Specifically, session type-specific differences in perceived exertion (RPE, dRPE) at pre-specified values of absolute and relative high-speed running distance were assessed. Although for explorations with RPE-L as response variable, density strips indicated some clear and practically relevant effects, both RPE-L and RPE-B exhibited high levels of agreement with global RPE regardless of whether external load is measured using absolute or individualised speed thresholds. Therefore, practitioners can confidently use global RPE to monitor players' internal responses across various training contexts.

7.2 General Discussion

The aim of this thesis was to investigate the quantification of the physical demands of training and match-play in elite youth soccer players. The following section aims to discuss the general outcomes of this thesis with reference to the theoretical and methodological frameworks associated with the relationship between external and internal training load in elite soccer.

Chapter 3 primarily focused on presenting a novel approach for assessing the validity of measurement tools in sports performance. This is the first attempt to integrate expert opinion into the statistical framework for determining the validity of an outcome measure in sports performance. Specifically, Chapter 3 utilised MSS obtained from both a criterion measure (100-Hz Laser) and a non-criterion measure (10-Hz GPS) to demonstrate a newly proposed method for validity assessment. This method incorporates equivalence testing, which is further informed by expert practitioner opinion. Here, practitioners (sport scientists, strength and conditioning coaches, and fitness coaches) currently working in elite soccer were asked about perception and practices of their teams' measurement of MSS. In line with previous research (Roe et al., 2017), our findings indicate that GPS-derived MSS is likely comparable to the criterion measure, suggesting that 10-Hz GPS can serve as a valid tool for assessing MSS. Consequently, practitioners should have continued confidence in using GPS technology for this purpose.

The findings in Chapter 3 offer significant practical advantages. By leveraging the use of GPS units which can be integrated into daily training routines, practitioners can assess player performance without the need for separate, time-consuming testing sessions. This not only saves time within the training session but also increases the efficiency of the overall training and assessment process. While prior studies have affirmed the validity of

10-Hz GPS for measuring MSS (Roe et al., 2017), these comparisons were based on standardised scales, which can sometimes lack real-world relevance and fail to address the specific needs of applied research (Pek & Flora, 2018). In contrast, our approach, which incorporates expert opinion within the statistical framework, provides a more contextually meaningful definition of practically important differences. This approach is particularly useful in determining an acceptable level of measurement error, as outlined in Chapter 3, and aligns with previous recommendations for considering expert input in the context of sports performance assessment (Lassere et al., 2001). By setting our equivalence bounds according to the acceptable amount of measurement error as determined by a relatively large sample of experienced practitioners, we address several key methodological concerns. This approach not only offers a more practical and contextually relevant definition of measurement error but also effectively resolves issues such as justifying the smallest effect size of interest for the equivalence bounds, a common challenge in equivalence testing (Lakens et al., 2018). By incorporating expert opinion, we ensure that the established bounds are both meaningful and applicable to real-world sports performance assessment, thereby enhancing the external validity of our findings. If standardised thresholds were used in this chapter 3, the resulting outcome for defining a meaningful difference between the criterion and non-criterion measures would have been unrealistic. For instance, the pooled standard deviation for the maximal sprinting speeds recorded by GPS and Laser was 0.32 m/s. When using 0.2 standard deviations as the smallest effect size, we obtain a value of 0.06 m/s, leading to an equivalence range of −0.03 m/s to +0.03 m/s. These values, however, lack practical relevance in the real world, since only 15 of 49 experts surveyed considered a measurement error of 0.10 m/s or less to be acceptable.

Chapter 3 also offered important insights into current practices related to the measurement of MSS in elite soccer. Survey responses indicated that laser or radar guns, fully automatic timing systems, and timing gates are most commonly regarded as the gold standard for MSS measurements. Interestingly, although GPS was the most frequently used system among respondents (49%) for assessing MSS, only 16% identified it as a gold standard method. This discrepancy highlights a potential gap between practical usage and perceived measurement accuracy within the field. The relatively low frequency of system validity checks reported in our study, where 40% of respondents indicated they had never conducted any form of validity assessment, may not necessarily reflect a lack of awareness or understanding among practitioners. Instead, it may also be indicative of practical constraints, particularly the time pressures inherent in high-performance sporting environments, which can limit the feasibility of conducting regular methodological evaluations.

Regarding the methods practitioners use to obtain MSS, our survey revealed that the most commonly reported single approach was through structured fitness testing, cited by 44% of respondents. In contrast, only a small proportion (14%) indicated that they assess MSS during regular training sessions. However, in light of the validity findings presented in Chapter 3, practitioners should have confidence in the use of GPS technology to monitor and assess MSS within the context of routine training. This not only supports more ecologically valid data collection but also offers a more time-efficient and integrated approach to performance monitoring in high-performance environments. Although many practitioners routinely implement fitness testing, either as standalone sessions or integrated within training, recent research has questioned the necessity of dedicated sprint testing. A study conducted in semi-professional senior players by Massard et al. (2018) found that MSS achieved during matches were actually higher than those recorded during a standard

40-metre maximal sprint test. These findings suggest that match-play may, in some cases, offer a more accurate reflection of an athlete's maximal sprinting capacity. Notably, this contrasts with earlier research in youth soccer populations, where MSS during match play were reported to be approximately 90% of those achieved in controlled 40-meters sprint tests (Mendez-Villanueva et al., 2011; Al Haddad et al., 2015).

The purpose of Chapter 4 was to investigate whether the key finding reported by Massard et al. (2018), that MSS achieved during match play can exceed those attained during formal sprint tests, could be replicated in elite youth soccer players across a wider range of soccer-specific activities. This line of inquiry is particularly relevant given that MSS serves as a central performance metric within this thesis, forming the basis for advancing the practice of individualised training prescription and more accurate training and match performance evaluation. The results of this study did not replicate the findings of Massard et al. (2018), as MSS captured via GPS during the 40-meters sprint test was greater than MSS observed during competitive matches. This outcome is in agreement with previous studies, which reported that elite youth soccer players tend to reach only approximately 90% of their top sprinting speed during match play (Mendez-Villanueva et al., 2011; Al Haddad et al., 2015). These findings reinforce the notion that maximal sprinting efforts are more consistently achieved in structured testing environments compared to the variable and unpredictable demands of match situations. This is likely attributable to the fact that match-play rarely affords players the opportunity to sprint at maximum velocity over sufficiently long distances; a limitation largely imposed by tactical constraints, positional responsibilities, and the spatial dynamics of the game itself (Mendez-Villanueva et al., 2011).

As previously discussed, the practical relevance of the findings presented in Chapter 4 lies in advancing the application of individualised training prescription and match evaluation. Given the inherently individualised nature of the exercise-intensity continuum, the use of absolute speed thresholds poses the risk of significant measurement and interpretive error when quantifying HSR distances. Defining speed zones relative to each player's physical capacities offers a promising alternative, as it may reduce such errors and enhance the accuracy of dose-response assessments in both training and competition settings (Hunter, 2014; Abbott et al., 2018). Whether applied independently or in conjunction with maximal aerobic speed, MSS remains a fundamental variable for the individualisation of external training loads (Mendez-Villanueva et al., 2013; Hunter et al., 2014; Abbott et al., 2018). Consequently, obtaining an accurate measure of this metric is essential.

In the current literature, various methods have been used to determine MSS for the purpose of individualised speed zones. These include using MSS attained at any point during the season (Reardon et al., 2015; Casamichana et al., 2018), during match play (Cahill et al., 2015), or through formal sprint testing protocols (Mendez-Villanueva et al., 2013; Hunter et al., 2014). Findings from the practitioner survey presented in Chapter 3 revealed that MSS is most commonly derived from sprint tests (44%), with a further 30% of practitioners reporting the use of a combination of methods. Deriving values from physical training sessions alone was less common (14%), and very few practitioners relied on match play (8%) or skill-based conditioning formats such as small- or medium-sided games (4%). Supporting this practical perspective, Chapter 4 demonstrated that MSS values achieved during a training session specifically designed to expose players to MSS were consistently higher than those observed during integrated soccer-based training activities, including small-sided, medium-sided, and large-sided games. Furthermore, even MSS recorded during match play exceeded those attained during SSGs and MSGs, reinforcing the idea that certain formats of soccer-specific training are not sufficient to elicit true maximal sprint efforts. Chapter 4 results align with previous research in elite youth soccer players (Djaoui et al., 2017; Olthof et al., 2018), which suggests that small-sided games (SSG), medium-sided games (MSG), and, to a lesser extent, large-sided games (LSG), may be insufficient for developing MSS. Given the limited sprinting demands typically elicited in these formats, it is recommended that coaches incorporate additional, targeted MSS training drills to ensure players are regularly exposed to adequate high-speed stimuli. Such practices are essential for optimally preparing players for the sprinting demands encountered during competitive match play (Djaoui et al., 2017). Although the analysis in this chapter was based on a relatively small number of matches, the variability observed in peak velocity remained low. This is noteworthy given the well-documented match-to-match fluctuations typically seen in sprinting (Gregson et al., 2010). Specifically, MSS varied by ~ 6%, which is in line with previous literature (Al Haddad et al., 2018) and markedly less than the reported variability for sprint distance, which can reach up to 30% (Gregson et al., 2010).

Following the focus on external load in Chapters 3 and 4; Chapters 5 and 6 provided a comprehensive investigation into the internal load responses elicited in response to soccer-specific external training (external load). Perceived exertion scales are now widely recognised as a valid and established method for obtaining proxy measures of internal load in soccer, both during training sessions and competitive match play (Wright et al., 2020; Maughan et al., 2020). Chapter 5 provided novel and detailed insights into the influence of familiarisation to the perceived exertion scales on the relationship between internal and external load indicators in youth soccer players. Chapter 5 specifically examined whether improvements in players' perceptual accuracy and rating precision, achieved through a structured familiarisation protocol (Macpherson et al., 2019), would strengthen the associations between commonly used measures of internal load (RPE and dRPE) and external load (accelerations, decelerations, HSR). Chapter 5 observed a stepwise improvement in players' performance on the blackness test, a task designed to assess perceptual cognitive alignment with physical exertion demands, across three familiarisation sessions. The proportion of correct responses increased markedly from 39% in the initial trial to 64% in the second, and 78% in the third session. Concurrently, the absolute error in exertion rating precision decreased progressively, from 9 AU in session one to 5 AU and 3 AU in sessions two and three, respectively. These improvements indicate that the familiarisation process successfully enhanced players' ability to interpret and communicate internal sensations of exertion in a more accurate and consistent manner.

Despite notable gains in perceptual accuracy and rating reliability on the blackness test, the analyses revealed that familiarisation did not substantially alter the strength or consistency of the relationship between internal and external load measures. This indicates that, although the familiarisation process enhances the reliability and construct validity of subjective measures such as the RPE and dRPE, it does not exert a statistically meaningful moderating effect on the association between internal and external load metrics. Familiarisation effects were not practically relevant for any RPE measurement irrespective of the number of acceleration or deceleration efforts and high-speed running distance covered; apart from the RPE-L at 30 acceleration efforts where higher scores were reported for players who did not undergo familiarisation versus players who completed the familiarisation. The reason for this occurrence is unclear. However, as RPE-L may represent a more accurate indicator of the peripheral load experienced by soccer players during training in small spaces with a high frequency of accelerations (Hampson et al., 2001; Vanrenterghem et al., 2017), it is possible that the precise demands of acceleration movements within small spaces are more difficult for less familiarized players to accurately perceive. A potential limitation of chapter 5 arises from the interpretation of familiarisation effects on dRPE scores without controlling for the influence of session type. As different training modalities may elicit varying perceptual responses, the absence of session-type stratification may confound the observed familiarisation effects. Nonetheless, findings of chapter 5 suggest that the practical utility of dedicating substantial time to familiarising players with exertional measurement procedures may be limited. Consequently, practitioners might achieve greater overall benefit by redirecting their efforts toward other aspects of load monitoring and performance management.

The final aim of the thesis was twofold. First, between-method agreement for the quantification of HSR distance was assessed by comparing absolute and relative speed threshold approaches. Analyses were conducted separately for different session types, game, strength, endurance, and speed sessions. Chapter 6 results confirm previous research (Scott & Novell, 2018) which demonstrated higher HSR distances when using absolute speed zones versus relative, irrespective of session type. The use of relative HSR thresholds resulted in consistently lower median high-speed running distances compared to absolute thresholds across strength (176 m vs. 168 m), endurance (268 m vs. 247 m), and speed (173 m vs. 146 m) sessions, suggesting that individualised thresholds provide a more conservative estimate of high-intensity running demands during different training modalities. Relative thresholds are particularly relevant for optimising individual physiological adaptations, as they account for inter-individual variability (Gualtieri et al., 2023). In contrast, absolute thresholds remain prevalent in applied practice due to their simplicity, ease of implementation, and utility in standardizing performance metrics across individuals and teams (Malone et al., 2017). These findings underscore the importance of integrating both absolute and relative speed thresholds in comprehensive training analyses, as this dual approach facilitates a more nuanced understanding of player load. Such insights support more precise training prescriptions and individualized recovery strategies (Gabbett et al., 2015; Malone et al., 2017).

The second aim of Chapter 6 was to investigate the associations between internal and external load (dose-response relationship). This chapter is the first to assess, session type-specific differences in perceived exertion (RPE, dRPE) at pre-specified values of absolute and relative HSR distance in elite youth soccer players. The results presented in Chapter 6 showed the global RPE response to external load remained similar whether analysed using absolute or relative speed zones. Moreover, global RPE did not change across the different type of training sessions. These findings are in agreement with previous research (Hutchinsona & Tenenbaum, 2006; Weston, 2015), indicating that although global RPE offers a general assessment of exercise intensity, it lacks the sensitivity required to capture the full spectrum of exertion signals during games or specific types of training sessions.

A deeper analysis of the dRPE measures reveals additional nuances in the exertional responses elicited by various training modalities. After a visual inspection of the density strips surrounding the mean estimate, with RPE-B as a response variable, most of the estimated effects did not exceed the predefined target of 8 au (Wright et al., 2020), therefore there they were not practically relevant. This suggests that RPE-B lacks sensitivity to variations in physiological stress induced by different training types, regardless of whether absolute or relative speed thresholds are employed. These results are consistent with previous studies conducted with professional soccer players (Maughan et al., 2020; Houtmayers et al., 2022), which demonstrated that RPE-B provides no clear evidence of a relationship with external load when using absolute thresholds. Conversely, a study involving rugby players (McLaren et al., 2017) indicated that RPE-B may successfully isolate specific perceptual demands of training when absolute thresholds are applied. This discrepancy in findings may be attributed to factors such as differences in the type of sport within the sample populations and the duration of the respective studies. Consequently, further research is warranted to better understand how these factors influence the sensitivity of RPE-B across various contexts.

In contrast to RPE-B, exploring RPE-L as the response variable, density strips identified clear and practically meaningful effects, especially at 500 m HSR distances, irrespective of whether absolute or relative HSR thresholds were employed. Specifically, differences in RPE-L were observed between game and endurance sessions (15 au vs. 14 au) as well as between game and speed sessions (16 au vs. 13 au). In contrast, the comparison between strength and endurance sessions at an absolute HSR distance of 500 m revealed a mean difference of 9 au. These results align with previous studies showing that RPE-L is responsive to changes in external load when absolute thresholds are used (McLaren et al., 2017; Wright et al., 2020). The findings presented in Chapter 6 suggest that RPE-L exhibits greater sensitivity to variations across different training modes compared to RPE-B. However, both measures maintain a strong association with global RPE. Notably, this relationship persists regardless of whether external load is assessed using absolute or individualised speed thresholds. These findings suggest that dRPE measures do not provide additional insight beyond what is captured by global RPE. As such, practitioners can confidently rely on global RPE to monitor players' internal responses across a variety of training contexts, without the added complexity of implementing dRPE protocols.

7.3 Practical Applications

A comprehensive understanding of the associations between internal and external loads is essential for optimising training prescription, informing periodisation frameworks, and enhancing player management, particularly as different training modalities distinctly affect the dose-response relationship when using external load individualised to players physiological capacities. The findings presented in this thesis offer important contributions to the current body of knowledge on this subject, enhancing the understanding of key concepts and providing new empirical evidence to support future research and practice. Through the application of an analytical framework informed by expert consensus on acceptable levels of measurement error in maximal sprinting speed assessment, this thesis provides evidence supporting the validity of GPS technology for evaluating MSS in elite youth soccer players. Moreover, the findings underscore the importance of adopting externally valid methodologies when determining thresholds for practically meaningful performance differences. This approach incorporates equivalence testing, guided by expert practitioner opinion. By establishing equivalence bounds based on the acceptable measurement error identified by a relatively large cohort of experienced practitioners, this method addresses several important methodological limitations commonly encountered in the assessment of maximal sprinting speed. Given the validity findings presented, practitioners can have increased confidence in the use of GPS technology to monitor and assess maximal sprinting speed within the context of their training routine.

Chapter 3 also provides valuable insights into prevailing practices for measuring MSS in elite soccer. Expert interviews revealed a concerning lack of routine validity checks on the systems used, which appears to stem not from a lack of awareness, but rather from time constraints faced by practitioners who nonetheless recognize the importance of such assessments. Moreover, in terms of the methods practitioners use to obtain MSS, our survey showed that the most commonly reported approach was through structured fitness testing and in less extent during regular training sessions and match-play. During match play, players typically reach only about 90% of their MSS, with sprinting efforts being more reliably achieved in controlled testing environments compared to the unpredictable and varied demands of match situations. Furthermore, the findings of this thesis revealed that maximal sprinting speeds attained during training sessions specifically designed to elicit maximum sprinting efforts were consistently higher than those observed during integrated soccer-based training activities, such as small-sided, medium-sided, and large-sided games. From a practical standpoint, soccer coaches should incorporate targeted sprint-specific drills into their training programs to better prepare players for the most demanding phases of match play. These drills are essential for simulating worst-case scenarios, such as high-intensity counterattacks or defensive recovery runs, where players must perform maximal-effort sprints, often under fatigue.

In the second part of this thesis, which focused on the assessment of training load, Chapter 5 demonstrated that, despite general recommendations advocating the use of educational tools, such as familiarisation with the exertional scales to enhance players' perceptual awareness when using exertional scoring methods, the findings of this study raise questions about the practical effectiveness of these tools in applied settings. The results of this chapter demonstrated that although familiarising players with exertional scales through the blackness test led to improvements in blackness test scores after only three sessions, familiarisation with exertional scales did not influence RPE ratings and their relationship to external load, when comparing players who completed the learning trial to those who did not receive any familiarisation. Therefore, coaches and practitioners can be reassured that exertional scales, such as the CR100, can be effectively employed without the need for extensive player familiarisation. Given that prior exposure to the scale does not appear to meaningfully influence RPE responses, practitioners may prioritise their time and resources toward other aspects of training and monitoring, rather than investing in additional familiarisation sessions.

The results of this Chapter 6 revealed that absolute HSR distances were consistently greater than those derived from relative thresholds across all training modalities. This finding underscores the importance of using both absolute and relative thresholds when evaluating training and match-play demands. Absolute thresholds allow for standardisation and easier comparison across athletes and time points, while relative thresholds provide individualised insight that accounts for variations in fitness, playing position, and training phase. Practitioners are therefore encouraged to adopt a dual-threshold approach, leveraging the practical advantages of absolute thresholds alongside the contextual accuracy of relative measures. In addition, chapter 6 suggests that practitioners can confidently rely on global RPE to monitor players' internal responses across a wide range of training contexts. While RPE-L demonstrated greater sensitivity to different training modalities compared to RPE-B, both measures showed strong alignment with global RPE scores. Importantly, this relationship held regardless of whether external load was quantified using absolute or individualised speed thresholds, reinforcing the robustness of global RPE as a simple yet effective tool for internal load monitoring. This provides strong justification for its continued use, especially in applied settings where time, resources, and player compliance may limit the feasibility of more complex monitoring protocols like dRPE.

In summary, the quantification of the training loads may assist a multidisciplinary approach to guide coaches in their training prescription. The success of such a framework will be greatly influenced by the honesty and compliance of individual players (i.e. truthful reporting of RPE, wearing their GPS units daily) and the buy-in of the coaching staff. It is crucial to establish a cohesive network of staff to ensure the efficient dissemination of data to coaches and players, thereby facilitating the development of an effective training load management system. Future considerations should examine the variations in training periodisation strategies within youth soccer, exploring how different training philosophies influence the distribution of training load, and assessing how these variations may affect player recovery and injury outcomes.

7.4 Conclusion

Chapter 3 is the first to integrate expert practitioner opinion into a statistical framework for evaluating validity within a sports performance context. Although assessing validity through practitioner-informed criteria, rather than relying exclusively on standardized thresholds, may be more time-intensive, it remains a methodologically accessible approach. Crucially, this integration enhances the external validity and applied relevance of the findings, thereby bridging the gap between empirical research and practical application in high-performance sport. Considering the pivotal role of sprinting in elite soccer performance alongside the increasing emphasis on individualised training prescription and match evaluation, it is essential that players are consistently exposed to high running velocities during training. Such exposure is most effectively facilitated through the inclusion of purposeful sprinting drills that provide adequate space, typically around 40 meters, to allow players to achieve near-maximal or maximal sprint speeds.

Chapters 5 and 6 investigated the associations between internal load and external load (dose-response relationship). First, a methodological approach study (chapter 5), demonstrated that although players demonstrated improved scores on the blackness test, this enhancement did not manifest in meaningful changes within the applied setting, as the internal and external load relationship remained largely stable across all RPE scores, regardless of familiarisation. Consequently, practitioners may be better served by directing their time and resources toward alternative strategies that more effectively support training load monitoring. Chapter 6 presents a novel and practical approach to evaluating session type-specific variations in perceived exertion, grounded in predetermined thresholds of both absolute and relative HSR distances. The findings demonstrate that absolute speed thresholds consistently yield higher HSR distances than relative thresholds, irrespective of session type. Moreover, dRPE measures did not offer additional value beyond that provided by global RPE, regardless of the thresholding method employed. These outcomes collectively suggest that global RPE remains a valid and efficient tool for monitoring internal responses to external training loads across various draining drills. As such, practitioners can confidently implement global RPE in daily training environments without the need for further dRPE measures.

CHAPTER 8: RECOMMENDATIONS FOR FUTURE RESEARCH

8. Recommendations for Future Research

The studies completed within this thesis provided novel information relating to the quantification of the physical demands of training in elite youth soccer players. Specifically, insights into, the validity of GPS-based speed measurements, contextual considerations for sprint performance assessment, and the use of perceived exertion scales to evaluate internal load, were attained. In achieving this, a number of issues have arisen which have prompted the formulation of recommendations for further research.

8.1 Research proposals in response to the findings in Chapter 3

Chapter 3 introduced a novel equivalence testing framework to assess the validity of 10-Hz GPS devices against a 100-Hz laser criterion for measuring maximal sprinting speed (MSS). While findings indicated likely equivalence based on expert-defined thresholds, future work could extend this methodology to other external load metrics such as acceleration, deceleration, and high-intensity efforts. These metrics are considered to be equally important for performance monitoring in soccer (Akenhead and Nassis, 2016) and may demonstrate different levels of sensitivity to measurement error (Buchheit et al., 2014). Furthermore, future studies should consider applying equivalence testing across a broader range of playing levels and environmental conditions (e.g., surface type, weather, footwear). Incorporating experts' opinion from real-world experience can enhance the development of practitioner-informed equivalence thresholds, ensuring that validation strategies remain closely aligned with the applied demands of high-performance sport (Dixon et al., 2018).

8.2 Research proposals in response to the findings in Chapter 4

Chapter 4 investigated whether MSS is more accurately captured during structured sprint testing or within soccer-specific contexts such as training sessions and match play. The findings demonstrated that 40-m sprint tests elicit significantly higher sprint velocities than those attained during typical soccer activities, reinforcing the value of formal testing protocols for assessing true maximal speed. Nevertheless, future research is warranted to determine the generalisability of these results across diverse populations, including various age categories (e.g., U17 vs. senior players) and levels of competition (e.g., amateur vs. professional).

Given the relatively low number of match observations in this chapter, future work should aim to replicate these findings across a larger match sample to further confirm the match-to-match reliability of maximal sprinting speed. While the variability observed here (~6%) was low and consistent with previous research (Al Haddad et al., 2018), increasing the number of observations could help validate this outcome across a broader range of competitive scenarios, particularly considering the known variability in sprinting metrics during match play (Gregson et al., 2010). Moreover, future studies should explore positional differences in maximal sprinting speed, which were not possible to examine here due to the limited subject sample. Given that sprint demands can differ significantly by playing position (Mendez-Villanueva et al., 2011; Djaoui et al., 2017), such differentiation would provide more nuanced, role-specific insights that can enhance position-tailored training and monitoring strategies. Longitudinal studies, tracking maximal sprinting speed over a season could reveal how training load, fatigue, and tactical context influence an athlete’s ability to reach MSS in matches. These insights could improve both sprint profiling and load management practices in elite soccer.

8.3 Research proposals in response to the findings in Chapter 5

Chapter 5 provides important insights into the role of familiarisation with perceived exertion scales and their influence on the relationship between internal and external training load in elite youth soccer. Although familiarisation improved players' conceptual understanding of the CR100 scale; as evidenced by higher scores in the blackness test (Macpherson et al., 2019), these improvements did not meaningfully moderate the internal-external load relationship during training and match-play. Familiarisation protocols themselves also warrant improvement and standardisation. While this chapter incorporated repeated exposure and blackness test validation, future work should explore more immersive approaches. These could include real-time feedback, contextual anchoring using video demonstrations, or coach-led discussions to help athletes better associate internal sensations with the scale's descriptors (Saw et al., 2017; Macpherson et al., 2019). Investigating whether such enriched familiarisation enhances rating accuracy or alignment with objective load metrics could further optimise RPE-based monitoring systems. Additionally, an important area for future inquiry is the interaction between psychological and physiological markers and dRPE in explaining internal load variation. Integrating subjective measures with physiological indicators (e.g., heart rate variability, neuromuscular fatigue, salivary biomarkers) and psychological assessments (e.g., stress, motivation, readiness) could support the development of more comprehensive, athlete-centred monitoring frameworks (Thorpe et al., 2017; Impellizzeri et al., 2019). These multifactorial approaches are particularly relevant in youth sport, where developmental, emotional, and contextual variables strongly influence how athletes perceive and report exertion.

Furthermore, the equivalence testing range used in this study (–4 to +4 AU) warrants further examination, particularly when considering its application across different populations, training environments, and levels of competition. Although this range was informed by prior research in youth female soccer (Wright et al., 2020), its transferability to other cohorts, such as elite youth male players, remains uncertain. Physiological responses, perceptual scales, and training load distributions can vary significantly across age groups, sexes, and playing standards, which may influence what constitutes a "practically meaningful" difference in RPE or other load-related measures. Future research should aim to establish empirically grounded, context-specific equivalence margins that reflect the unique demands and variability of the targeted athlete group, thereby improving the interpretability and practical relevance of dose-response analyses.

8.4 Research proposals in response to the findings in Chapter 6

The findings presented in Chapter 6 provide new insights into the associations between internal and external load in soccer, particularly through the novel integration of individualised speed thresholds and dRPE across various field-based training modalities. Chapter's findings confirm previous observations which demonstrated higher high-speed running distances when using absolute speed zones versus relative, irrespective of session type (Scott & Novell, 2018). Current practices for individualised speed thresholds typically use maximal sprint speed (MSS) (Harley et al., 2010; Cahill et al., 2015; Gabbett, 2015; Reardon et al., 2015), or a combination of maximal aerobic speed (MAS) and MSS (Mendez-Villanueva et al., 2013; Hunter et al., 2015; Scott & Lovell, 2017; Abbott et al., 2018). However, athlete capacity can fluctuate over time due to training adaptations, fatigue, or injury. Therefore, future studies should evaluate the benefits of dynamically updated thresholds and their impact on the accuracy of training load monitoring and decision-making. Furthermore, implementing individualised thresholds requires time, testing, and system integration, which may present challenges for practitioners working in high-pressure environments. Applied research is needed to assess the feasibility, scalability, and compliance associated with these monitoring protocols

Furthermore, RPE-L is more sensitive to different modes of training than RPE-B but provides information consistent with global RPE independent of whether absolute or individualised speed thresholds are used to measure external load. Given the observed inconsistency in RPE-B sensitivity across studies, further work should aim to outline the specific conditions under which RPE-B may or may not provide meaningful and valid insights into internal load. These inconsistencies suggest that RPE-B may be context-dependent, influenced by a range of interacting factors related to the nature of the exercise stimulus, the athlete's physiological status, and the perceptual complexity of exertion. Future studies should systematically examine session-specific variables such as exercise intensity, session duration, work-to-rest ratios, and the type and structure of drills or conditioning activities to determine how these factors modulate breathlessness and its perceptual differentiation from muscular fatigue (Weston et al., 2015; McLaren et al., 2017; Wright et al., 2020). In contrast, as RPE-L specifically targets peripheral exertion, typically associated with muscular fatigue and neuromuscular stress, it has the potential to provide a more nuanced view of localized load, especially in sessions that emphasize strength, sprinting, or eccentric loading (Weston et al., 2015; Houtmeyers et al., 2022). To further validate RPE-L, its relationships with both objective neuromuscular load indicators and subjective perceptions of muscular fatigue should be explored. This may include correlations with metrics such as sessional volume of eccentric loading, MSS, or delayed onset muscle soreness (DOMS). Research in this direction will help determine whether RPE-L can serve as a more accurate proxy for musculoskeletal stress than global RPE, thereby improving the precision and effectiveness of training prescription and recovery management in elite sport settings.

CHAPTER 9: REFERENCES

9. References

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CHAPTER 10: APPENDIX

10. Appendix

A NOVEL APPROACH TO ASSESSING VALIDITY IN SPORTS PERFORMANCE RESEARCH: INTEGRATING EXPERT OPINION INTO THE STATISTICAL ANALYSIS

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TO MEASURE PEAK VELOCITY IN SOCCER, LET THE PLAYERS SPRINT

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INCONSISTENT EFFECT OF PSYCHOMETRIC-SCALE FAMILIARIZATION ON THE RELATIONSHIP BETWEEN RATINGS OF PERCEIVED EXERTION AND EXTERNAL LOAD MEASURES IN ELITE YOUTH SOCCER PLAYERS

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